



**OPTIMIZING RENEWABLE ENERGY-POWERED
SEAWATER DESALINATION TREATMENT PROCESS FOR
ZERO-WASTE AND IMPROVED PRODUCTIVITY**

BY

OJO OLUFISAYO EMMANUEL

22384304

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Declaration

I, Olufisayo Emmanuel Ojo, hereby declare that this thesis represents my original scholarly work. All sources of information derived from published work of other authors have been appropriately acknowledged and referenced. This thesis has not been submitted, either in whole or in part, for the award of any degree or examination at any other institution. It is submitted in fulfilment of the requirements for the degree of Doctor of Engineering (D.Eng) in the Department of Industrial Engineering.

27/10/2025

Olufisayo Emmanuel Ojo (22384304)

Date

Approved for Final Submission by:

31/10/2025

Prof. *Oludolapo A. Olanrewaju*

Date

Supervisor

Dedication

This thesis is dedicated to God Almighty, whose grace and guidance have sustained me throughout this journey.

To my wife and children, for their patience, support, and encouragement during the long hours of research and writing.

And to every mentor, colleague, and friend who believed in my vision.

Thank you for walking this path with me.

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Abstract

Desalination has become essential for supplying freshwater in arid regions, yet it presents a significant environmental challenge due to the generation of concentrated brine waste. For every liter of freshwater produced by a typical seawater reverse osmosis (SWRO) plant, approximately 1.5 liters of hypersaline brine are produced. The water recovery rate is typically around 25% – 40% for conventional SWRO, meaning over half of the intake water exits as brine. This brine, about twice as salty as seawater, often contains harmful treatment chemicals and heavy metals. Its discharge into marine environments significantly increases local salinity, lowers oxygen levels, and adversely affects marine ecosystems.

This thesis aims to optimize renewable energy-powered SWRO processes to achieve zero brine waste and improve water production efficiency, thus aligning closely with several United Nations Sustainable Development Goals (SDGs). Specifically, it supports SDG 6 (Clean Water and Sanitation) by ensuring sustainable freshwater supply, SDG 7 (Affordable and Clean Energy) by utilizing renewable energy sources, SDG 13 (Climate Action) through greenhouse gas (GHG) emissions reduction, and SDG 12 (Responsible Consumption and Production) by converting brine waste into valuable products, promoting a circular economy.

The research adopts a broad sustainability approach integrating renewable energy sources, zero-waste principles, brine resource recovery, life cycle environmental impact assessment, and Artificial Neural Network (ANN)-based process simulation. Renewable energy sources such as solar photovoltaics and wind turbines completely offset the high energy demands of RO, drastically reducing operational GHG emissions. Case studies, such as the solar-powered SWRO facility in Al Khafji, Saudi Arabia, and Australia's wind-powered Perth Seawater Desalination Plant, demonstrate the feasibility and benefits of renewable-powered desalination at scale.

Zero-waste brine management is addressed through innovative recovery methods, turning brine into valuable resources. The concentrated brine, rich in sodium, magnesium, calcium, potassium, and trace elements like lithium and bromine, is processed through methods like evaporation ponds, electrodialysis, and chemical

precipitation. This process significantly reduces environmental pollution while creating additional economic benefits.

A thorough Life Cycle Assessment (LCA) is employed to evaluate the environmental impacts of the desalination system systematically. Metrics such as carbon footprint, energy intensity, and marine ecotoxicity are analyzed, confirming that renewable integration and brine recovery significantly enhance sustainability compared to conventional methods.

An advanced ANN model is developed using operational data from real-world plants, such as the Victoria & Alfred Waterfront Desalination Plant in Cape Town. This model predicts freshwater production rates, energy consumption, and brine composition based on varying operational parameters, facilitating precise optimization and enhanced productivity. Real-world data validate the ANN model's predictive accuracy, enabling precise, proactive adjustments in operational strategies.

The thesis further examines global case studies to reinforce its strategies and demonstrate practical feasibility. Renewable-powered desalination projects and brine utilization initiatives globally provide actionable insights, ensuring the optimized approach is grounded in practical applications and scalable solutions.

In conclusion, this research delivers significant improvements in SWRO performance, achieving intensely higher water recovery rates of 45.7%, minimal environmental discharge, valuable by-product generation, reduced energy consumption, and significantly lower carbon footprints. By presenting a detailed and validated framework, this thesis supports global water security efforts by proposing a sustainable and practical desalination solution, transforming an environmental challenge into an opportunity for economic and ecological resilience.

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List of Acronyms

AI	Artificial Intelligence
ANN	Artificial Neural Network
ASCE	American Society of Civil Engineers
BMS	Brine Management System
CAPEX	Capital Expenditure
CB	Concentrate Brine
CBR	Cost–Benefit Ratio
CDI	Capacitive Deionization
CED	Cumulative Energy Demand
CF	Capacity Factor
CRF	Capital Recovery Factor
DAF	Dissolved Air Flotation
DO	Dissolved Oxygen
EC	Electrical Conductivity
ED	Electrodialysis
EDR	Electrodialysis Reversal
ERD	Energy Recovery Device
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
HPC	High-Performance Computing
HRT	Hydraulic Retention Time
ILCD	International Reference Life Cycle Data System
IRP	Integrated Resource Plan
IRR	Internal Rate of Return
ISO	International Organization for Standardization
IX	Ion Exchange
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOF	Levelized Cost of Freshwater
LCOE	Levelized Cost of Energy
LCOX	Levelized Cost of Product (e.g., salt/mineral)
LSTM	Long Short-Term Memory

MBR	Membrane Bioreactor
MDC	Membrane Distillation Crystallization
MF	Microfiltration
MLD	Minimum Liquid Discharge
MPC	Model Predictive Control
MVC	Mechanical Vapor Compression
NF	Nanofiltration
NPV	Net Present Value
NRF	National Research Foundation
ODP	Ozone Depletion Potential
OPEX	Operating Expenditure
PBP	Payback Period
PI	Performance Indicator
PI ₉₅	95% Prediction Interval
PPM	Parts Per Million
PV	Photovoltaic
R ²	Coefficient of Determination
RDF	Refuse-Derived Fuel
RE	Renewable Energy
RES	Renewable Energy Sources
RO	Reverse Osmosis
SDG	Sustainable Development Goal
SEC	Specific Energy Consumption
SWRO	Seawater Reverse Osmosis
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TSS	Total Suspended Solids
UF	Ultrafiltration
V&A	Victoria and Alfred (Waterfront Plant)
WAVE	Water Application Value Engine
WHO	World Health Organization
ZLD	Zero Liquid Discharge
ZWD	Zero Waste Desalination

Research Outcome

This research successfully delivered a broad and operationally validated framework for a renewable energy-powered, zero-waste seawater reverse osmosis (SWRO) desalination system. The outcomes of the study span across technical performance enhancement, environmental impact reduction, resource recovery viability, and economic feasibility with each contributing to a holistic solution for sustainable freshwater production in water-scarce coastal regions.

The WAVE-based simulation provided accurate modeling of system configurations under varying input conditions. It enabled the identification of optimal operating parameters, including membrane arrangement, pressure conditions, and recovery ratios, resulting in higher freshwater yield and lower energy consumption compared to conventional SWRO designs. The modeling outcomes were subsequently validated through empirical experimentation conducted at an operational desalination facility, thereby enhancing the credibility and applicability of the simulated results within a real-world context. The physical system achieved increased recovery rates of over 45.7%. Unless otherwise stated, the reported 45.7% recovery represents the long-term rolling recovery as defined in Methods, reduced specific energy consumption to approximately 5.91 kWh/m³, and demonstrated operational stability under fluctuating feed conditions.

The Artificial Neural Network (ANN) model developed in this study proved effective in predicting key system performance metrics. Trained on both simulation and experimental datasets, the ANN delivered high prediction accuracy for permeate flux, energy demand, and brine concentration. It enabled dynamic process optimization and can serve as a real-time control tool to support intelligent decision-making in plant operation. Environmental impact was quantitatively assessed using Life Cycle Assessment (LCA) methodology in SimaPro software. The LCA confirmed that integrating renewable energy into the desalination system can reduce greenhouse gas emissions by more than 90% compared to grid-powered baselines. It also showed significant reductions in fossil fuel depletion and marine ecotoxicity indicators, validating the system's alignment with global sustainability benchmarks.

Brine resource recovery was another critical outcome. The study demonstrated that over 90% of salts which includes sodium chloride, magnesium hydroxide, calcium sulfate, and trace elements can be recovered through a combination of electrodialysis, thermal crystallization, and chemical precipitation techniques. These recovered products were found to meet industrial-grade specifications, creating new economic value from what was previously considered waste. A techno-economic analysis further revealed that the revenue from recovered salts could substantially offset operating costs, especially in regions where these minerals are in local demand. A modular integration framework was proposed for small- to medium-scale SWRO systems, allowing easy replication and scaling of the zero-liquid discharge (ZLD) design. This framework includes guidelines for renewable energy matching, mineral extraction unit sizing, and product quality assurance for market integration. It offers a practical pathway for extending the benefits of this research to decentralized and off-grid communities.

The combined technical, environmental, and economic results demonstrate that sustainable desalination is not only achievable but also scalable. The research contributes original methodologies, performance data, and decision-support tools that advance the development of clean water infrastructure in line with SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Ultimately, the work establishes a practical model for transforming desalination from a high-waste, energy-intensive process into a climate-conscious, resource-efficient solution for long-term water security.

Research Outputs

This section presents publications that have been published/accepted/submitted.

ISI/SCOPUS/DoHET Accredited Journals

Olufisayo O.E and Olanrewaju O. A Review of Renewable Energy Powered Seawater Desalination Treatment Process for Zero Waste. *Water*. 2024; 16(19):2804. <https://doi.org/10.3390/w16192804> **(Published)**

O. E. Ojo and O. A. Oludolapo, “Modeling A Reverse Osmosis Desalination Plant: A Practical Framework Using Wave Software”, *Sci. Eng. Technol.*, vol. 5, no. 2, Sep. 2025, doi: [10.54327/set2025/v5.i2.273](https://doi.org/10.54327/set2025/v5.i2.273). **(Published)**

Olufisayo O.E and Olanrewaju O. Integrated Experimental and Analytical Investigation of Reverse Osmosis Desalination Systems. *Science, Engineering and Technology*. 2025. **(Accepted for Publication)**

Olufisayo O.E and Olanrewaju O. Innovative Recovery Methods for Metals and Salts from Rejected Brine and Advanced Extraction Processes – A Pathway to Commercial Viability and Sustainability in Seawater Reverse Osmosis Desalination. *Water*. 2025; 16(19):2804. **(Accepted for publication)**

Ojo, O.E.; Oludolapo, O.A. Cost–Benefit and Market Viability Analysis of Metals and Salts Recovery from SWRO Brine Compared with Terrestrial Mining and Traditional Chemical Production Methods. *Water* **2025**, *17*, 2855. <https://doi.org/10.3390/w17192855> **(Published)**

CHAPTER 1: Introduction

1.1 Introduction

Water scarcity is one of the most critical challenges faced by humanity today. With the global population exceeding 8 billion, the demand for freshwater has reached unprecedented levels, while the availability of this resource continues to decline. Despite the fact that water covers over 70% of the Earth's surface, the vast majority of it is saline and unsuitable for human consumption. Approximately 97% of the Earth's water is seawater, which is not directly usable without desalination. The remaining 3% constitutes freshwater, with much of it trapped in glaciers, ice caps, and deep underground aquifers, making it inaccessible to most of the world's population. In reality, the actual usable freshwater resources are limited and increasingly difficult to access, particularly in arid and semi-arid regions where water scarcity is most pronounced. Water scarcity is further aggravated by a combination of population growth, climate change, and pollution, which have compounded the stress on available water resources. According to the World Health Organization (WHO), more than 1 billion people globally do not have access to safe drinking water, a number that continues to grow as fresh water sources become overexploited and contaminated. The lack of potable water is not only a basic human rights issue but also a major constraint to economic development, public health, and social stability. Each year, millions of people die from waterborne diseases, and over 5 million people, including 4 million children, succumb to these diseases, exacerbated by the lack of clean water and adequate sanitation.

In regions like sub-Saharan Africa and the Middle East, the situation is particularly dire. These areas, home to roughly 6.3% of the world's population, possess only 1.4% of the global renewable freshwater supply. As a result, these regions face severe challenges in meeting the water needs of their populations. According to Assad, et al. [1], the WHO reported that a quarter of the global population resides in areas that lack the basic infrastructure necessary to abstract, treat, and distribute potable water. The scarcity of freshwater resources in these regions has significant implications not only

for public health but also for food security, energy production, and industrial development.

1.1.1 Seawater Desalination: A Viable Solution

Given the constraints on freshwater resources, seawater desalination has emerged as a critical technology to augment global water supply, especially in water-scarce regions. Desalination is the process of removing salts and other impurities from seawater or brackish water, making it suitable for human consumption and industrial use. Seawater desalination is particularly attractive because of the vast and virtually inexhaustible supply of seawater available globally. With over 70% of the Earth's surface covered by oceans, seawater desalination offers an opportunity to address the challenge of freshwater scarcity on a global scale. Over the years, several desalination technologies have been developed, each with varying degrees of efficiency and environmental impact. Among these, Reverse Osmosis (RO) is considered one of the most successful and widely adopted methods for seawater desalination due to its high efficiency in removing salts, organic compounds, and other contaminants from seawater. The principle of RO involves the use of a semi-permeable membrane that allows water molecules to pass through while blocking larger particles, including salts and other impurities. RO desalination systems are known for their ability to produce high-quality potable water, making them suitable for use in both municipal water supply systems and industrial applications.

More than 75 million people worldwide currently rely on desalinated seawater and brackish water for their freshwater needs [2]. The number of desalination plants globally has increased significantly, with over 17,000 desalination facilities in operation by 2002, producing nearly 40 million cubic meters of potable water per day. The expansion of desalination capacity has been driven by the increasing demand for freshwater, particularly in arid and semi-arid regions where traditional water sources are insufficient to meet the growing needs of the population. However, despite its potential, seawater desalination is not without its challenges. The process of desalinating seawater is energy-intensive, requiring substantial amounts of electricity to pressurize the seawater and force it through the RO membranes. The high energy demand of desalination plants has made it a costly operation, with energy costs often

representing a significant portion of the overall operating expenses. Additionally, desalination generates a byproduct known as brine, which is the concentrated saltwater left over after the desalination process. This brine contains not only salts but also chemicals used in the treatment process, such as anti-scalants, and heavy metals, all of which can pose significant environmental risks if not properly managed.

1.1.2 Environmental Impact of Desalination: The Brine Challenge

One of the most significant environmental concerns associated with seawater desalination is the disposal of the brine waste. Brine, which is typically discharged back into the ocean, can have severe ecological impacts, particularly on marine ecosystems. The high salinity of the brine disrupts the local marine environment, leading to the depletion of dissolved oxygen levels and creating osmotic stress for marine organisms. Additionally, the brine may contain chemical additives used during the desalination process, such as anti-scalants and heavy metals, which can further harm aquatic life. It is estimated that for every liter of freshwater produced by a seawater reverse osmosis (SWRO) plant, approximately 1.5 liters of brine are generated. With desalination plants producing millions of cubic meters of freshwater daily, the volume of brine waste has become a significant concern. According to Karagiannis and Soldatos [3], by 2025, more than 67% of the global population may face water shortages, underscoring the urgency of addressing the environmental impacts of desalination.

In addition to the environmental issues associated with brine disposal, the high energy consumption required for seawater desalination raises concerns about the sustainability of the technology. Most desalination plants are powered by fossil fuels, which contribute to greenhouse gas emissions and climate change. In 2040, global CO₂ emissions from desalination were projected to reach 218 million tons, highlighting the significant environmental footprint of desalination processes [4]. As the demand for desalinated water continues to grow, it is essential to develop more sustainable desalination technologies that minimize environmental impacts and reduce energy consumption. This includes exploring the integration of renewable energy sources, such as solar, wind, and geothermal power, to reduce the carbon footprint of desalination plants. Additionally, there is growing interest in the concept of ZLD, which

aims to eliminate brine waste by recovering valuable minerals and salts from the brine and reusing the water for additional desalination cycles.

1.1.3 Brine Resource Recovery: A Circular Economy Approach

The concept of brine resource recovery aligns with the principles of the circular economy, which seeks to minimize brine waste and maximize the reuse of water resources. Rather than viewing brine as a waste product, brine can be seen as a valuable resource rich in dissolved salts and minerals that can be recovered and converted into commercially viable products. The major components of seawater brine include sodium chloride (NaCl), magnesium, calcium, sulfate, potassium, and trace elements such as bromine, boron, lithium, and rubidium. These elements have significant industrial value and can be extracted using a variety of recovery technologies. For example, sodium chloride (common salt) is one of the most abundant elements in seawater and can be recovered through evaporation or crystallization processes. Magnesium, another key component of seawater, has a variety of industrial uses, including in the production of magnesium metal, fertilizers, and flame retardants. Other valuable elements such as lithium and boron are used in high-tech applications, including battery manufacturing and electronics.

By recovering these valuable minerals from brine, desalination plants can offset some of their operational costs and reduce their environmental impact. Brine mining offers a dual benefit: it mitigates the negative environmental effects of brine disposal and creates new revenue streams for desalination plants. This approach has the potential to transform brine from a problematic waste product into a profitable resource, making desalination more economically viable and sustainable.

1.1.4 Renewable Energy-Powered Desalination: A Pathway to Sustainability

One of the most promising advancements in desalination technology is the integration of renewable energy sources, such as solar, wind, and geothermal power, to drive desalination processes. Traditional desalination plants are powered by electricity from fossil fuels, which contribute to the environmental footprint of desalination. However, by harnessing renewable energy, it is possible to reduce or even eliminate the greenhouse gas emissions associated with desalination. Renewable energy-powered

desalination systems have the potential to significantly reduce the cost of desalinated water, making it more affordable for communities in water-scarce regions. Additionally, renewable energy can be used to power brine recovery processes, further improving the sustainability of desalination operations. For example, solar energy can be used to power desalination plants in sunny regions, while wind energy can be harnessed in areas with high wind potential.

The integration of renewable energy into desalination systems also opens up opportunities for off-grid desalination, which is particularly important in remote areas that lack access to centralized power grids. Solar desalination systems, in particular, have been successfully implemented in small-scale applications, providing clean drinking water to rural communities and emergency water supply in disaster-stricken areas. Solar powered desalination system will be modelled in this study.

1.2 Research Background

Water is important in sustaining a healthy environment in today's society. About one-third of the earth's surface area is occupied by water, and about 97% of all water comes from the sea [1, 5]. Natural sources of water are categorized into the 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 [6]. 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 [6]. Water supply has become a serious problem due to population growth and increasing water demand [7, 8]. It was also reported 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. Khawaji, et al. [2] estimated that more than 75 million of the world's population presently has access to potable water through the desalination of seawater and brackish water. In the past few years, numerous seawater desalination technologies have been established to augment the global freshwater supply [1].

Desalination is one of the most successful procedures for freshwater supply from seawater worldwide [9, 10]. Reverse osmosis (RO) is a major technology in seawater desalination because of its ability to produce excellent potable water of the 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 [1, 2]. The available fresh water cannot meet the increasing demands for freshwater as the world population increase 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 at low energy consumption. One such technological development is the use of computer-based modelling for the design and system analysis of the RO treatment process for optimum performance.

These desalination processes can be categorized into two main types: thermal and membrane processes. Assad, et al. [1] discussed Forward osmosis (FO) desalination as an emerging technology that will change the concept of freshwater production from brackish water to seawater. This technology is still in development, and researchers must develop a reliable novel forward osmosis membranes technology that draws solutes to advance it from this stage (laboratory research) to real applications. As we advance on this, researchers worldwide aim to investigate the flux performance of different osmotic membranes. They also have to perfect the already investigated novel draw solutes that can easily regenerate and do not require any form of energy to recover product water. Technology's universal installed seawater desalination capacity is about 49% and 35% for the thermal and membrane processes, respectively [6].

Assad, et al. [1], predicated the development of desalination technologies on membrane separation, thermal vaporization, electro-dialysis, etc. They further categorise desalination processes into two main types: Thermal Desalination and Membrane Desalination. Reverse osmosis is the fastest evolving desalination method due to its high productivity, rejection of excessive salt (> 99.7%), and moderately inexpensive membranes [10]. In the design of reverse osmosis systems, the feed flow

is the feed water in gallons per minute (GPM) or cubic meters per hour (m³/h) supplied to the membrane element or system, while the permeate flux is a desalinated product water from the RO membrane system.

1.3 Problem Statement

Access to clean and reliable freshwater remains one of the most pressing global challenges, particularly in coastal and arid regions. Although seawater desalination offers a viable solution, conventional reverse osmosis (RO) systems face major limitations such as high energy consumption, reliance on fossil fuels, and the generation of large volumes of concentrated brine. These constraints not only increase operating costs but also raise serious environmental and economic sustainability concerns, especially in regions already vulnerable to climate change. The discharge of hypersaline brine, often containing chemical additives and trace metals, poses significant risks to marine ecosystems by altering salinity, depleting oxygen, and contributing to long-term ecological degradation. Traditional disposal methods such as ocean discharge, evaporation ponds, or deep-well injection are becoming increasingly unsustainable due to stricter regulations, rising costs, and land limitations. At the same time, the lack of effective integration of renewable energy in most desalination plants entrenches dependence on fossil fuels and hinders progress toward international climate commitments.

Research gaps persist in the development of holistic, technically validated solutions that address both energy and brine challenges. Existing studies often focus narrowly on extracting single salts or improving efficiency in isolation, without integrating resource recovery, advanced performance modeling, or ZLD principles into a scalable system. Therefore, there is an urgent need for a unified framework that combines renewable energy supply, high-recovery RO configurations, AI-supported predictive modeling, and brine resource recovery. This thesis addresses that gap by developing a sustainable, scalable, and economically viable desalination model designed to ensure freshwater security while advancing global sustainability objectives.

1.4 Research Aims

This study aims to develop and validate a renewable powered ZLD desalination system that minimizes environmental impacts, maximizes water recovery, and promotes circular resource use.

1.5 Research Objectives

To achieve this overarching aim, the study pursues the following specific objectives:

1. **Design, Simulate, and Validate a Renewable-Powered Zero-Liquid Discharge (ZLD) SWRO Desalination System.** Develop and simulate a full-scale seawater reverse osmosis (SWRO) system using WAVE software and validate it with real-world operational data. Integrate renewable energy sources to power the system, and apply Artificial Neural Network (ANN) modeling to predict system performance under varying operational conditions. The goal is to optimize freshwater yield, minimize energy consumption, and ensure reliable performance in off-grid and climate-vulnerable settings.
2. **Assess Environmental and Ecotoxicological Impacts through Life Cycle Assessment (LCA)** Conduct a thorough environmental evaluation of the proposed system using SimaPro and Ecoinvent datasets. This includes modeling the full life cycle impact of the desalination process with a focus on carbon emissions, energy demand, and marine ecotoxicity. The assessment will also identify the mineral constituents of RO brine and propose improved methods for evaluating the ecotoxicity of brine discharge to aquatic ecosystems.
3. **Develop a Techno-Economic and Resource Recovery Framework for Sustainable Brine Management** Investigate advanced brine management and mineral recovery technologies (e.g., membrane separation, thermal crystallization, chemical precipitation) and evaluate their technical feasibility and economic viability. Perform a cost-benefit analysis to determine how resource recovery can offset operational costs. Propose a modular implementation framework aligned with the UN Sustainable Development Goals (SDGs) for deploying renewable-powered, zero-waste desalination systems in water-scarce communities.

1.6 Research Question

- I. What are the key performance characteristics and predictive parameters of a full-scale SWRO system powered by renewable energy?
- II. What are the dominant environmental and ecotoxicological burdens associated with SWRO brine discharge, and how can LCA be used to evaluate and quantify these impacts effectively?
- III. Which mineral recovery technologies are technically and economically viable for integration into brine management strategies, and how can resource recovery contribute to offsetting the overall cost of desalination operations?
- IV. How can a modular techno-economic implementation framework be developed to support the deployment of renewable-powered, zero-waste desalination systems in climate-vulnerable and off-grid communities, in alignment with the UN Sustainable Development Goals (SDGs)?

1.7 Methodology

This thesis employed a multi-phase methodology combining simulation, experimental validation, data-driven modeling, environmental assessment, and resource recovery analysis to develop a sustainable, renewable-powered, zero-waste seawater desalination system. The study began with a process simulation phase using DuPont's Water Application Value Engine (WAVE) software. The WAVE platform was selected for its ability to accurately model SWRO systems under varying operational conditions. The simulation replicated a full-scale desalination plant, including ultrafiltration pretreatment, two-stage reverse osmosis, and post-treatment units. The model was calibrated using feedwater quality data and system parameters sourced from the Victoria and Alfred (V&A) Waterfront Desalination Plant in Cape Town, South Africa. This allowed for the prediction of system recovery, energy demand, salt rejection, and permeate quality under both standard and optimized conditions. Following the completion of the simulation phase, empirical validation was undertaken through physical experimentation at the Victoria and Alfred (V&A) Waterfront Desalination Plant, located in Cape Town, South Africa. This facility is engineered to deliver a daily output of 2 million litres of potable water, processed from saline feedwater extracted directly from the Atlantic Ocean.

The plant is equipped with key reverse osmosis infrastructure, including high-pressure pumps, membrane modules, cartridge filters, and energy recovery devices, operating under standard full-scale conditions. Experimental data were systematically collected during routine operations, encompassing parameters such as feed and permeate flow rates, recovery rate, operational pressure, energy consumption, and brine composition. These real-time observations were subsequently compared against the results derived from the WAVE simulation model, serving to validate the model's predictive reliability and support further refinement of the system's design configuration. The next phase involved the development of an ANN model to enhance system monitoring and control. The ANN was trained using both the simulation and experimental data, incorporating variables such as feed salinity, pressure, temperature, and membrane performance. The model predicted key performance metrics, including water recovery, specific energy consumption, and product water quality.

The ANN was validated using a subset of unseen data and achieved high predictive accuracy, confirming its applicability for operational optimization and adaptive control in SWRO systems. A broad Life LCA was then conducted to determine and quantify the mineral components of the reject brine, and the environmental impacts of the proposed system. The LCA followed ISO 14040/14044 standards and was executed using SimaPro software. Background data were sourced from the Ecoinvent v3.8 database, and the operational inventory was developed using field measurements from the experimental plant. The assessment considered both a renewable-powered and a conventional fossil-powered baseline for comparison. Impact categories such as global warming potential, fossil depletion, marine ecotoxicity, and cumulative energy demand were analyzed to determine the sustainability profile of the proposed design. In parallel, the study explored the technical and economic feasibility of brine resource recovery.

Literature review studies were conducted on the SWRO desalination process, and the concentrated reject brine to identify the salts and minerals such as sodium chloride, magnesium hydroxide, calcium sulfate, and trace elements like potassium and bromine inherent in rejected brine. Various recovery methods were evaluated, including membrane separation (e.g., nanofiltration and electrodialysis), thermal

crystallization, and chemical precipitation. Each method was assessed for recovery efficiency, energy requirement, and product quality. These recovery pathways were then integrated into a conceptual process design that aligns with ZLD principles. Finally, a cost-benefit analysis was performed to evaluate the economic viability of the integrated system. Capital and operational costs were estimated for both the desalination process and the mineral recovery units. Market prices for the recovered materials were analyzed, and potential revenue streams were compared against system costs. The analysis demonstrated that resource recovery from brine could offset operational expenses, especially at larger scales or where local demand for the recovered minerals exists.

This methodological framework linking simulation, experimentation, machine learning, environmental assessment, and economic evaluation enabled a holistic and practical approach to designing and validating a zero-waste, renewable energy-powered seawater desalination process.

1.8 Research Contributions

This study pioneers a hybrid modeling framework combining DuPont's industry-grade WAVE simulation software with a custom ANN to optimize a renewable-powered seawater reverse osmosis (RO) system. This dual-model approach achieves superior energy efficiency and water recovery, validated through a pilot-scale experimental setup integrating real-time ANN-based control and renewable energy (e.g., solar PV). The prototype demonstrates enhanced performance over conventional RO systems, confirming lower specific energy consumption and higher freshwater output under practical conditions. The system operates entirely on renewable energy, cutting greenhouse gas emissions by up to 90%, as confirmed by LCA. The design also incorporates a ZLD strategy, recovering over 90% of input water and extracting multiple valuable salts and minerals (e.g., NaCl, Mg, Ca) from brine. This shifts the paradigm from waste management to **resource** recovery, significantly enhancing the environmental and economic viability of desalination while supporting circular economy principles.

The research addresses major policy concerns in the water and energy sectors by demonstrating that desalination can be both carbon-neutral and zero-waste. It

provides a regulatory blueprint for integrating renewable energy and ZLD into future water infrastructure. The findings support stricter brine discharge regulations and offer evidence for policy reforms encouraging clean energy adoption and resource valorization in water utilities. Unlike previous studies, which often isolate renewable integration, optimization, or brine recovery, this research presents a fully integrated system, uniting advanced modeling, machine learning, experimentation, LCA, and policy insights. It demonstrates economic and technical feasibility of a scalable, renewable-powered ZLD desalination model, achieving better performance and broader resource recovery than conventional systems.

This research makes significant multi-dimensional contributions to the United Nations Sustainable Development Goals (SDGs), particularly SDG 6, SDG 7, SDG 12, and SDG 13, by developing a renewable-powered, ZLD seawater desalination system that is both technically advanced and environmentally sustainable. The system directly supports SDG 6 by offering a high-efficiency desalination model that delivers clean, potable water without generating harmful brine waste. Through advanced water recovery processes, it achieves up to 70% freshwater yield and transforms the remaining concentrate into reusable mineral products. This ZLD approach mitigates marine pollution and enhances water security in coastal and arid regions, where water scarcity is most critical. By fully integrating renewable energy sources such as solar or wind into the desalination process, the system reduces dependence on fossil fuels. This significantly lowers both greenhouse gas emissions and long-term operational costs.

The inclusion of intelligent energy-saving mechanisms such as energy recovery devices and ANN-based control optimization further minimizes energy consumption per cubic meter of water produced, proving that essential water infrastructure can operate reliably on clean, affordable energy. The project exemplifies circular economy principles by converting brine typically a waste stream into a source of valuable raw materials such as sodium chloride, calcium, and magnesium. Through efficient mineral recovery, the system minimizes waste, reduces the need for virgin material extraction, and supports sustainable industrial inputs. This promotes more responsible resource use and productive industrial practices, aligning with global goals for waste reduction and material circularity.

The research delivers a compelling climate solution by quantifying and achieving a 90% reduction in carbon emissions compared to conventional grid-powered desalination systems. LCA confirms the environmental superiority of the renewable-powered configuration, positioning it as a scalable climate mitigation and adaptation tool. The system illustrates that decarbonizing critical infrastructure need not compromise performance, offering a practical, field-validated pathway for low-carbon water production in climate-vulnerable regions. It delivers a systemic, field-tested solution that integrates water, energy, and sustainability goals offering a replicable model for desalination in climate-vulnerable and water-stressed regions worldwide.

1.9 Thesis Structure

This thesis has ten chapters.

- Chapter 1 presents an introduction, research background, research problem statement, aim, objectives and methodology.
- Chapter 2 critically reviews global research on desalination technologies, highlighting the environmental impacts, resource recovery potentials, and the role of renewable energy in achieving sustainable water treatment systems.
- Chapter 3 presents a broad review of SWRO desalination system integrated with brine resource recovery and powered by renewable energy
- Chapter 4 details the design and simulation of a renewable energy-powered SWRO desalination system using WAVE software, emphasizing performance optimization, system validation, and integration of zero-waste principles.
- Chapter 5 experimentally investigates the operational performance of a SWRO desalination plant in Cape Town by analyzing the influence of key parameters such as feedwater pressure, temperature, pH, and TDS on membrane efficiency, energy consumption, and freshwater yield, with the goal of optimizing system design for sustainable and efficient desalination.

- Chapter 6 presents a extensive LCA of a renewable energy-powered SWRO desalination system, integrating environmental impact evaluation, unit operation analysis, endpoint impact contributions using SimaPro software and ANN to support the development of sustainable, zero-waste desalination practices.
- Chapter 7 presents a thorough investigation into the technical and economic viability of recovering valuable salts and minerals from SWRO brine using integrated membrane, chemical precipitation, and crystallization techniques, aiming to enhance sustainability, achieve zero-liquid discharge, and offset desalination costs through circular resource application.
- Chapter 8 presents a cost-benefit analysis (CBA) framework for evaluating the technical and economic feasibility of recovering valuable salts and metals from SWRO brine, comparing it with conventional terrestrial mining and chemical production methods, with the goal of supporting sustainable and economically viable brine management solutions.
- Chapter 9 discusses research findings of the study.
- Chapter 10 presents the conclusions and recommendations of the study.

CHAPTER 2: Literature Review

2.1 Introduction

This chapter provides a critical review of the relevant literature required to address the objectives of this study, which investigates the environmental, economic, and technological dimensions of renewable energy-powered SWRO desalination systems. The review focuses on three interconnected research components which are the application of LCA methodologies to SWRO desalination systems using SimaPro software, emerging and innovative recovery techniques for valuable metals and salts from rejected brine; and the cost-benefit and market viability analysis of mineral recovery from brine in comparison with conventional terrestrial mining and industrial chemical production methods.

The first section of this review explains the increasing global reliance on seawater desalination to meet potable water demands, particularly in water-stressed coastal regions. With energy consumption being a major contributor to the environmental footprint of desalination, this study gives emphasis to renewable energy integration and its implications for lifecycle performance. Particular attention is given to the structure and capabilities of SimaPro software and the ReCiPe 2016 impact assessment methodology in quantifying midpoint and endpoint environmental burdens.

The second section explores the scientific and technical advancements in brine management, highlighting novel recovery pathways for lithium, magnesium, potassium, and sodium chloride through precipitation, crystallization, and membrane-based processes. It further reviews the potential for converting brine from waste into a valuable resource stream, advancing both sustainability goals and the commercial attractiveness of SWRO systems.

Finally, the third section evaluates the economic competitiveness and environmental advantages of brine-based mineral recovery relative to traditional terrestrial extraction methods and chemical manufacturing. This includes a synthesis of techno-economic

assessments, market trends, and regulatory drivers influencing the feasibility of this approach. Collectively, this literature review establishes a foundational understanding of the environmental modeling tools, resource recovery innovations, and economic frameworks that support the integrated sustainability assessment presented in subsequent chapters.

2.1.1 Global Water Scarcity and the Role of Desalination

Water scarcity is a worsening reality in many regions. Population growth, climate change, pollution, and mismanagement of resources all strain freshwater supplies [11]. Studies estimate that roughly 25% of the world's population is experiencing severe water scarcity, a figure expected to rise without new solutions [11]. Approximately 80% of people globally may face water shortages under certain definitions [11]. Conventional water sources such as rivers and groundwater are increasingly unable to meet the rising demand in many regions. This raises a critical question for water resource planners and policymakers: What strategies will be employed to ensure water security when local surface and subsurface supplies are no longer viable?

Desalination, the process of extracting freshwater from the Earth's abundant saline water reserves, is increasingly recognized as a critical component of global water resource strategies. With over 97% of the planet's water existing in saline form, harnessing even a small proportion of oceanic water has the potential to significantly augment potable water supply. As a result, desalination has evolved from a specialized technology into a strategically important solution for addressing freshwater scarcity. It has gained widespread acceptance as a viable alternative, particularly in countries experiencing severe depletion of conventional freshwater sources. Consequently, saltwater desalination has emerged as a priority on the international policy agenda aimed at enhancing water availability in arid and water-stressed regions [11].

The expanding role of desalination in global water supply systems is substantiated by empirical data. A broad study by the United Nations reported the existence of approximately 16,000 desalination plants operating in 177 countries, collectively

generating a volume of freshwater comparable to nearly half the average discharge rate of Niagara Falls. This highlights the scale and strategic significance of desalination as a response to increasing freshwater scarcity [12]. Desalination plays a central role in securing water supply for several regions globally. In many small island nations, such as the Bahamas, desalinated water constitutes nearly the entire potable water supply. Similarly, in the Middle East, desalination has become integral to national water security strategies.

For instance, Saudi Arabia derives approximately 50% of its drinking water from seawater desalination, highlighting the technology's critical function in sustaining domestic water availability in arid environments [12-14]. These cases demonstrate that in water-scarce coastal regions, desalination has transitioned from a supplementary measure to an essential component of national and regional water supply systems. Despite its growing importance, conventional desalination presents significant sustainability challenges that warrant critical attention. This review examines these challenges and evaluates how the integration of renewable energy sources and zero-waste strategies can enhance the environmental viability of desalination. Specifically, the analysis focuses on the current status of reverse osmosis, the predominant desalination technology alongside developments in clean energy integration, brine management techniques aimed at minimizing environmental discharge, advanced modeling and control systems, and the alignment of these innovations with international sustainability objectives.

2.1.2 Reverse Osmosis Technology and Its Limitations

Reverse osmosis (RO) represents the principal technology employed in modern seawater desalination. In this process, seawater is subjected to high pressure and forced through semi-permeable membranes that selectively permit the passage of water molecules while effectively rejecting dissolved salt ions and other impurities [15]. The reverse osmosis process yields two distinct output streams: a low-salinity product water known as permeate and a high-salinity concentrate referred to as brine. RO has emerged as the leading desalination technology primarily due to its comparatively lower energy consumption. Producing one cubic meter of freshwater via RO typically requires approximately 3 to 4 kWh of electricity, which is significantly lower than the

energy demands of conventional thermal distillation methods, where consumption often ranges between 10 and 20 kWh per cubic meter [15]. Ongoing advancements in membrane technology and the integration of energy recovery devices have progressively reduced the specific energy consumption of reverse osmosis systems over recent decades. As a result, RO has become a technically reliable and economically competitive method for converting seawater into potable water [11].

2.2 LCA of Desalination Systems

In evaluating the sustainability of desalination systems, a broad perspective is essential. LCA provides a standardized methodological framework to quantify environmental impacts across all phases of a system's life span, from raw material extraction and component manufacturing to system operation and end-of-life disposal. Within the context of seawater desalination, LCA enables the assessment of the total environmental burden associated with producing one cubic meter of potable water. This includes emissions and resource consumption linked to plant construction, chemical usage, energy demand during operation, and waste management, particularly brine disposal. The outcomes of such analyses are instrumental in identifying critical stages where interventions can yield the most significant environmental benefits.

To support such sustainability-oriented initiatives, LCA has emerged as a critical methodological tool. According to ISO 14040 (ISO 2006a), LCA provides a “cradle-to-grave” analytical approach that captures the full spectrum of environmental impacts associated with a product or system throughout its entire life cycle. Applied to seawater desalination, this framework facilitates the thorough evaluation of environmental loads linked to each stage of the process, including the extraction of raw materials, construction of facilities, energy usage during operation, production and application of treatment chemicals, membrane fabrication, and final waste management practices. This holistic assessment enables the identification of key environmental thematic areas and supports data-driven decision-making for more sustainable desalination practices.

The LCA methodology, as prescribed in ISO 14040 and ISO 14044 standards (ISO 2006a, b), is structured into four sequential phases. The first phase, known as goal

and scope definition, establishes the analytical framework of the study. This includes determining the boundaries and functional unit usually set as one cubic meter (1 m^3) of desalinated [16]. The system boundary is defined to specify the extent of processes covered, and this is typically influenced by the geographical, pertinent time limit, and methodological context of the study [17].

The second phase, Life Cycle Inventory (LCI), involves the systematic quantification of all material and energy inputs, as well as emissions and waste outputs, associated with each stage of the desalination system [18]. These inventory data form the basis for the third phase, Life Cycle Impact Assessment (LCIA), where the environmental relevance of these flows is assessed. The LCIA process consists of characterization which is an obligatory step that converts inventory results into potential impacts using scientifically derived equivalency factors, and optionally, normalization and weighting procedures. Impact categories addressed in this phase may include global warming potential, ecotoxicity, freshwater consumption, and land occupation. In some frameworks, results are further aggregated into endpoint indicators, such as disability-adjusted life years or biodiversity loss metrics [18].

The final phase, interpretation, supports robust decision-making which evaluates the reliability and implications of the results. This includes the application of various analytical techniques such as contribution analysis, sensitivity testing, and uncertainty evaluation to identify key impact drivers and assess the robustness of the conclusions (ISO 2006b). Through this structured approach, LCA provides a scientifically grounded basis for assessing and improving the environmental performance of desalination technologies.

Initial comparative studies, such as the qualitative study conducted by Bali and Ghanem [19], investigated seawater desalination facilities in the Mediterranean and reported that reverse osmosis (RO) systems exhibited lower discharges of pollutants into marine and atmospheric environments compared to multi-stage flash (MSF) distillation. Following the establishment of standardized LCA methodologies, subsequent research has provided quantitative comparisons of environmental performance across desalination technologies. For instance, [20] analyzed MSF, multi-effect distillation (MED), and RO processes, concluding that RO generally

resulted in an environmental impact approximately an order of magnitude lower than that associated with thermal technologies, when residual heat utilization was not considered.

Beyond comparisons among desalination methods, researchers have also benchmarked desalination technologies against conventional water treatment systems. [21] examined ozonation coupled with microfiltration. Despite the relatively high energy demands of desalination, particularly for seawater reverse osmosis, while [22] compared desalination with ion exchange processes, these studies demonstrate that it can achieve effluent quality levels comparable to or exceeding those of alternative treatment methods.

2.2.1 Energy Use

Energy consumption during the operational phase constitutes the predominant contributor to the environmental impacts of SWRO desalination systems, as consistently demonstrated across numerous LCA studies [23]. In grid-connected SWRO facilities, electricity used to operate high-pressure pumps accounts for more than 80% of the total global warming potential [23, 24]. For instance, one LCA study reported that a seawater RO plant powered by a conventional fossil fuel-based grid emitted approximately 1.5 to 2.0 kg of CO₂ per cubic meter of freshwater produced, although this figure varies depending on plant efficiency and the carbon intensity of the local power supply [25]. In contrast, environmental impacts associated with construction, chemical use, and material inputs are comparatively minor. Therefore, decarbonizing the energy supply or improving energy efficiency offers the most significant opportunity to reduce the life cycle environmental burden of desalination process. Integrating renewable energy sources such as solar or wind into the power supply of RO plants can substantially lower or virtually eliminate operational greenhouse gas emissions per cubic meter of water produced. This transition primarily alters the life cycle emissions profile of desalination and reinforces the strategic importance of renewable energy integration from a sustainability standpoint.

2.2.2 Material and Construction Impacts

Building a desalination plant is material-intensive, tons of concrete for structures, steel for pipes and pressure vessels, plastics (PVC, PE) for piping and membranes are involved. These materials carry “embodied” impacts from their production (cement manufacturing CO₂, steel production emissions, etc.). LCA studies have noted that concrete and stainless steel are significant contributors to the overall CO₂ footprint of a plant, especially if the energy is clean [26]. In cases where renewable energy is used (thus cutting operational emissions), the relative share of construction materials in total impact becomes more prominent. However, typically, even when using conventional energy, construction can account for perhaps 10-20% of the carbon footprint (depending on plant size and lifetime), while operation is the rest. Other impact categories like metal depletion or particulate matter formation can be influenced by plant construction [26]. Designing plants to last longer (20+ years) and using materials efficiently can mitigate these impacts per unit of water.

2.2.3 Chemical Usage

Desalination relies on various chemicals such as coagulants, biocides, antiscalants, cleaning agents. Producing these chemicals and the handling them has environmental impacts like toxicity categories, eutrophication potential if they end up in water bodies. LCA includes these by examining the supply chain of chemicals. While usually minor compared to energy, in an LCA of a RO plant, chemicals can contribute to impacts like marine ecotoxicity or human toxicity potentials. A study in Kuwait found that both MSF and RO plants had non-negligible impacts in categories such as acidification and eutrophication, partly due to chemical use and emissions [27]. The disposal of spent membrane elements which are made of polymers and fiber glass is another aspect.

2.2.4 Comparing Desalination Technologies

LCA has been used to compare RO with thermal desalination (MSF, MED). Generally, RO comes out ahead in carbon footprint and many other impact categories, because of its lower energy requirement. MSF’s higher energy use, often coupled with fossil fuel use means more GHGs and air pollution per m³, e.g. one review noted MSF could be 2–3 times the CO₂ per m³ of RO under similar conditions [28]. However, if thermal desalination is coupled to waste heat (cogeneration) and if the power plant’s impacts

are co-allocated, results can differ. Hybrid systems (RO + thermal) have their own profile, sometimes balancing the impacts.

2.2.5 Improvements through LCA

LCA constitutes a robust analytical framework for identifying the principal environmental burdens associated with desalination processes. Evaluating impacts in a systematic manner across all stages of the system life cycle which includes infrastructure development, material production, operational energy consumption, and waste discharge. LCA facilitates the recognition of key environmental thematic areas. These understandings enable researchers, engineers, and decision-makers to prioritize areas for targeted intervention. Improvement efforts guided by LCA findings may involve optimizing energy sources, refining system configurations, or enhancing waste management strategies. Such evidence-based approaches contribute to the advancement of desalination technologies with lower environmental impacts per unit of freshwater produced.

As discussed above, shifting to renewable power drastically cuts climate change impact, which is a major goal (SDG 13). Jacangelo, et al. [29] carbon footprint study confirmed that grid decarbonization and renewable integration are vital for desalination to achieve carbon neutrality. Better energy recovery devices, high-efficiency motors, and system optimization can trim energy per m³, yielding proportional reductions in many impacts. Some LCA studies evaluate scenarios with and without energy recovery with the latter having significantly higher impacts [30]. Extending the operational lifespan of reverse osmosis membranes or reducing the frequency and intensity of chemical cleaning requirements directly lowers the frequency of membrane replacement. This, in turn, diminishes the environmental impacts associated with the production, transportation, and disposal of new membrane units. Several LCA studies have incorporated membrane durability as a variable, demonstrating that improvements in membrane longevity yield measurable reductions in the overall environmental footprint of desalination systems [31, 32].

2.2.6 Brine Management in LCA

Incorporating brine management strategies such as ZLD or resource recovery into LCA frameworks enables the identification of environmental compromise across impact categories. While these processes typically result in higher energy consumption, which may adversely affect climate-related indicators, they can substantially reduce marine ecotoxicity and other ecosystem-related burdens by mitigating direct brine discharge. Furthermore, if valuable minerals are extracted from the concentrate stream, environmental credits may be applied to account for the avoided impacts associated with conventional mining and processing of those materials. Recent research has demonstrated that resource recovery from desalination brine has the potential to offset a portion of the system's environmental footprint and contribute to a more circular and sustainable operational model [33].

LCA offers a broad framework for evaluating the sustainability of desalination systems by accounting for environmental impacts across the entire system lifecycle. Even in cases where a desalination facility employs ZLD and is powered entirely by renewable energy, LCA highlights that material extraction, construction, operation, and maintenance still contribute to the overall environmental burden. These understandings underline the need for continuous efforts to reduce residual impacts throughout the system's lifecycle. LCA also serves as a validation tool for sustainability strategies, demonstrating that renewable-powered, zero-waste desalination configurations substantially reduce key impact categories compared to conventional fossil-based systems. For example, recent assessments report that hybrid nanofiltration–reverse osmosis (NF-RO) systems operating on renewable energy can achieve global warming potentials as low as approximately 1.74 kg CO₂-equivalent per cubic meter of water produced which is significantly lower than traditional setups [25, 34].

Transitioning to low-carbon energy sources and improving operational efficiency mitigates the majority of the environmental burden associated with desalination processes. However, outstanding challenges such as the consumption of construction materials and the management of brine concentrate though smaller in relative magnitude, remain critical considerations in the pursuit of genuinely sustainable desalination systems. A broad LCA ensures that measures aimed at reducing impacts,

including renewable energy integration and resource recovery from brine, produce net environmental benefits without introducing hidden negative outcomes.

Future desalination projects can leverage LCA during the design phase to make informed decisions among alternative technologies and configurations. Comparative LCA studies enable stakeholders to quantitatively assess whether prioritizing additional photovoltaic capacity, advanced brine recovery systems, or material improvements yields the most favorable environmental performance per functional unit.

2.2.7 key Limitations of LCA as Sustainability Assessment Tool

LCA is useful, but not enough on its own because.

- Results depend on boundary and allocation choices, which can change the answer.
- Data gaps and uncertainty (old or regional data) can weaken reliability.
- Poor spatial and temporal detail, the local impacts and time-varying conditions are often missed.
- Standard LCA is attributional, so it may not capture market or policy knock-on effects.
- Some impact models such as toxicity, biodiversity, water scarcity are still weak.
- It excludes economics and social factors such as cost, equity, jobs, feasibility.
- It does not measure risk or reliability (operability, resilience, safety).

Table 2.1 summarizes major desalination LCA studies, covering scope and system boundaries, functional units, electricity accounting, allocation choices, impact categories, and key findings to benchmark and contextualize the methods and results presented in this thesis.

Table 2-1 Summary of LCA Studies, Methods, and Findings

Study (Year)	Scope / Boundary	Functional Unit	Electricity Source & Accounting	Allocation / Credits	Impact Categories Reported	Key Findings	Relevance to This Thesis
[Greenlee et al., 2009]	SWRO; cradle-to-gate	1 m ³ permeate	Grid (location-based)	None	GWP, eutrophication, acidification	Electricity dominates GWP; chemicals meaningful secondary load	Baseline reference for grid-only case
[Ghaffour et al., 2013]	SWRO vs. thermal	1 m ³	Grid; regional factors	None	GWP, energy intensity	SWRO lower GWP than MSF/MED at modern SEC	Supports SWRO baseline selection
[Mannan et al., 2019]	Regional SWRO case	1 m ³	Grid (ME); sensitivity on EF	None	GWP, water use	Grid EF materially drives GWP variance	Justifies EF sensitivity (§6.9.5)
[Najjar et al., 2022]	SWRO with RE	1 m ³	PPA (market-based) + grid import	None / scenario	GWP, AP, EP	High RE share cuts GWP >70%	Grounds our RE-mix scenarios
[Panagopoulos, 2021–2022]	ZLD/MLD hybrids	1 m ³	Grid/RE mixes	System expansion for salts (sens.)	GWP, ecotox, AP, EP	Credits can be material; report with/without	Mirrors our credits policy

2.3 Artificial Neural Networks (ANNs) for Process Prediction and Control

The operation of a desalination plant involves managing numerous interdependent variables and complex nonlinear interactions. Factors such as variations in feedwater quality, progressive membrane fouling, and the dynamic adjustment of pumps and valves to maintain target output levels contribute to the system's integral complexity. While traditional mechanical modeling approaches such as those applied in WAVE software provide valuable understandings based on established physical and chemical principles, they may not fully capture the unpredictable and time-varying nature of real-world plant operations. In this context, ANNs offer a data-driven alternative capable of learning system behavior directly from historical and real-time operational data. ANNs enable the development of predictive models that can support performance forecasting, fault detection, and process optimization, thereby complementing conventional modeling techniques and enhancing overall plant control strategies.

2.3.1 ANNs for Performance Prediction

An ANN is a computational framework modeled after the structure and functioning of biological neurons. It is capable of learning complex, nonlinear relationships between input and output variables by being trained on historical data. In the context of desalination, ANNs have been widely applied to predict key operational parameters such as permeate total dissolved solids (TDS), permeate flux, required operating pressure, and membrane fouling indicators. For example, given a dataset comprising operational parameters from a reverse osmosis (RO) plant such as feedwater quality, feed pressure, and flow rates, an ANN can be trained to accurately predict the resulting product water TDS under varying conditions. Empirical studies have demonstrated the high predictive accuracy of ANN models in desalination applications. For instance, Chan, et al. [35] reported an ANN model capable of predicting RO permeate flux with a coefficient of determination (R^2) of 0.999, which indicate a near-perfect fit and outperforming other techniques such as support vector machines (SVM), which achieved an R^2 of approximately 0.98. In another case, an ANN model achieved a mean absolute error (MAE) of 3.5% in predicting overall plant performance, compared to 4.8% for a traditional regression model [35].

From an operational and design perspective, the implications of ANN integration are significant. ANNs can function as virtual sensors or soft sensors, providing real-time estimations of critical variables that are otherwise difficult or expensive to measure directly [35]. For example, based on observed energy consumption and flow patterns, an ANN can infer the extent of membrane fouling or estimate the remaining service life of membrane modules. Furthermore, ANNs possess the capability to interpolate and extrapolate within the domain of their training data, enabling reliable performance predictions across a range of operational conditions, such as varying feedwater temperatures [36]. This makes ANNs valuable tools for both system monitoring and decision support in advanced desalination plant control architectures. ANNs offer several key advantages when applied to the modeling of desalination processes. Desalination operations, particularly reverse osmosis, exhibit nonlinear behavior, for instance, the relationship between permeate flux and feed pressure becomes nonlinear under conditions influenced by membrane fouling. ANNs are well-suited to capture such complexities, provided that they are trained on sufficiently representative datasets [37].

Unlike mechanistic models that require the formulation of detailed governing equations such as those describing membrane fouling kinetics or mass transfer phenomena, ANNs learn the underlying relationships directly from input-output data. This allows them to approximate complex system behavior without the need for explicit physical parameterization [37]. Once an ANN model is trained, it can generate predictions with minimal computational delay. This real-time responsiveness makes ANNs particularly suitable for online monitoring and control applications, where rapid estimation of performance indicators is essential for effective system management [38, 39].

ANNs have been extensively applied in the field of desalination to model and predict system performance under varying operational conditions. [15], Abuwatfa, et al. [37] demonstrated the effectiveness of ANNs to quantify the effects of feedwater salinity and feed pressure on key performance indicators such as salt rejection and permeate flux. For example, Mahadeva, et al. [40] developed an ANN model using input variables including feedwater temperature, flow rate, and salinity to accurately predict permeate flux in a reverse osmosis (RO) system. In a related study, another research group employed ANN techniques to evaluate the impact of incorporating nano-additives into membrane structures, using the model to correlate material composition and operational parameters with system outputs such as flux and salt rejection [15]. These examples highlight the versatility of ANN-based modeling in both process simulation and membrane material development, highlighting its value as a predictive tool across multiple dimensions of desalination research.

2.3.2 ANNs for Control

In addition to their predictive capabilities, ANNs can play a critical role in advanced control architectures for desalination systems. A widely studied application involves the integration of ANNs, particularly recurrent neural networks such as Long Short-Term Memory (LSTM) models within Model Predictive Control (MPC) frameworks. This approach is especially effective in managing the dynamic and nonlinear behavior characteristic of reverse osmosis (RO) processes. For instance, consider the objective to maintain a consistent permeate flow rate and salt concentration in an RO plant

despite fluctuations in feedwater quality and progressive membrane fouling. Conventional control strategies, such as proportional–integral–derivative (PID) loops, often prove inadequate due to the system's nonlinear response characteristics and operational constraints. In contrast, a neural MPC scheme leverages an LSTM network trained on historical operational data or high-fidelity simulations of the RO system. The trained LSTM model serves as a forward predictor, which estimate future system outputs such as permeate flux and salt rejection based on the current state and a sequence of proposed control inputs (e.g., high-pressure pump speed, valve settings).

The MPC algorithm then uses these predictions to solve a constrained optimization problem over a specified prediction limit, and identify a control trajectory that drives the outputs toward desired setpoints while adhering to operational constraints, such as maximum allowable membrane pressure. This integration of machine learning with predictive control offers enhanced robustness and adaptability, enabling desalination systems to maintain stable and efficient performance under variable and uncertain conditions [41]. A study conducted in 2020 by [41] exemplified the application of artificial neural networks in advanced control of reverse osmosis (RO) desalination systems. The researchers developed a nonlinear model predictive control (NMPC) framework in which a Long Short-Term Memory (LSTM) network served as the internal predictive model. The primary control objectives were to maintain a target permeate flow rate and ensure that the permeate salinity remained below a specified threshold. This was achieved by manipulating the frequency of the high-pressure pump, thereby adjusting the feed pressure. The LSTM model effectively captured the nonlinear and dynamic behavior of the RO process, including the impacts of membrane fouling and inherent system time delays. Experimental results demonstrated that the control system consistently met performance targets and maintained operational stability even under disturbing conditions such as abrupt changes in feedwater salinity and partial membrane fouling.

The LSTM-based predictive model enabled the controller to anticipate system responses such as the initial increase in permeate flux accompanied by a transient rise in salt passage following a pressure increase, and adjust control actions proactively [41]. This capability highlights the superior adaptability and predictive

accuracy of ANN-based controllers compared to traditional fixed-gain control strategies. ANN-driven control are particularly advantageous in desalination systems powered by renewable energy sources for handling the fluctuations associated with renewable energy input. For example, if a desalination plant is powered by solar and the power available varies, an ANN-based controller could adjust the operating setpoints in real-time to efficiently use available power while maintaining water quality [42].

Beyond their application within Model Predictive Control (MPC) frameworks, ANNs are also widely used for multi-objective process optimization and fault detection tasks [43]. In optimization contexts, ANNs facilitate the identification of operational setpoints that achieve a balance between conflicting objectives, such as reducing energy consumption while maximizing permeate throughput. For fault detection, ANNs can be trained to recognize the normal operating behavior of the plant. Significant deviations between predicted and actual performance may serve as indicators of anomalies, such as sensor drift, equipment malfunction, or membrane degradation. ANNs thus serve as a multipurpose toolset for modeling, optimization, and control in reverse osmosis (RO) desalination systems. They provide a data-driven complement to physical models and are particularly effective in capturing nonlinear and time-dependent dynamics. By leveraging ANN-based systems, plant operators can achieve improved operational stability and efficiency. Practical applications include predictive maintenance such as anticipating membrane cleaning needs before performance declines, and real-time adjustment to fluctuating power inputs in solar-powered systems.

Nevertheless, the effectiveness of ANN-based methods is contingent upon the availability of high-quality training data and rigorous model validation. Improperly trained models can yield inaccurate predictions and lead to wrong decisions. As desalination facilities continue to expand their instrumentation and sensor networks, the volume and quality of operational data are expected to improve, enabling more robust and adaptive machine learning applications. The integration of ANN-based methodologies represents a significant advancement toward the realization of intelligent, self-regulating desalination plants capable of delivering reliable, efficient, and environmentally sustainable freshwater production.

Table 2-2 summarizes ANN studies in desalination, outlining plant context, predicted targets, dataset characteristics, model types, validation protocols, performance metrics, and key findings to frame their applicability to this thesis.

Table 2-2 Summary of ANN Studies, Methods, and Findings in Desalination

Study (Year)	Plant / Process	Targets Predicted	Data Size & Features	Model Type	Validation Protocol	Performance (Test)	Key Findings	Limitations	Applicability Here
Lee et al. (2009)	Full-scale SWRO	Throughput, SEC	[n] days; ops set-points	ANN (MLP)	Hold-out	$R^2 \approx [0.9]$	ANN captures nonlinear ops	Limited features	Early proof-of-concept
Khayet et al. (2011)	RO lab/pilot	Flux, rejection	Controlled tests	ANN + RSM	k-fold	RMSE↓ vs. regress.	Hybrid improves fit	Lab-scale only	Feature ideas for plant data
Cabrera et al. (2017)	SWRO	Variable ops control	SCADA archives	ANN online	Rolling window	SEC↓, stability↑	ANN for variable ops	Site-specific	Supports dispatchable ops
Mahadeva et al. (2019)	RO	Process opt.	Mixed datasets	ANN survey	—	—	Survey of ANN wins	Heterogeneous quality	Method inventory

2.4 Conclusion

This chapter critically examined the global challenges of freshwater scarcity and positioned seawater desalination specifically reverse osmosis (RO) as a strategic response to the growing water demand. It evaluated the environmental limitations of conventional desalination processes and emphasized the potential of renewable energy integration to reduce operational emissions. Furthermore, the chapter introduced LCA as a robust methodological framework to quantify the environmental impacts of desalination systems across their entire life cycle. It detailed the four sequential LCA phases of goal and scope definition, inventory analysis, impact assessment, and interpretation while highlighting key impact categories such as energy use, material inputs, chemical consumption, and brine discharge. The chapter concluded by exploring the adoption of Artificial Neural Networks (ANNs) in predicting and optimizing RO system performance, and highlighted the role of LCA and ANN-based analytics in developing sustainable, intelligent, and zero-waste desalination systems.

CHAPTER 3: A Review of Renewable Energy Powered Seawater Desalination Treatment Process for Zero Waste

Seawater desalination remains a key solution for addressing freshwater scarcity in arid and semi-arid regions. Despite its importance, conventional desalination systems are heavily dependent on fossil fuels, resulting in high energy consumption and significant environmental impacts. One critical challenge is the management of concentrated brine, which has become increasingly complex due to the scale of operations, stricter discharge regulations, and limited disposal options in inland and coastal regions. These constraints are more pronounced in semi-arid zones, where natural dilution or discharge avenues are minimal.

This chapter reviews the optimization of seawater desalination systems powered by renewable energy, focusing on strategies aimed at achieving zero-liquid discharge (ZLD) and improved operational productivity. Emphasis is placed on advanced system configurations, energy integration techniques, and process-level improvements that reduce waste and environmental problem. Key research efforts and technological innovations were analyzed to assess progress, gaps, and emerging directions in the field.

The findings presented in this review are derived from a blend of recent peer-reviewed literature and project case studies and contribute to the broader academic discourse on sustainable desalination. The content in this chapter, co-authored with Prof. Oludolapo A. Olanrewaju, has been published in “Water”, an open access journal from MDPI.

3.1 Introduction

In the modern world, water is essential for preserving a healthy environment, with the sea providing about 97% of the Earth's water. [44]. Surface and subsurface water are the two types of natural water sources. Most of the world's fresh water supply is found in surface water, such as lakes and rivers. However, recent below-average rainfall has severely reduced this water supply. The scarcity of or progressive decline in the annual worldwide rainfall has also caused subsurface water sources, which are meant to be more dependable, to fail [45]. Globally there are an estimated one billion people

who lack access to potable water, which has led to more than five million water-borne disease fatalities annually four million of these being children [6]. Population growth and rising water demands have made the availability of water a major issue [7, 8]. Although freshwater is thought to be widely available, it is difficult to access in its unlimited cradle. There is a severe shortage of potable water in several nations across the world. However, seawater must undergo extensive processing before it can be consumed by humans. Khawaji, et al. [2] estimated that desalinating brackish water and seawater could provide access to drinkable water for over 75 million people worldwide. According to Inventory [46], at the end of 2002, there were 17,348 seawater and brackish water desalination plants worldwide, generating 37.8 million cubic meters of drinking water daily. According to Assad, et al. [1], the World Health Organization (WHO) reported that 25% of people on Earth reside in areas without access to potable water because these areas lack the basic infrastructure required to extract and purify water from subterranean natural reservoirs and watercourses.

Today, the world is plagued by widespread water scarcity, with Africa and the Arab world being the most afflicted. Although 6.3% of the world's population lives in these places, only 1.4% of the globe's freshwater resources are renewable [1, 2]. Desalination techniques for seawater and brackish water need to deal with the persistent issue of the growing need for potable water and limited availability. Karagiannis and Soldatos [3] predict that by 2025, if water demand is not reduced or substitute/additional water sources are not significantly established, over 67% of the world's population including those in both developed and developing nations may be at risk of a water shortage. This paper identifies available technologies to address the global water scarcity problems with specific focus on optimizing a renewable energy-powered seawater reverse osmosis system for zero waste. The operational conditions and variable parameters of an effective full-sized seawater reverse osmosis (RO) desalination system can be challenging to model because they vary constantly due to seasonal variations and progressive membrane fouling over long-term filtration.

Similarly, investors and consulting engineers must carefully assess the design of the RO plant, as well as the estimated capital and operational costs for large projects. These factors play a significant role in the pre-construction planning and evaluation

processes and by thoroughly analyzing these factors, stakeholders can be able to make informed decisions and ensure the success of such projects. Brine waste or concentrate from the desalination process, which mainly contains organic matter, metals, surfactants and toxic substances, is another key problem that impacts the RO system's rate of recovery, thereby causing an increase in cost per unit of potable water production. The concentrate is typically rich in colour, chemical oxygen demand (COD), total dissolved solids (TDS), and salinity. Brine concentrate management requires a well-operated, low-cost technology to moderate the environmental impact of the brine discharge on the community. Significant economic advantages can be achieved from the brine concentrate through innovative processing technology to recover the constituent salts for commercial purposes. Seawater's desalination treatment process is usually characterised by the generation of highly contaminated rejected brine streams. This rejected brine concentrate requires well-operated, low-cost technology to reduce the environmental impact for safe disposal. Significant economic improvements can be realized by recovering high purity industrial grade salt, bromine, boron, potassium, lithium, rubidium, calcium sulphate and magnesium from brine concentrate.

The next section of the paper discusses water scarcity and the need for further research on this topic. Section 5 elaborates on desalination as one of the solutions to global water scarcity, while Section 6 highlights the reverse osmosis process as the most efficient method of desalination. Section 9 and Section 10 delve into the key issues associated with the reverse osmosis process, including high operational power demand and significant waste volumes generated from the system, and explore the available solutions to these problems. Section 11 identifies the challenges and issues of the SWRO process, while Section 12 concludes the review paper. The objective of this review paper is to evaluate the current state of renewable energy-powered desalination technology and strategies for achieving a zero-waste paradigm, focusing on waste management and energy efficiency.

3.2 Methodology

The planning stage began by defining the objective of the literature review, focusing on themes like water scarcity, seawater availability, desalination challenges, and potential solutions. After establishing the primary research objective, we formulated

sub-topics for qualitative reviews. A search and evaluation procedure for information was then created to ensure article quality, selecting content from peer-reviewed journals indexed by DHET and Scopus [47]. The literature search in the selected databases initiated the implementation phase. Duplicate articles identified during the review were consolidated and analysed. Each article was assessed as relevant or irrelevant based on its abstract and title. Following this, the “Quality assessment” was completed for the relevant articles. The authors then chose the publications most closely related to the topic after a careful review of the literature. Relevant data were cross-checked, as per the previous phase [48]. The analytical process began with “data extraction”, which involved gathering information relevant to the study’s objectives. Methodological guidelines were adhered to while systematically identifying and evaluating the data and evidence from the articles. Evidence was collected, coded and assessed through comparisons to establish linkages between the articles, ultimately providing conclusive support for the proposed issues and emerging answers [49]. The reporting stage commenced with the integration of the study findings, which were methodically presented through qualitative summaries, figures, and tables. The analysed data were then published.

3.3 Water Scarcity

The availability of water resources, population expansion, climate change, pollution, poor resource management, the speed of water consumption and water withdrawal globally are some of the variables that contribute to water scarcity. Additionally, the unequal distribution of water resources both geographically and socially can also contribute to water scarcity. Furthermore, the ever-growing demand for water due to urbanization, industrialization, and (increased) agricultural activities puts pressure on already scarce water resources. Water scarcity will remain a major problem impacting countries and communities globally in the absence of effective water management and conservation initiatives. Azevedo [50] observed that local needs, which vary globally based on location, are connected to water scarcity. According to Ceribasi, et al. [44], approximately 80 % of people globally may be exposed to water scarcity. Karagiannis and Soldatos [3] estimate that roughly 25% of the world’s population is experiencing severe water scarcity, which is predicted to leave many people without access to potable water. Drought, desertification, and global warming are predicted to

exacerbate the issue to the point where even nations without current water shortages may face them in the near future.

Pangarkar, et al. [6] claimed that the gap between the world's demand and supply of water has grown to the point where, in some regions, it poses a serious threat to human survival. According to Pangarkar, et al. [7], the issue of fresh water scarcity is becoming more and more of a global concern because so little of the water on Earth is fit for human use and this percentage comes from non-saline sources. Similarly, Greenlee, et al. [8] reported findings from a geological survey conducted in the United States, which revealed that approximately 96.5% of the world's (potential) water resources exist in the oceans and seas. Only around 1.7% of the global water supply consists of ice. The remaining percentage consists of groundwater located in salty aquifers, as well as brackish water and weakly saline water. This distribution of water resources highlights the dominance of oceans and seas as the primary repositories of Earth's water, with a relatively small portion held in ice and other sources. Ceribasi, et al. [44] concluded that saltwater desalination has become increasingly popular since saline water makes up more than 97% of the world's water, found in oceans, seas, and other saline water sources. This process has attracted significant recognition as a practical alternative water supply, especially in countries where freshwater resources are depleted or misused. Being one of the most important issues facing the world, the urgent demand for freshwater supplies has been elevated to the top priority of the international agenda.

Water withdrawal is the quantity of water extracted for any purpose from a river, lake, or aquifer, whereas water consumption is the portion of the extracted water that evaporates as a result of vaporization, absorption, chemical conversion, or transmission, or is rendered unavailable for further use as a result of human use or consumption [50]. Recent statistics have shown that agricultural sector activities account for approximately 70% of freshwater withdrawals worldwide. This staggering figure highlights the heavy reliance of the agricultural sector on water resources. In comparison, commercial activities utilize around 20% of potable water, while the domestic sector accounts for the remaining 10% [51]. Over 90% of freshwater withdrawals in less-developed countries are attributed to agriculture, whereas in wealthier nations, industry accounts for a considerably higher share of freshwater

withdrawals. The majority of freshwater extraction and consumption figures are based on estimates rather than on accurate calculations. The OECD predicts that the increase in domestic consumption (130%), industrial demand (400%), and thermal electricity generation (140%) will result in a 55% increase in worldwide water withdrawals [51]. Approximately 2.8 billion people on Earth currently live in regions vulnerable to water scarcity and of this number, 1.2 billion live in locations where water scarcity is already a problem, and half a billion people are rapidly approaching this status. Commercial water scarcity affects the remaining 1.1 billion individuals who experience water scarcity. This population resides in regions of the world where water is readily supplied by nature, but their access to it is restricted due to institutional, financial, or distribution infrastructure problems, even though the amount of water that is available is adequate to cater for their needs. This is the situation in the sub-Saharan region of Africa. Shortage of water in the physical sense is when a community lacks an adequate water supply to satisfy its needs. This kind of scarcity is prevalent in arid areas. Shortage in other regions experiencing artificially induced water shortage is triggered by excessive water withdrawal, resulting in environmental damage to groundwater tables and river systems.

3.4 Seawater Availability

A community's economy and quality of life both improve when enough water is available. Even though over half of the surface of the earth is covered in water, only around 3% of that water is freshwater [3]. Seawater, covering about 71% of the Earth's surface and making up 97% of its water, is one of the planet's most abundant resources [52, 53]. However, due to its high salinity, it is unsuitable for direct consumption or use, posing significant challenges in water-scarce regions [54]. To address this, desalination techniques are essential for converting the oceans' plentiful saline water into clean drinking water [55]. According to Ceribasi, et al. [44], finding an effective desalination technique and the high expense of desalinating saltwater have put pressure on scientists to arrive at a solution. Because of this, a large number of current seawater desalination research projects focus on developing affordable techniques for creating freshwater suitable for human use. Despite the ease of access to data on water precipitation, Azevedo [50] noted that monitoring groundwater levels and river runoff is very expensive and challenging in many places. Groundwater and surface water are examples of regenerative water, often referred to as renewable

water. On the other hand, deep aquifers that recharge at a negligible rate during a period of time based on the human time scale are considered non-regenerative water sources.

3.5 Desalination

Various methods of desalinating seawater are being identified and investigated to increase the amount of available potable water. The desalination process is classified into two based on the process's physical characteristics [56]. The two categories are membrane technology and thermal technology. Thermal technology uses the concept of vaporization/evaporation to separate salinity from water, whereas membrane technology uses a filtering device to produce potable water from saltwater. Thermal technology is subdivided into multistage flash distillation, freeze separation techniques, multiple effect distillation, solar still distillation, and vapour compression. Membrane technology is divided into reverse osmosis (RO) and electro dialysis procedures (Figure 3-1).

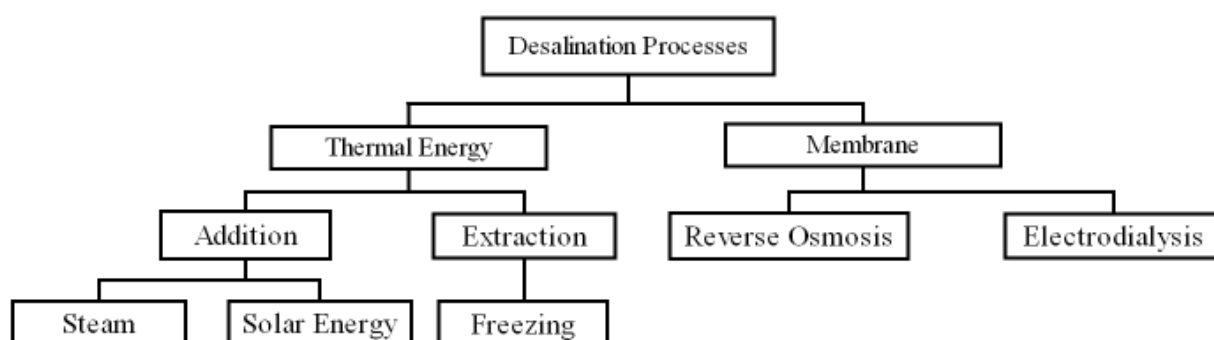


Figure 3-1 Desalination technology [57].

A new desalination method, known as forward osmosis desalination, is poised to transform the concept of generating freshwater from brackish water or saltwater. This innovative method enhances desalination's cost-effectiveness and energy efficiency by extracting water from dissolved salts through a semi-permeable membrane. By harnessing osmotic pressure differences, forward osmosis desalination can revolutionise water treatment and provide sustainable solutions to resolve freshwater scarcity worldwide [44]. It will take the development of dependable new forward osmosis membranes and the extraction of solutes for this technology to progress from the laboratory to practical applications. Flux behaviour across a variety of osmotic membranes is presently being studied. There is also research being carried out on

novel draw solutes that can readily regenerate and do not require energy for water recovery. The study conducted by Kamble and Pitale [58] investigated various solar-powered desalination systems, including but not limited to MSF, MED, humidification–dehumidification, electrodialysis, solar still, and adsorption systems. It concluded that, of all the desalination methods previously discussed, solar-powered RO desalination systems based on solar photovoltaic technology are the most widely utilized and embraced since the RO and the PV are readily available and adaptable. The global saltwater desalination plants installed and categorized by technology are roughly 49% for thermal processes and 35% for membrane systems [6]. According to Ceribasi, et al. [44], the principles of membrane separation, thermal vaporization, electro-dialysis, etc. have served as the foundation for the development of desalination technologies. The authors proceeded to further classify desalination processes into two main groups: membrane and thermal desalination technologies. The least expensive and most practical method of desalination is the solar still [59]. A solar still is a compact device that utilizes solar energy to extract potable water from contaminated water. It operates on the basic principle that water vaporized from an exposed container in an open space will recondense into water on a chilled surface.

3.5.1 Thermal Desalination Processes

The thermal desalination process involves heating seawater as a source of saline water or other saline sources to create steam, which will require cooling to generate condensed water with less salt [44]. In thermal desalination, pressure is lowered to reduce the amount of heat needed for the saline water to evaporate. According to Research and Clayton [60], thermal desalination systems can reduce saline water's salt concentration to as little as 10 mg/L or even less for TDS, between 60,000 and 70,000 mg/L.

3.5.2 Membrane Desalination Processes

The most common method for desalinating seawater is membrane desalination [44]. There are diverse applications for membrane technology when brackish water and seawater desalination challenges are encountered. Seawater desalination technology can be classified according to the range of involved components and the prime mover input used. The membrane desalination process relies on the semi-permeable

membrane's ability to selectively allow water molecules to pass through. Forward and Reverse Osmosis are the two fundamental desalination techniques used in membrane-type desalination, and they can be used to categorize the membrane desalination process. According to Lattemann, et al. [61], Forward and Reverse Osmosis were concepts that scientists discovered many years ago. However, the concept of utilizing RO in the desalination process is somewhat novel. Osmosis is the movement of water from a low-concentration solution to a high-concentration solution across a semi-permeable membrane. The reverse osmosis process happens when external pressure to the membrane's higher-concentration side is applied causing the higher-concentration solution to diffuse into the lower-concentration solution. According to Ceribasi, et al. [44], RO desalination is the process by means of which a semi-permeable membrane rejects salt and only permits pure water to flow through. When the feed water is pushed to one side of a semi-permeable membrane, the hydrodynamic pressure needs to be high enough to surpass the osmotic pressure in order to produce a reverse water flow. This is shown in Figure 3-2. Fikana and Raafi'u [62] reiterated that RO has been established to be the most widely accepted desalination method worldwide.

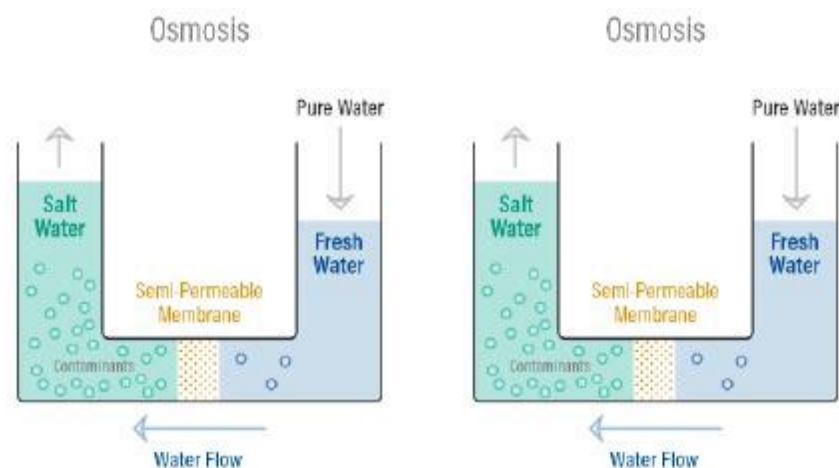


Figure 3-2 Reverse osmosis [57].

Ceribasi, et al. [44], investigated the continuous mobility of industrial RO processes, where the use of a high-pressure pump is necessary to apply external force to the systems. This process involves delivering the salt water at high pressure before it is dispensed for membrane separation. When dealing with seawater, the input feed pressure must be increased to between 40 and 82 bars (600 and 1200 psi), and when

dealing with brackish water, it must be increased to between 2 and 17 bars (30 and 250 psi).

3.5.3 Reverse Osmosis Process

Primarily, any floating materials that can give the membrane a foul smell are eliminated from the flow of the sea water or brackish water sources using a hydraulic strainer. Depending on the salinity level, the remaining flow is elevated to the functional pressure of the system before being sent to the desalination unit. During the desalination process, water permeates through the membrane and accumulates as a permeate flux downstream of the membrane. The standard water treatment methodology will be used during the after-treatment phase to treat the permeate flux to the WHO-safe water standard. Strohwald [63] reported that RO systems have been investigated and shown to be successful in desalinating seawater. Choosing an efficient pre-treatment system was stressed in one of the studies. Despite the low quality of the raw water source, the use of a low-cost tubular ultra-filtration system in conjunction with a double media and cartridge filtration resulted in extremely good RO residual water of exceptional quality. Even in situations where ultra-filtration membrane fouling is evident, sponge balls can aid in restoring flow. Using a scale inhibitor allows for reverse osmosis reclamations of 40% without damaging the membranes. The single-stage RO unit's residual water quality is often well within the approved SABS limits for home supply and free of RO membrane fouling.

3.5.4 Energy and rate of water desalination

Conventional sources and renewable sources are the two primary types of energy sources used in desalination systems freshwater [3]. Renewable-powered desalination is the solution to sustainability, reducing energy usage and CO₂ emissions while also having a positive climate impact. Renewable-sourced energy can be in three forms for desalination systems. Wind, solar (photovoltaics or solar collectors), and geothermal energy are the three renewable energy sources. Renewable energy systems can also be adapted to a conventional energy source (e.g., local power grid) as a backup. The most commonly used membrane technique is RO. When it comes to effectively desalinating saline seawater, thermal methods appear to be more efficient than the membrane approach. However, critical research

has revealed that thermal methods are costlier since an enormous quantity of fuel is needed to cause the saline water to evaporate. The use of membrane techniques, namely RO, has replaced thermal technologies in favour of a more cost-effective way to desalinate brackish water. However, membrane technologies are not commonly utilized for desalination due to the exorbitant price of replacing the membranes. Nthunya, et al. [64] reaffirmed that advancements in technology have contributed to a reduction in the overall cost of desalination by optimizing energy efficiency (via hybrid systems or multi-flash distillation), enhancing energy recycling through cogeneration, and enhancing transfer procedures.

3.6 Seawater Reverse Osmosis

Large volumes of standard potable water can be produced using desalination system technologies at a cost that is competitively low, but the system's high energy consumption is still a significant drawback [6]. The most current advancements in membrane technology, such as Reverse Osmosis (RO), Nano-Filtration (NF), and Electro-Dialysis (ED), have garnered recognition recently due to their dependable capabilities for separation. Since RO membrane technology is appropriate for applications involving both seawater and brackish water, it has been largely regarded as the best option for desalination systems. Higher permeate flux, lower salt rejection and lower osmotic pressure are common characteristics of brackish water desalination (RO) membranes. This desalination process also requires lower operational pressures [65]. However, this approach is usually identified to have inherent challenges as a result of polarization films and byproducts, which can lead to the growth of bacteria and pollutants. According to Pangarkar, et al. [6], problems like this are addressed by employing alternative membrane technology like membrane distillation for desalination of subsurface water. Typically, RO membrane desalination methods are tailored to adopt either pressure or traditional electrical-driven technologies. There are four groups under which the pressure-driven membrane process can be classified: Reverse Osmosis (RO), Ultra-Filtration (UF), Micro-Filtration (MF), and Nano-Filtration (NF). Nano-filtration processes are recognized for their effectiveness in salt desalination.

Four main sub-systems make up a typical RO system, according to Poullikkas [66]: the membrane module, the high-pressure pump, the pre-treatment system, and the

post-treatment system. When a high-pressure pump is activated, the pre-treated feed water is directed to pass through the surface of the membrane. For brackish water, the working pressure of RO ranges from 17 to 27 bars, while for seawater, it varies from 55 to 82 bars. According to Strohwald [63], seawater desalination has been a commercial application for RO membranes ever since Loeb and Sourirajan developed asymmetric cellulose acetate membranes in the early 1960s. According to the paper, the majority of prominent membrane manufacturers, such as DuPont (USA), Filmtec (USA), and Toyobo (Japan), developed membranes using synthetic polymers designed especially for seawater desalination. In the middle of the 1970s, desalination plants began to appear all over the world as the RO method of producing water from seawater became increasingly popular. The author notes that because there is no phase shift involved, RO desalination has lower running costs than MSF evaporation. Due to economic factors, excessive energy usage and advancement in RO technology, the market share of MSF evaporation plummeted from 67% in the early 1980s to 3% in 1989, and in the same timeframe, RO increased from 23% to 85% [67]. The desalination of seawater and brackish water is receiving increased attention due to the rapid depletion of water resources [68]. Nowadays, desalination requires a substantial amount of energy, which makes it less economical.

According to Tzen and Morris [69], the most popular and cost-effective way to desalinate brackish water is by using RO. Other approaches do exist; however, they are not that common. However, one instance may be found on the Greek island of Kimolos, where the MED process uses the island's plentiful geothermal energy to produce 80 m³/day of potable water at a rate of 2.00 h/m³. The total dissolved solids (TDS) in brackish water impacts the daily cost of potable water production, which ranges from 2000 ppm to 10,000 ppm. Raju and Ravinder [68] compared the expenses linked to brackish water desalination. The desalination plant for 230 ppm brackish water in Jordan costs a low 0.26 USD/m³, whereas the plant for 5000 ppm brackish water in Florida costs a low 0.27 USD/m³. Their study revealed that comparable systems employing varying total dissolved solids (TDS) levels generally exhibit notable cost variations. According to Tzen and Morris [69], desalinating 10,000 parts per million brackish water with conventional energy sources costs 0.43 USD/m³, but in a similar scenario, employing renewable energy sources can cost as much as 10.32 USD/m³. At the initial stage, the desalination cost using traditional energy

sources like gas, oil, or electricity is initially cheaper than using renewable energy. However, renewable energy proves to be more cost-effective in the long run. The RO desalination process, as seen in Figure 3-3, has gained popularity in recent years due to the decreasing cost of membranes. RO was mostly employed for brackish water desalination a few years ago but because of its reduced energy requirements, it has recently emerged as the most widely used technique for desalinating varied types of water. Consequently, larger facilities that can produce in excess of 320,000 m³ per day are now using RO technology.

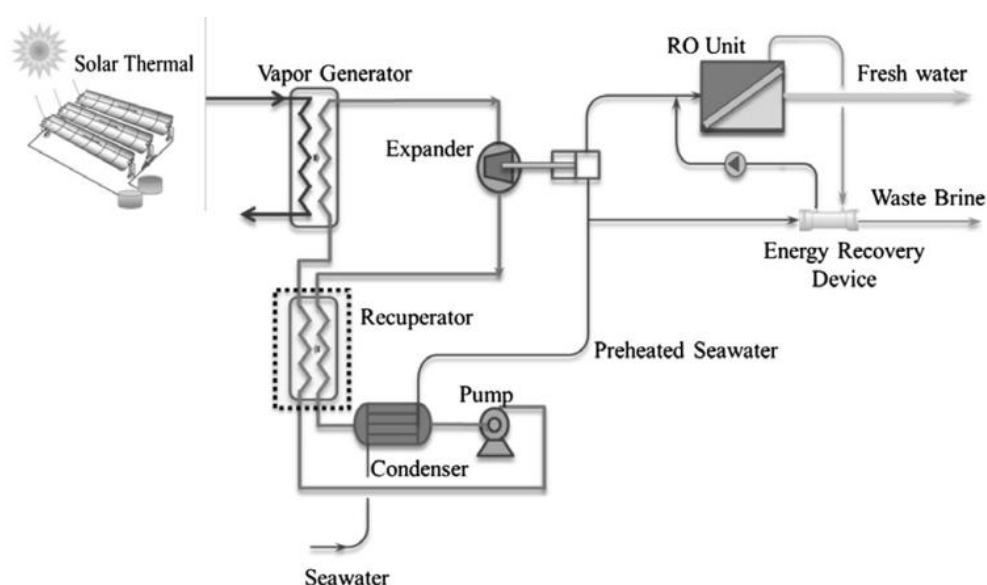


Figure 3-3 Reverse Osmosis [57].

3.6.1 Pretreatment and Post-Treatment

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 clean and in good condition at all times [70]. There are two types of pretreatment methods for an RO desalination system: the conventional pretreatment system and the 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 a pretreatment system for any reverse osmosis operation depends on the number 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 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 than the biggest size of the UF membrane pore are disallowed and retained in the concentrate, while liquid and other floating particles that are smaller than the largest pore size of UF membranes are able to penetrate to the permeate side of the membrane. The presence of flocs, or suspended solids in raw seawater, if not properly removed, can cause serious damage to the 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 on 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, reducing the durability of the membrane and increasing operating costs [5]. The accumulation of external matter from feed water on the exterior of the dynamic membrane and/or in the feed spacer leading to operational problems 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.

Raju and Ravinder [68] classified membrane fouling into three common types, namely 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 accumulation 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 offer 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, favour 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., groundwater or surface water). Groundwater is generally a constant source of feed water with little potential for fouling. Acidification and/or anti-sealant dosing plus the use of a cartridge filter are simple pretreatments for this water. On the other hand, surface water varies according to the season with high potential for microbiological and colloidal fouling. Surface water pretreatment is usually more intensive than groundwater pretreatment [68]. Most surface water and groundwater in the natural state are practically saturated with CaCO_3 according to [71]. The solubility of the water sources depends on the pH value, as shown in Eq. (3-1):



The addition of H^+ as an acid shifts the equilibrium of the equation to the 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 and 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:

$$\text{LSI} = \text{pH} - \text{pHs} \quad (\text{TDS} < 10,000 \text{ mg/L}) \quad \text{Eq. (3-2)}$$

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

Eq. (3-3)

It should be noted that the methods used for predicting the PHs for LSI and S&DSI are different in regulating 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 [71]. 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 larger particles that can precipitate. Scale inhibitors are effective in controlling carbonate, sulfate and fluoride scale [5]. 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 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 frequent use. The UF membrane pretreatment benefits include reduced 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 [57]. However, improved quality permeate flow from a UF membrane pretreatment procedure can bring down the overall cost (initial and subsequent) of maintaining more recent RO operation with regard to 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 [57]. Post-treatment is the process of stabilizing the water and preparing it for distribution. Since most alkaline mineral components in water appear to be 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 [57]. 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 [70]. 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 offset with chemical treatment by adding sodium carbonate or sodium bicarbonate. Adding hardness 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 an 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 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 [72-74].

3.6.2 Basic Principles of the Reverse Osmosis Process

According to Greenlee, et al. [8], Osmosis is the process by which water moves from a less concentrated saline solution across a semi-permeable membrane to a region with a higher concentration of saline solution. A semi-permeable material will allow only pure water to pass through and disallow saline liquid. A semi-permeable membrane allows water to pass through when there is pure water on one side and a salt solution on the other while preventing the passage of salt. Greenlee, et al. [8] in their study further elucidated the concept of osmotic pressure within the realm of reverse osmosis (RO) by characterizing it as the utmost vertical disparity in water levels as water migrates from a region of lower solute concentration through a semi-permeable barrier to an area of higher concentration. To ensure that the solution strength is balanced, reverse osmosis changes the direction of water flow when the pressure applied is higher than the osmotic pressure. Desalination is accomplished by the system's attempt to keep the equilibrium in position by letting water move from the clear water compartment to the salt solution compartment. This dilutes and equalizes the concentration on both sides of the membrane. Osmosis may produce a rise in the salt solution level, which will keep rising until the salt solution pressure in the water column rises to the point where the force of the water column stops the inflow. Osmotic pressure is the water level equilibrium point measured in terms of the water pressure exerted on the membrane (Figure 3-4).

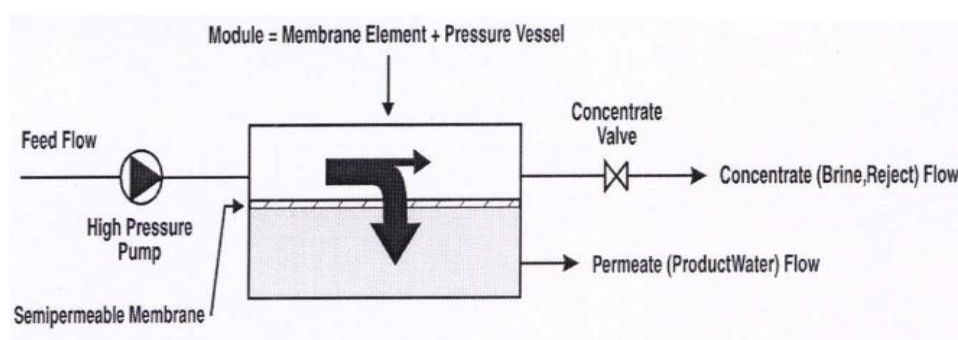


Figure 3-4 Reverse osmosis process

Reverse osmosis is a method in which pressure is used to change the direction of the water flow across a membrane, leading to the creation of clear water from a saline solution because the membrane does not allow salt to pass through [8]. Manolakos, et al. [75] described reverse osmosis (RO) as a physical process that uses the osmotic differential pressure between saline and clear water to separate salt from water. Raju and Ravinder [68] also described reverse osmosis (RO) as a process where an input stream is forced through a semi-permeable membrane under high pressure, resulting in two separate aqueous streams, with one containing high salt concentration and the other containing low salt concentration. According to Tewari [76], when the applied pressure exceeds the osmotic pressure, clear water flows through the membrane, thereby gathering brine as a byproduct. This process leads to concentrated brine remaining in the feed section of the system, while low-salt water flows through the membrane. According to Raju and Ravinder [68], The osmotic pressure of brackish groundwater is usually much lower than that of seawater, requiring less energy for desalination. This reduced pressure allows for the use of inexpensive plastic components in RO systems. Tzen and Morris [69] accounted that a polymer substance is used to create RO membranes that produce a coated, web-like structure. Feed water is intended to pass through a convoluted pathway under high pressure to access the membrane and then penetrate the permeate side of the system. According to Maalouf [71], high-salt rejection membranes are commonly used in RO plants. These membranes are designed to have a lifespan of about seven years with proper pretreatment. Factors such as target recovery, temperature, salinity, and cleaning methods can affect the membrane's efficiency for salt passage. To convert seawater into potable water (as shown in Table 3-1, it is necessary to reduce TDS levels. This can be achieved through various desalination methods including traditional techniques or more advanced ones such as electrode ionization (EDI), multi-effect distillation (MED), electrodialysis (ED), and multi-stage flash (MSF) distillation. In some instances, a hybrid configuration combining multiple desalination approaches can yield optimal outcomes while saving energy.

Table 3-1 Potable water organoleptic properties [77].

CONCENTRATION (MG/L)	CLASSIFICATION

$\text{TDS} \leq 300$	Excellent
$300 \leq \text{TDS} \leq 600$	Good
$600 \leq \text{TDS} \leq 900$	Fair
$900 \leq \text{TDS} \leq 1,200$	Poor
$\text{TDS} > 1,200$	Unacceptable

3.6.3 Reverse Osmosis Membrane Fouling

Raju and Ravinder [68] pointed out that the use of RO in potable water production has become problematic due to RO membrane fouling, aggravated by high concentrations of inorganic and organic elements. The authors highlighted that suspended particles, bacteria, floating solids, and melting inorganic substances (BaSO_4 , CaSO_4 , and CaCO_3) are the usual causes of membrane fouling. Organic compounds such as humic acid can also exacerbate the problem. Xiao, et al. [78] classified pollution as organic, inorganic, or biofouling. The main elements in the contaminating deposits include organic matter, iron, phosphorus, and microorganisms, and these are mixed with chemical components present in saltwater or surface water. Pangarkar, et al. [6] concluded that salt precipitation and membrane scaling are typically the cause of the acute fouling problem in brackish RO systems. The author also mentioned that it is crucial to consider concentration polarization when inorganic pollutants contaminate membranes. Fouling typically raises the resistance, thereby reducing the permeated flux. The resistances responsible for reducing the flux are membrane resistance (R_m), concentration polarization resistance (R_{cp}), cake resistance (R_c), and pore blocking resistance (R_p). The total resistance during membrane filtration can be taken as:

$$RT = R_m + R_{cp} + R_c + R_p. \quad \text{Eq. (3-4)}$$

The type of membrane, porous or nonporous determines the flux resistance caused by inorganic fouling. The non-porous membranes are not subject to R_p . Feed

pretreatment and membrane cleaning are the primary technologies/techniques always employed to control fouling. The main objective of any RO pretreatment system for brackish water or seawater is to reduce the fouling tendency of the system.

3.7 Properties of Saline and Product Water Produced with Brine

3.7.1 Physicochemical Properties

The quality and volume of RO waste brine are influenced by the feed water quality, pre-treatment approach, desalination process, water recovery rate, and waste disposal method [79]. Omerspahic, et al. [15] reported in their study that during the feedwater pretreatment phase of membrane desalination, chemicals such as acids, biocides, antiscalants, antifoams, and corrosion inhibitors are commonly used, impacting the physicochemical composition of the resulting brine. Additionally, environmental factors like temperature, pH, and ionic strength can influence the concentration of pollutants in desalination brine. The quality of the brine is also affected by the membrane pore size used in the process [80, 81].

According to Jones, et al. [82], the desalination plant's capacity and the water recovery rate, which is the proportion of freshwater generated relative to the total volume of feed water used, determine the quantity of brine produced. Better quality feed water leads to a greater recovery rate, as higher salinity levels in the feed water will result in more concentrated brine if the water recovery rate stays the same. As the water recovery rate increases, the amount of brine produced is reduced and is more concentrated. Even though RO is dependent on hydraulic pressure and does not alter the temperature of the seawater it processes, it requires a number of extremely intricate pre-treatment steps, such as the addition of coagulants and antiscalants, which have the potential to alter the pH of the water and produce brine with a salinity that is significantly higher than ambient water [83]. According to the WHO—Geneva [84], 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 45,000 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

providing clean water with allowable limits of 500 ppm or less [72]. The density of freshwater is 1.00 (grams/mL or kg/L), which can be increased by adding salt. The more salty the water is, the higher its density. Water will expand and become less dense when it becomes hot. The colder the water, the higher the density. Figure 3-5 shows the relationship between temperature, salinity and density. The Pacific Ocean has the lightest water with a density of less than 26.0; the Atlantic has the densest water, between 27.5 and 28.0. Antarctic bottom water is densest in the Pacific and Indian Oceans, but not the Atlantic [85]. Dissolved gases 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 content 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 the gas molecules increases, and facilitates their discharge from the water, which reduces the quantity of gas that dissolves.

According to Mustafa Omerspahic et al., desalination brine effluents include significant levels of Cl^- and Na^+ , as well as other ions such as Ca^{2+} , Mg^{2+} , and SO_4^{2-} [79]. Several studies have been published on the presence of heavy metals such as copper (Cu) in desalination brine effluents and seawater. Brine discharges from RO often include metals in trace quantities, such as iron (Fe), nickel (Ni), chromium (Cr), and molybdenum (Mo). Furthermore, chemicals such as biocides, surface-active agents, anti-scale additives, and solid residues from filter backflushing may be present in the effluent discharge on a continuous or periodic basis, posing a risk to the environment. Brine effluents from RO desalination plants not only have a high salt content but typically also contain compounds from the desalination process, such as phosphonate-based antiscalants and ferric sulphate (or alum)-based coagulants [86]. Table 3-2 shows the salt ion content of different seawater sources.

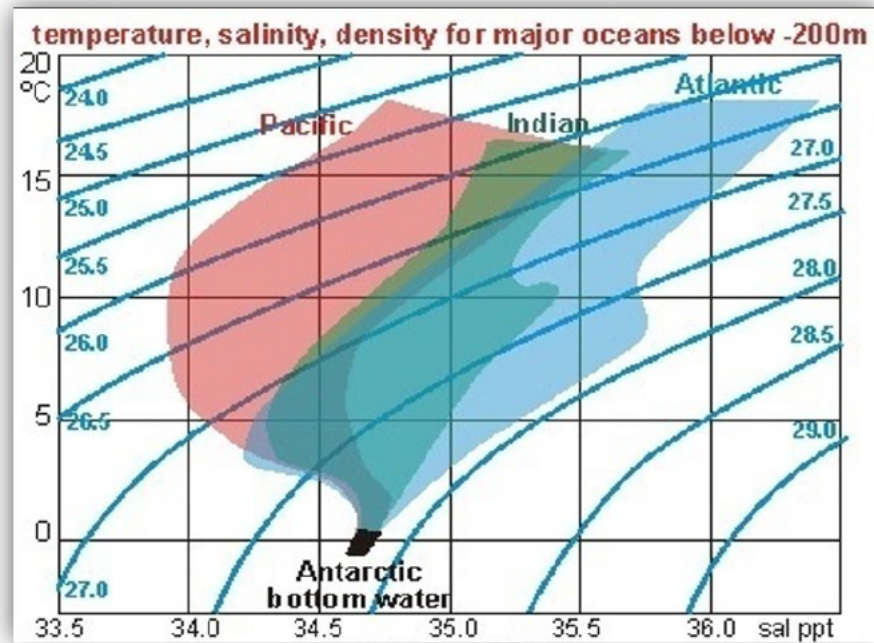


Figure 3-5 Relationship between temperature, salinity and density.

Table 3-2 Ion composition of Seawater [87]

Constituent	Normal Seawater	Eastern Mediterranean	Arabian Gulf At Kuwait	Red sea At Jeddah
Chloride (Cl^{-1})	18,890	21,200	23,000	22,219
Sodium (Na^{+1})	10,556	11,800	15,850	14,225
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	-	-
Flouride (F^{-1})	1	-	-	-
Silicate (SiO_3^{-2})	1	-	1.5	-
Iodide (I^{-1})	<1	2	-	-
Other	1	-	-	-
Total dissolves solids	34,483	38,600	45,000	41,000

Shomar and Hawari [88] highlighted the differences between natural and desalinated waters, noting that natural waters exhibit a wide range of physical, chemical, and biological characteristics influenced by climatic and biogeochemical factors, while desalinated water has a controlled chemical profile. The study also indicated that the quality and appearance of desalinated water depend on the chemicals and materials used in the desalination process. Although groundwater is sometimes mixed with desalinated water to reduce corrosion and stabilize quality, post-treatment procedures often result in inconsistent quality [89]. Water with a Total Dissolved Solids (TDS) level of 25–50 mg/L is reported to be less thirst-quenching and may have undesirable flavours (tasteless, metallic) [77].

3.7.2 Thermodynamics Property of Saline Water

In his research, Kalogirou [72] examined seawater salinity, defining saline water as a blend of salt and pure water. The desalination process yields two output streams: brine, which contains a high concentration of dissolved salts, and desalinated water, which has a low concentration. Thus, the properties of pure water and salt are essential considerations in desalination operations. Parts per million (ppm) is the standard unit

for salinity, defined as $\text{ppm} = mf_s \times 10^6$. A salinity of 1000 ppm is equivalent to 0.1% salinity, or $mf_s = 0.001$ salt mass fraction. Consequently, the mole fraction of salt, x_s , is determined by Eq. (3-5) [72, 90]:

$$mf_s = \frac{m_s}{m_{sw}} = \frac{N_s M_s}{N_{sw} M_{sw}} = x_s \frac{M_s}{M_{sw}} \quad \text{and} \quad mf_w = x_w \quad \text{Eq. (3-5)}$$

where N is the number of moles, x is the mole fraction, m is mass, and M is the molar mass. Salt, water, and saline water are represented by the subscripts s , w , and sw , respectively. The apparent molar mass of saline water is determined by Eq (3-6) below. NaCl and water molar masses are 58.5 and 18.0 kg/kmol, respectively. Salinity is typically expressed in terms of mass fractions, but the minimum work calculations require mole fractions. By combining Eq (3-5) and (3-6) and taking into account that $x_s + x_w = 1$, the following relations in Eq. (3-7) are obtained for converting mass fractions to mole fractions [91]:

$$M_{sw} = \frac{m_{sw}}{N_{sw}} = \frac{N_s M_s + N_w M_w}{N_{sw}} = x_s M_s + x_w M_w \quad \text{Eq. (3-6)}$$

$$x_s = \frac{M_w}{M_w(1/mf_s - 1) + M_s} \quad \text{and} \quad x_w = \frac{M_s}{M_w(1/mf_w - 1) + M_s} \quad \text{Eq. (3-7)}$$

Dilute solutions have a concentration of less than 5% and behave similarly to ideal solutions, resulting in minimal interaction between different molecules [91]. The extensive properties of a mixture equal the sum of its individual components' properties. Consequently, Eq. (3-8) can be used to determine the mixture's enthalpy and entropy, and Equation (9) can be used to calculate the quantities per unit mass of the mixture. In an ideal gas mixture, no heat is generated or absorbed during mixing, resulting in a zero enthalpy of mixing. This implies that neither the mixture's enthalpy nor that of its components changes. Therefore, the total enthalpy of the individual components at a given temperature and pressure equals the enthalpy of the mixture at those conditions [92]. This principle also applies to saline solutions.

$$H = \sum m_i h_i = m_s h_s + m_w h_w \text{ and}$$

$$S = \sum m_i s_i = m_s s_s + m_w s_w \quad \text{Eq. (3-8)}$$

$$h = \sum m f_i h_i = m f_s h_s + m f_w h_w \text{ and}$$

$$S = \sum m f_i s_i = m f_s s_s + m f_w s_w \quad \text{Eq. (3-9)}$$

The seawater used for desalination is at a temperature of about 15 °C (288.15 K), and a pressure of 1 The seawater used in desalination typically has a salinity ranging from 1500 to 35,000 parts per million (ppm), a pressure of 1 atmosphere, and a temperature of approximately 15 °C (288.15 K). These conditions are considered representative of the surrounding environment. Thermodynamic principles for solids are applied to determine the properties of salt. The enthalpy and entropy values of salt are defined as zero at the reference state, which is the state of salt at 0 °C. Eq. (3-10) can therefore be used to calculate the enthalpy and entropy of salt at temperature T , as shown below. Using a specific heat of salt of $C_{ps} = 0.8368$ kJ/kg K, the salt's entropy and enthalpy at $T_o = 288.15$ K are calculated as $h_{so} = 12.552$ kJ/kg and $S_{so} = 0.04473$ kJ/kg K, respectively. It is important to note that the enthalpy and entropy of incompressible substances are independent of pressure [91]. Since mixing is irreversible, the entropy of the mixture at a given temperature and pressure must exceed the sum of the entropies of its components at the same conditions prior to mixing. Eq. (3-11) below shows the entropy of a component per mole in an ideal solution at temperature T and pressure P [93]:

$$h_s = h_{so} + c_{ps}(T - T_o) \text{ and } S_s = s_{so} + c_{ps} \ln(T/T_o) \quad \text{Eq. (3-10)}$$

$$s_i = s_{i,pure}(T, P) - R \ln(x_i) \quad \text{Eq. (3-11)}$$

Since x_i is less than 1, $\ln(x_i)$ is a negative value; thus, $-R\ln(x_i)$ is always a positive value. As a result, at the temperature and pressure of the mixture, the entropy of a component in a mixture is always greater than the entropy of that component when it exists alone. Therefore, as shown in Eq. (13-2) below, the entropy of a saline solution is equal to the sum of the entropies of salt and water in the saline solution [91].

$$\begin{aligned}
s &= x_s s_s + x_w s_w = x_s [s_{w,pure}(T, P) - R \ln(x_s)] \\
&+ x_w [s_{w,pure}(T, P) - R \ln(x_w)] = x_s s_{s,pure}(T, P) \quad \text{Eq. (3-12)} \\
&- R[x_s \ln(x_s) + x_w \ln(x_w)]
\end{aligned}$$

By dividing the given quantity (per unit mole) by the molar mass of salty water, we can determine the entropy of saline water per unit mass as shown in Eq. (3-13):

$$\begin{aligned}
s &= m f_s s_{s,pure}(T, P) + m f_w s_{w,pure}(T, P) - R[x_s \ln(x_s) \\
&+ x_w \ln(x_w)] (kJ/Kg K) \quad \text{Eq. (3-13)}
\end{aligned}$$

3.8 Desalination Energy Requirements and Recovery

Azevedo [50] established that compared to other water treatment methods, desalination is considered energy-intensive due to its higher energy consumption per litre. The amount of energy used in the desalination process can vary depending on factors like facility design, technology, temperature, feed water quality, energy recovery equipment, and the desired water quality. Technological advancements in the last forty years have reduced the energy needed for desalination, with this trend expected to continue as technology evolves. Areas for improving desalination energy consumption include: (a) enhanced system design; (b) efficient pumping methods; (c) energy recovery systems; (d) innovative membrane materials; and (e) advanced technology. The primary determinant of energy consumption in membrane desalination systems is the feed water's salinity and the recovery rate. For Reverse Osmosis, energy is primarily used for pumping the feed water. The consumption of energy in RO processes typically varies from 3.7 kWh/m³ to 8 kWh/m³ for seawater, depending on the facility size. With energy recovery systems, a seawater RO unit with a daily capacity of 24,000 m³ consumes about 4 to 6 kWh/m³. Conversely, a brackish water RO system's energy consumption ranges from 1.5 to 2.5 kWh/m³ [94].

According to Raju and Ravinder [68], brackish water or seawater desalination technology is the most efficient way to generate high amounts of potable water at a competitive cost; nevertheless, the considerable energy usage of the system has continued to pose a significant challenge. According to Muthumariappan and Engineer [95]. The feed pressure required to pump water determines the flow rate of the

desalination system, and this pressure serves as the main power source in the RO system. To achieve the desired permeate flux, the high concentration of brine in seawater requires a hydrostatic pressure of up to 7000 kPa, and the higher the salt content, the higher the pressure and pumping power that the system will require. The high-pressure pump unit, responsible for about 70% of the total energy required for the RO process, represents the primary energy cost. The hydrostatic pressure applied must exceed the osmotic pressure of the membrane's feed water portion. The osmotic pressure on the feed compartment of the membrane increases as the (RO) unit recovery rate increases, leading to a rise in the required feed pressure. The brine waste produced by the system has high pressure having shared a significant portion of the feed pressure. This resultant brine waste pressure can be used effectively to boost the raw water feed pressure through the use of suitable technology, known as the energy recovery system. The total energy consumed by the RO unit can be reduced with the help of this energy recovery technology by utilizing the pressure from the brine waste to assist in boosting the feed pressure of the raw water, thus increasing the efficiency of the system. By implementing this technology, not only can the feed pressure requirement be met more effectively, but also the operating costs of the RO unit can be significantly reduced.

3.9 Renewable Energy Power Solution

Desalinating brackish water and sea water has become a widely accepted method for producing potable water globally. Due to their isolation from larger cities, some communities in third-world nations are frequently cut off from the national energy grid. This has left a significant gap in the availability of potable water supplies, which are typically fueled by conventional electricity. Desalinating seawater to remove salt is highly energy-intensive and costly. This process presents challenges such as high energy consumption and environmental pollution from fossil fuel combustion. According to [72], producing 22 million m³ per day requires 203 million tons of oil annually, equating to about 8.5 EJ/yr or 2.36×10^{10} kWh/yr of fuel. Consequently, the operating costs of running a desalination plant with fossil fuel-based energy are significantly high. Similarly, using fossil fuels to supply fresh water is counterproductive and harmful to the climate, particularly given rising concerns about fossil fuel-related environmental issues and carbon emissions. Thus, along with its high energy demand, water desalination poses a significant environmental contamination risk.

To address this and minimize environmental impact, desalination plants need an energy source with low emissions and must be cost-effective. These challenges can be tackled by leveraging renewable sources such as solar photovoltaic, wind, thermal, or geothermal energy. Since the capacity of desalination currently exceeds 70 million m³/day worldwide, Lotfy, et al. [96] justified desalination using renewable energy to reduce greenhouse gas emissions. It is anticipated that the cost of renewable energy solutions will mean that these solutions will continue to be unattractive to isolated communities and areas with sparse populations and inadequate infrastructure. Less than 1% of the world's desalination capacity is now accounted for by renewable-powered plants and facilities. The majority of these desalination plants use RO technology, which accounts for 62% of global capacity, followed by MSF and MED. The primary renewable energy source used for water desalination facilities is solar photovoltaic (PV), which powers 43% of all desalination plants. Thermal and wind energy are the next most common renewable energy sources [50]. The feasibility of establishing a renewable energy plant is contingent upon several criteria, such as the salinity of the feed water, the plant's location, the accessibility of renewable energy sources, and the availability of the national electricity grid.

3.9.1 Solar PV System

PV (photovoltaic) systems use semi-conductors and PV cells to convert solar radiation into direct current. The PV modules consist of photovoltaic cells that generate direct current, which can be collected and stored in a battery or sent straight into an inverter for conversion into alternating power [50]. The RO desalination pumping system is directly coupled to the solar PV system. The system consists of a collection of batteries for energy storage and a charge controller that prevents deep discharges and overcharging while monitoring and controlling the charging process. The membrane system produces a set amount of high-quality water while maintaining consistent pressure and flow. Research on battery-less membrane systems is crucial due to the impacts of sun irradiation fluctuations. Real-world tests have shown these systems can generate high-quality water, although the outcome may vary based on the membrane used. An advantage of RO desalination is its ability to adjust capacity according to the energy supply. The novel RO technique by ENERCON GmbH Germany, allowing

variable energy input degrees and utilizing a piston system for energy recovery, was discussed by Ghafoor, et al. [67]. Utilization of this innovative technology in reverse osmosis systems enables adjustment of production output from 12.5% to 100% of standard capacity through piston speed modifications and control of energy input or water demand. Other companies are also exploring and creating similar demand–response systems. Ghafoor, et al. [67] conducted a study on a 500 L/h solar-powered RO desalination system and it was revealed that for every 1 °C rise in feed water temperature, membrane output increased, resulting in 60% permeate flux and 40% brine production.

Elmaadawy, et al. [97] conducted an evaluation of the economics and efficiency of an RO system integrated with a PV system and diesel generator, only a diesel generator, and a PV system without battery storage. Research findings indicated that 20 m³/d capacity was attained through the combination of PV-RO with the diesel generator, 20 m³/d capacity using solely the diesel generator, and 44 m³/d water yield was accomplished using solar-powered RO specifically on sunny days. Figure 3-6 illustrates a diagram outlining a PV-RO system design. Bilal, et al. [98] conducted an investigation on PV systems both with and without batteries for use in running RO systems. According to the findings, 5.9 L/h of permeate flux was generated for five hours while the battery was used, and 3.8 L/h when it was not. Compared to a PV system without a battery, the freshwater throughput with a battery-dependent system was 9.8% greater. The authors came to the conclusion that while both kinds of PV systems had advantages, battery-less systems were more financially viable than battery-based systems.

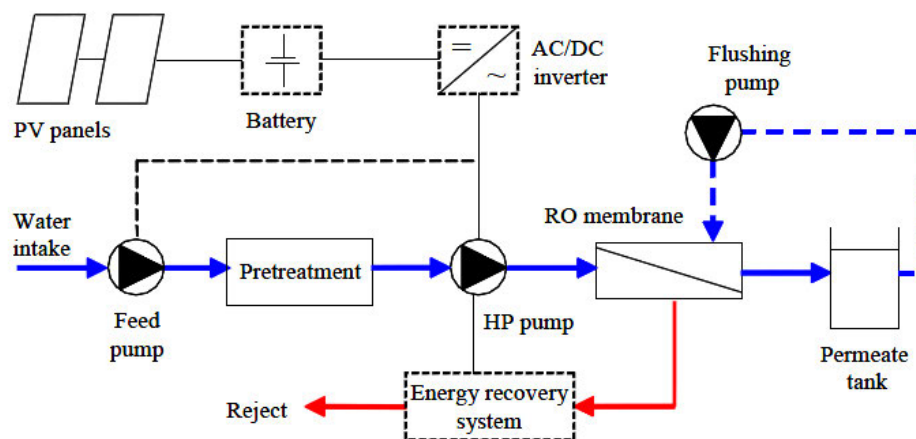


Figure 3-6 Schematic of PV-RO system [57].

Azevedo [50] concluded that the PV-RO system as shown in Figure 3-6 has been regarded as one of the most reliable solutions for desalination driven by renewable energy, particularly for rural places given that both PV and RO are modular and easily accessible. The modularity of the system, which has reduced the cost of production through economies of scale, has allowed small-scale systems to be created by directly connecting the DC output of PV modules to DC pumps and electronics, which in turn increases the system's overall efficiency by 5% to 10% by preventing losses in DC-AC power conversion and AC-DC rectification [99].

3.10 Zero Waste Seawater Desalination

The seawater desalination technology has been classified as a low-profit investment due to its high operating costs, low recovery of permeate flux, and high system-generated brine concentrate [57]. Separating salt concentration and useful metals from brine before disposal greatly lowers the cost of producing clean water from seawater reverse osmosis (SWRO) while also removing the harmful environmental effects of discarding brine concentrate without metals and salt into the sea. The elevated levels of salt, organic debris, and other additional materials in brine can pose serious environmental risks if released into the environment. According to Cipolletta, et al. [33], the present global brine production stands at about 141.5 million m³/day, accumulating to 51.7 billion m³/year. This number encompasses a high dissolved salt concentration (up to 400,000 mg/L total dissolved solids (TDS)) with organic matter, metals, nutrients and a low percentage of pathogenic substances. Rejected brine negatively impacts the ecosystem by causing eutrophication, pH fluctuations, and an accumulation of heavy metals. Consequently, the concept of treating brine rather than discarding it is highly favoured and promoted. Brine treatment not only reduces negative environmental effects but also makes it possible to recover excess freshwater and/or valuable substances (like salts) that would otherwise have been lost.

Additionally, the operating cost of a desalination system is very high as a result of the high volume of brine waste generated and the high power requirement. This high cost of production can be alleviated with the envisaged income from brine waste management thereby positioning the system for attractive investment. The management and disposal of brine have been among the top research works

worldwide [100]. Historically, brine has been managed using different methods such as evaporation ponds, deep well injection, ocean/sea discharge, and sewage outflow. These practices are no longer feasible due to rising management costs, tighter discharge regulations, and environmental risks [101]. To lessen the effects of brine discharge on the environment, brine concentrate management requires using economically viable, accurately operated technologies. Finding a technically, environmentally, and financially feasible system of managing brine concentration is getting more and more difficult, thus making the process very complex and economically unviable. To achieve maximum production of freshwater with minimal output waste, the concepts of Minimum Liquid Discharge (MLD) or Zero Liquid Discharge (ZLD) have to be implemented in brine waste management [33]. About 95% and 100% of the freshwater in MLD and ZLD, respectively, is reclaimed while valuable metals, salts and energy can also be recovered [102].

Creating practical selections for salt reutilization and definitive methods for salt extraction is also crucial for lowering the overall total cost of the process [103]. de Nicolás, et al. [104] describe MLD as a brine management model that recovers over 95% of freshwater while minimizing brine discharge with the concentrated effluent constituting just 5% of the total volume which can be managed more sustainably. The level of resource and water recovery, as well as the volume and quality of effluent produced, differentiates MLD from ZLD. The MLD process is designed for a high but incomplete recovery of water and resources, resulting in reduced liquid effluent, while ZLD targets 100% recovery, eliminating any liquid effluent [105-107]. The following phases are typically involved in the ZLD and MLD stages: firstly, a pre-treatment step that eliminates suspended solids, organic matter, and other contaminants from wastewater through physical, chemical, or biological methods (e.g., filtration, coagulation, flocculation, sedimentation, flotation, oxidation, or biodegradation). This step is crucial to avoid fouling, scaling, or wetting of membranes and evaporators in subsequent processes. Secondly, a concentration step separates water from dissolved salts and solutes using thermal or membrane technologies, resulting in a permeate stream of potable water and a high salinity concentrate for further treatment.

The final phase involves evaporation and crystallization, employing thermally based technologies to further concentrate the concentrate stream until the solutes saturate

and crystallize. This process produces a solid stream of recoverable or disposable salt crystals, along with a high-quality distillate stream of water that can be recycled or reused [79, 105]. Based on our review, not very many research studies have been carried out on brine management considering the methods for metal recovery, life cycle assessment (LCA), and the development of desalination technologies. The emphasis of previous research has been more on identifying methods and techniques of recovering either one or two metallic salts from the brine concentrate, with no work completed on determining or identifying the metallic salt constituent of the brine waste.

Both the natural environment and humanity depend on water as a resource. However, in many regions of the world, rising urbanisation has increased the demand for freshwater. In light of this, desalination is regarded as a dependable and practical solution to the growing need for freshwater. Desalination technology is being explored in more than 150 countries, and globally, approximately 21,000 desalination facilities produce more than 120 million cubic meters of freshwater per day in countries like Kuwait, France, the United States of America, Saudi Arabia, and others [102]. Since desalination is being used in a growing number of both coastal and inland locations, the subject of brine discharge has emerged as a significant concern, and it has been shown in numerous studies to have detrimental effects on the environment.

Apart from high salinity, brine may also comprise chemical deposits like antiscalants, flocculants and coagulants from pre- and post-treatment procedures. As of 2019, the estimated amount of desalination brine produced worldwide was 128,652,000 m³/day [108]. Various practices for the disposal of brine have been employed, including land application, sewage disposal, deep-well injection, and surface water disposal and numerous studies have shown that some of these disposal practices have negative ecological effects. Specifically, deep-well injection is inappropriate in regions with potential for seismic and/or volcanic activity, such as Greece, as well as inland locations due to possible pollution of the water sources and sewage discharge [79]. In summary, zero liquid discharge (ZLD), a substitute and more environmentally friendly method, has been taken into consideration to mitigate the effects of brine discharge. Farizoglu and Uzuner [109] investigated the suitability of using a ceramic membrane filtration unit, an aerobic jet loop reactor, and a high-performance bioreactor for the treatment of wastewater from dairy processing.

The research findings of Ji, et al. [110] indicated that fully functional reverse osmosis (RO), forward osmosis (FO), and membrane distillation (MD) technologies have been adopted to treat the concentrate brine solution to lower the amount of brine that enters into a commercial crystallizer. It further highlighted the fact that multiple processes (such as brine concentration and salt crystallization) are required to recover water and salts in the abovementioned membrane-based technologies thereby increasing their complexity and making the process economically unviable. Unlike the conventional minimal liquid discharge (MLD) and zero liquid discharge (ZLD) processes that demand high energy to completely extract and harvest valuable solid salts and freshwater from brine, it is considered to be more desirable to advance simple ZLD or MLD procedures that consume less energy to sustainably manage brine. Consequently, the study of Ji, et al. [110] demonstrated a novel and efficient membrane-promoted crystallization (MPC) method for effectively recovering water and KCl from KCl concentrate under mild circumstances without the need for anticorrosive tools and which simplifies the production of KCl by combining salt crystallization and brine concentration into a single unit through the use of a tubular hierarchical ceramic membrane (macroporous α -Al₂O₃ hollow substrate, γ -Al₂O₃ interlayer and mesoporous ZrO₂ top layer). Another research study conducted by Li, et al. [111] methodically assessed the viability of the concentration process of a prototype textile wastewater system using three distinct kinds of FO membranes under three different modes of operation and suggested a hybrid FO-MD process using a bespoke self-standing and symmetrical membrane, as well as a hydrophobic polytetrafluoroethylene membrane in the FO and MD units, respectively.

The research study by Panagopoulos, et al. [79], Panagopoulos [108] offered a financial and environmental evaluation of the ZLD seawater desalination systems and ZLD brackish water desalination systems in the Eastern Mediterranean region. The findings highlight the promising performance of ZLD systems in treating and optimizing the value of desalination brine. Furthermore, the report recommends further research in vital areas like integrating ZLD systems with Renewable Energy Sources (RES) and utilizing advanced ZLD technologies to minimize significant energy usage and accompanying greenhouse gas emissions, thereby enhancing the environmental sustainability of ZLD systems. Cipolletta, et al. [33] in their study examined the

technologies for brine treatment aimed at Minimum Liquid Discharge (MLD)/Zero Liquid Discharge (ZLD) and resource recovery and demonstrated their benefits and drawbacks. The report suggested that the correct combination of different treatment methods can greatly improve brine management and shift the emphasis to recovery and reuse rather than removal. The author concluded that ZLD technologies aim to recover 100% of the water using both membrane and thermal-based technologies, but the processes are frequently hampered by their high cost and high energy needs. MLD is adjudged to be a viable solution that can extract up to 95% water primarily through membrane-based technologies. The study highlighted that resource recovery from brine and potential valorization pathways for the reclaimed materials are factors that contributed to the reduction in the general plant costs and assisted them in achieving the goals of a circular economy.

Another research study by Lugo, et al. [112] produced an extensive framework for techno-economic assessments (TEAs) to evaluate an innovative algae resource recovery and near-zero-liquid discharge potable reuse system versus a traditional potable water reuse system. The levelized costs of water from individual units are estimated by the TEA study, and the integrated processes include sludge treatment, enhanced water purification for drinking water reuse, and secondary wastewater treatment. Based on the study's results, the existing efforts to treat wastewater and recycle drinking water are deemed unsustainable from both environmental and economic standpoints. This is attributed to their costly nature, substantial energy requirements, resource depletion, and notable greenhouse gas emissions. The study by Panagopoulos and Haralambous [102] examined the minimum energy consumption (MEC) compared to the popular research on minimum energy consumption in seawater desalination. The research presented the actual energy consumption (AEC) of desalination technologies and introduced a mathematical model for the calculation of the minimum energy consumption (MEC) in desalination brine treatment. The study showed that MEC increases with a higher recovery rate, feed brine salinity, feed brine temperature, and freshwater purity, while it decreases with an increased molar mass of dissolved salt. The model considered various parameters such as type of dissolved salt, salinity, and temperature. The research study by Mansour, et al. [113] examined brine concentrate which characteristically comprises dissolved salts and residual chemicals, and which can include a variety of agents, such as coagulants, antiscalants,

biocide/antifouling agents, and anti-foaming agents, as well as potentially heavy metals. It went further to verify that the particular breakdown of brine components varies depending on the industry and the brine source.

A demonstration of brine concentrate produced by desalination technologies was provided, which typically includes minerals like calcium, barium, silica, and sulfate that contribute to hardness. Conversely, a municipal wastewater treatment plant has a high level of organic carbon that must be reduced when it exceeds a certain threshold before further treatment. The study concluded that the range of technologies compatible with the system depends heavily on the elements of the brine feed. This is because some components and/or compounds are too strong for some technologies to cope with them beyond a certain level or threshold. In different circumstances, the total quantity of dissolved solids present in the feed stream determines which technology can best be used. Certain technologies, for instance, can only be used in brackish water and cannot withstand water that contains more solids than a predetermined level, highlighting the role of filters that can be placed in the feed stream in each technology, whether it be the presence of a specific substance or the total amount of dissolved solids in the stream blocked from entering by the technology.

3.11 What Are the Future Challenges?

According to Strohwalde [63], RO units can produce high-quality drinking water, but there are risks involved such as early capacity reduction and inadequate salt rejection. These problems may arise from malfunctioning pretreatment and maintenance systems, potentially exposing the membranes to the following:

- Chlorine leakage from the pretreatment area
- Bacterial contamination
- Residual membrane fouling missed during pretreatment, undetected by the plugging index determination
- Pump grease contamination.

The following operational/system design problems were identified in recent studies conducted on seawater desalination for producing drinking water in a naval setting:

- i. High-pressure pump vibration and noise. High-pressure positive displacement pumps often encounter problems like cracked plungers, failed bearings, valve pitting, and water leaks past the pump packing stage. Some DuPont preempts may also suffer

damage due to incorrect intake plumbing sizing and routing, along with intense pump vibration causing high mechanical noise and cavitation issues. These challenges underscore the importance of correctly sizing suction and discharge pipework and strategically positioning pulsation dampeners in the design phase [63].

- ii. High-pressure pumps. Choosing the wrong pump for the specific function and operation can result in excessive vibration and eventual failure. Difficulties may also arise in sourcing replacement parts for pumps sourced from foreign countries. It is essential to select pumps that are tailor-made for RO applications.
- iii. Pretreatment. Premature fouling of RO membranes due to insufficient and unsuitable equipment has led to reduced capacity and product quality. Despite the system's proven ability to generate drinking water from seawater and brackish water, these particular challenges have fostered the misconception that RO is unreliable and excessively costly. The best approach to debunk this fallacy is to showcase the effectiveness of well-designed plants in the industry [63].
- iv. Management of bacteria. When using chlorine as a bactericide, caution is vital to prevent a chlorine leak from the pretreatment area. Although chlorine is effective in halting germ growth, it can be harmful to the sensitive RO membranes, causing a breakdown in their function if chlorine breakthrough occurs.

3.12 Conclusions

This review paper concludes that reverse osmosis (RO) technology is an excellent desalination process to produce zero liquid discharge (ZLD) if properly integrated. It can produce large quantities of clean drinking water cost-effectively and is the most commonly used membrane technology for treating brackish water and seawater. Nonetheless, the primary disadvantage of an RO system is its high energy usage. This study also evaluated the economic viability of RO systems powered by renewable energy sources for achieving Zero Liquid Discharge (ZLD). This review study also came to the conclusion that, in the long term, managing brine is crucial for safeguarding the ecosystem and preserving the environment. The study found that the best way to control brine is by using appropriate technology that enables ZLD to minimize its volume as much as possible. While the resulting salts could be disposed of on land or in water, the environmental impact would be minimal. It is evident that emerging technologies can effectively reduce brine volume based on the study findings. Various metals and salts hold economic value and can be sold for profit. Effective brine

management involves integrating multiple processes to recover water and chemicals. Ultimately, brine should be seen as a resource, not waste, to ensure sustainable management practices.

In conclusion, addressing water scarcity requires a multifaceted strategy involving conservation efforts, sustainable water management practices, infrastructure funding, and supportive legislation for water efficiency which can address the root causes of water scarcity and ensure a sustainable future for upcoming generations.

CHAPTER 4: Modeling A Reverse Osmosis Desalination Plant: A Practical Framework Using Wave Software

Reverse osmosis (RO) has become a dominant method for converting seawater into potable water due to its high recovery rates and comparatively low energy demands. Despite its growing application, accurately modeling full-scale RO systems remains complex, particularly under real-world conditions influenced by seasonal fluctuations, membrane fouling, and variable feed characteristics. These dynamic conditions introduce uncertainty into operational planning and cost estimation for plant designers and operators.

This chapter presents a detailed modeling framework for seawater reverse osmosis (SWRO) using DuPont's Water Application Value Engine (WAVE) software. The model reflects the real configuration of the Victoria & Alfred Waterfront desalination plant in Cape Town, South Africa. It incorporates ultrafiltration (UF) for pretreatment and ion exchange (IX) for post-treatment, simulating both hydraulic and separation performance under steady-state conditions. The model parameters were based on actual plant data, including salinity levels, membrane layout, operating pressure, and flow rates. Comparative analysis shows that the simulated plant achieved improved freshwater recovery of 45.7% as against 31%, and reduced specific energy consumption of 5.91 kWh/m³ as against 6.58 kWh/m³, validating the predictive strength of the WAVE model. These results support its potential as a decision-support tool for performance forecasting, system optimization, and cost reduction in desalination system design. The content in this chapter, co-authored with Prof. Oludolapo A. Olanrewaju, has been accepted for publication in "Science, Engineering and Technology journal".

4.1 Introduction

Seawater desalination is considered a viable solution for producing drinkable water from seawater, especially as global freshwater resources are rapidly depleting. In recent years, reverse osmosis (RO) has emerged as a leading desalination technology [114, 115]. This technology adopts a semi-permeable membrane for water purification,

effectively removing organic compounds, metals, and toxic substances that are typically difficult to eliminate with conventional water treatment processes [116]. RO has been increasingly employed in water treatment, particularly for seawater and brackish water desalination in water-scarce regions. However, the technology has its limitation which includes membrane fouling, high energy demand, and high brine waste generation. The membrane fouling, which results from an accumulation of foulants in the feed solution on the membranes' surface, is another significant problem for RO systems [117]. Membrane fouling is a complex process where various foulants accumulate on the membrane surface, decreasing its permeability and increasing energy demands. A suitable pretreatment process is typically implemented to reduce fouling, which also requires energy for operation [118]. RO desalination technology requires significant energy to pressurize the feed flow and overcome the osmotic pressure of the solution. While technological advancements over the years have greatly reduced the energy requirements, these still remain high [119].

Additionally, the disposal of RO rejected brine from the system is a great environmental concern for marine ecosystems [120]. The advancements in membrane performance have expanded the versatility and applicability of RO technology for water desalination across a wider range of pH, pressure, and temperature, and the technology is characterized by low energy consumption, operation at relatively low temperatures, a abridged system footprint, and lower overall water production costs. However, RO technology performance is principally dependent on the quality of the feed water and the operating conditions. Therefore, a reliable RO model is crucial for an efficient desalination process. [121, 122]. Given that the performance of an RO system is heavily influenced by its design and operating conditions, access to reliable RO models is crucial to ensure efficient system planning and operation. [123]. While numerous computer models are available to assist engineers in designing RO plants, the majority primarily emphasize performance evaluation of individual RO modules rather than comprehensive optimization of the process for energy efficiency and water quality. Only a limited number of studies have concentrated on developing advanced RO models aimed at optimizing membrane modules and overall desalination plant performance. [124-126]. However, the influence of different design and operational parameters on the performance of RO desalination systems has not been thoroughly explored using these existing models.

This paper aims to develop a WAVE-based model capable of simulating the efficiency of a full-scale seawater reverse osmosis desalination plant while accounting for the influence of operating conditions. Operating parameters such as recovery ratio, salinity, and temperature were quantitatively evaluated, and the RO desalination system was optimized with respect to energy consumption and brine discharge [127]. This study presents a novel application of DuPont's Water Application Value Engine (WAVE) software for the full-scale simulation and optimization of a seawater reverse osmosis (SWRO) desalination plant, uniquely integrating ultrafiltration pretreatment, two-stage reverse osmosis processing, and ion exchange polishing into a unified modeling framework. Contrary to existing models that focus on isolated RO components, this work is distinguished by its direct validation against real-world operational data from the V&A Waterfront desalination facility in Cape Town, achieving high predictive accuracy across key performance metrics. The model not only quantifies improvements in system recovery and specific energy consumption but also identifies critical operational bottlenecks and proposes optimization strategies for enhanced plant efficiency. This research extends the conventional use of WAVE software beyond membrane sizing to comprehensive system simulation, providing a scalable and practical tool for design, performance forecasting, and adaptive infrastructure planning in water-stressed regions.

The next section of the paper presents the Victoria and Alfred (V & A) desalination plant in Cape Town, South Africa and the studied system. Section 3 discusses model development using WAVE software, while Section 4 details the system configuration and operational regimes of the desalination process. Section 5 outlines the equations governing WAVE and the general water desalination process. Section 6 describes the methodology used in this study, and Section 7 focuses on modelling and simulation for efficient separation. Section 8 explores key design considerations, and Section 9 discusses the simulation results. Section 10 concludes the review paper.

4.2 Studied System

The V&A desalination plant in Cape Town's waterfront is a containerised facility that produces 2 million litres per day (MLD) of potable water from saline water sourced from the Atlantic Ocean. It comprises three treatment trains: the first and second each

produce 500,000 litres per day, while the third generates 1 MLD, totalling a daily capacity of 2 MLD. The trains are designated as 500-3, 500-4, and 1000-10. The plant's key systems include the intake, raw water pretreatment unit with cartridge filters, high-pressure pump, reverse osmosis (RO) membrane unit, energy recovery device, and post-treatment system.

4.3 Model Development

This study details modelling a seawater reverse osmosis (SWRO) desalination plant using modelling software and validated with operational data from an already existing facility in Cape Town. Various operational stages of the desalination process will be efficiently simulated during the study to reflect a complete water treatment system from source works to clear water. The process will encompass the entire plant control system and replicate full-scale plant operations, and its versatility will make it suitable for diverse research applications, such as performance analysis, and health monitoring. Dupont's Water Application Value Engine (WAVE), a leading software for reverse osmosis (RO) membrane design, will be employed in this RO modelling study.

The key inputs for this software are:

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

In response to the given inputs, the software calculates the feed water's Total Dissolved Solids (TDS) and its scaling tendency. Based on these results, the software makes decisions regarding the use of acid/anti-scalant dosage and helps in selecting the type and size of the membrane. It also sets the initial membrane configuration and estimates the number of membrane pieces. Typically, for a flow rate of 5 m³/hr, 8-inch membranes are recommended. After receiving this data, the software produces output related to the following parameters:

1. Detailed analysis of the permeate and rejected water.
2. Scaling tendency of the water.
3. Net head pressure requirement.
4. Concentration polarisation (beta factor).

The membrane system computer models listed have demonstrated effectiveness when used according to the manufacturer's guidelines, but they have certain limitations. Designers must understand these limitations to ensure the correct application of data outputs during the design phase of the reverse osmosis membrane system. There are countless configurations of membranes, pumps, energy recovery mechanisms, and more that can be considered for a SWRO desalination system [128].

4.4 Configuration Of Water Desalination System

This study applied DuPont's WAVE water solution software to simulate a reverse osmosis (RO) desalination system. Figure 4-1 illustrates the four distinct steps involved in the reverse osmosis desalination process. Before entering the ultrafiltration (UF) pretreatment system, the water from the system feed source passes through a strainer equipped with fine and coarse screens to eliminate any floating particles in the feed stream.

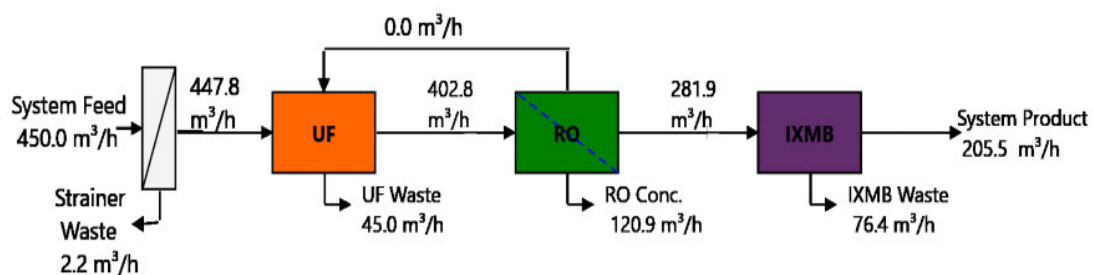


Figure 4-1 UF, RO, IX system configuration.

The ultrafiltration unit comprised six online trains, each containing 34 1.86-meter-long Integralflex SFP-2860 XP modules that are internally branched and interlocked in tandem. The module occupies a total area of 51 m with a diameter of 0.225 m as shown in Table 4-1. The module provided a total volume of 35 litres. A CIP water source is provided from the RO permeate flux for the UF system. 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 flows across a semi-permeable membrane barrier as shown in Figure 4-2. The solvent flows through the membrane faster than the dissolved solids. The difference in this flow rate results in the 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.

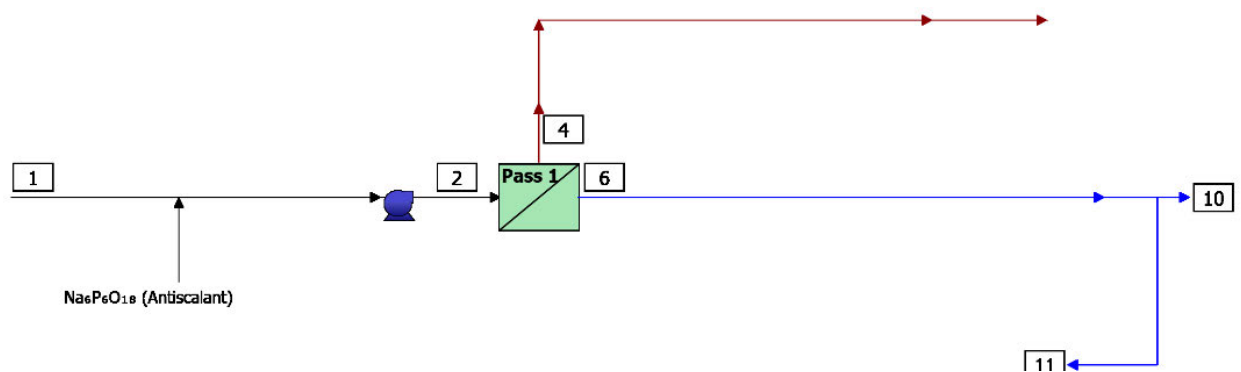


Figure 4-2 RO system configuration.

Table 4-1 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 Office Trains	1	Weight (water filled)	83 kg	183 lb
Modules/Train	34	Water Volume	35.0 L	9.2 gal
Total Modules	204			

The reverse osmosis system is configured as a two-stage pressure vessel (PV) setup. It has a seawater RO (SWRO) production capacity of 9,000 m³ per day, operating at a recovery rate of 70%, while the ultrafiltration (UF) process is designed to achieve a 90% recovery rate, and the IX polish (post-treatment) system is designed with a 72.9% recovery rate. The ultrafiltration (UF) permeate produced during the pretreatment stage met the required water quality standards for RO feed, with total suspended solids (TSS) not exceeding 10 mg/L, turbidity below 1.7 NTU, and a silt density index (SDI) of 2.5 or less. This feed water is then pressurized using a high-pressure pump

(HPP) before entering the reverse osmosis (RO) system, which is configured into two pressure vessel (PV) stages consisting of 36 PVs in the first stage and 18 in the second., with each PV having six seamaxx™ - 440i elements installed. Specifically, it is essential to highlight that the retentate from the first-stage pressure vessels, which serves as the feed water for the second-stage PVs in the RO process, was not further pressurized by an interstage booster pump (IBP), and the difference in intake feed pressures between the first-stage and second-stage PV systems confirms this. 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.

4.5 Governing Equation

According to Anqi, et al. [129], who studied two-dimensional steady and transient flows in the feed channel of a reverse osmosis (RO) membrane system, assuming incompressible flow and constant fluid physical properties, including a constant diffusion coefficient. The equations for fluid motion and concentration fields are provided below.

The continuity

$$\frac{\partial u_i}{\partial x_i} = 0, \quad \text{Eq. (4-1)}$$

The conservation of momentum

$$\frac{\partial u_i}{\partial t} + U_j \frac{\partial u_i}{\partial x_j} = - \frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} \quad \text{Eq. (4 - 2)}$$

and the mass transport equation

$$\frac{\partial c}{\partial t} + u_j \frac{\partial c}{\partial x_j} = D \frac{\partial^2 c}{\partial x_j \partial x_j} \quad \text{Eq. (4 - 3)}$$

Where D represents the diffusion coefficient, ρ is the density, and μ is the viscosity. The velocity components are $u_1 = u$ and $u_2 = v$, with summation indices i and j . The spatial coordinates are $x_1 = x$ and $x_2 = y$, time is t , pressure is p , and the kinematic viscosity ($\nu = \mu/\rho$) is ν .

According to Filmtec [130], the performance of a reverse osmosis (RO) system is primarily determined by its feed pressure (or permeate flow when feed pressure is unspecified) and salt passage. The permeate flow (Q) through an RO membrane is mathematically expressed as proportional to the product of the wetted surface area (S) and net driving pressure ($\Delta P - \Delta \pi$), with the proportionality constant being the membrane permeability coefficient commonly known as A - value, as shown in the water permeation equation.

$$Q = (A)(S)(\Delta P - \Delta \pi) \quad \text{Eq. (4-4)}$$

Salt passage in reverse osmosis occurs through diffusion, with the salt flux (N_A) directly proportional to the salt concentration difference across the membrane. This relationship is characterized by the proportionality constant, which is the salt diffusion coefficient also known as B-value, where C_{fc} represents the average feed-concentrate concentration and C_p is the permeate concentration.

$$N_A = B(C_{fc} - C_p) \quad \text{Eq. (4-5)}$$

Where

C_{fc} = feed – concentrate average concentration

C_p = Permeate Concentration

Element-to-Element method is used to calculate the performance of a specified design as shown below

4.5.1 Element-to-Element Approach

The equations below show the design equations for projecting RO system performance and individual element performance. The water permeation equation is expanded to Eq. 4-6 to determine the values of A, ΔP , and $\Delta \pi$ from Eq. 4-4.

Permeate flow of Element i(gpd)

$$Q_i = A_i S_i (\text{TCF})(\text{FF}) \left(P_{ff} - \frac{\Delta P_{fci}}{2} - P_{pi} - \pi + \pi_{pi} \right) \quad \text{Eq. (4-6)}$$

Average Concentrate-side osmotic pressure

$$\pi = \pi_i \left(\frac{C_{fc}}{C_f} \right) P^f \quad \text{Eq. (4-7)}$$

Average Permeate-side osmotic pressure

$$\pi_{pi} - \pi_{fi} (1 - R_1) \quad \text{Eq. (4-8)}$$

Ratio: arithmetic Average Concentrate-side to feed concentration for Element i

$$\frac{C_{fci}}{C_{fi}} = \frac{1}{2} \left(1 + \frac{C_{ci}}{C_{fi}} \right) \quad \text{Eq. (4-9)}$$

Ratio: Concentrate to feed concentration for Element i

$$\frac{C_{fci}}{C_{fi}} = \frac{1 - Y_i (1 - R_i)}{(1 - Y_i)} \quad \text{Eq. (4-10)}$$

Fredwater osmotic pressure

$$\pi_i = 1.12(273 + \tau) \sum m_i \quad \text{Eq. (4-11)}$$

Temperature correction factor for RO and NF membrane

$$TCF = EXP \left[2640 \left(\frac{1}{298} - \frac{1}{273 + \tau} \right) \right] T \geq 25^\circ\text{C} \quad \text{Eq. (4-12)}$$

$$TCF = EXP \left[3020 \left(\frac{1}{298} - \frac{1}{273 + \tau} \right) \right] T \leq 25^\circ\text{C} \quad \text{Eq. (4-13)}$$

Concentration Polarization factor for 8-inch Elements

$$P_{fi} = EXP(0.7Y_i) \quad \text{Eq. (4-14)}$$

System recovery

$$Y = 1 - [(1 - Y_1)(1 - Y_2) \dots (1 - Y_n)] = 1 - \prod_{i=1}^n (1 - Y_i) \quad \text{Eq. (4-15)}$$

Permeate Concentration

$$C_{pj} = B(C_{fc})(Pf_i)(TCF) \frac{S_E}{Q_i} \quad \text{Eq. (4-16)}$$

Where Q_i is the Permeate flow of Element i (gpd), $A_i \pi_f$ is the Membrane permeability at 25°C for element i . a function of the average concentrate side osmotic pressure (gfd/psi, S_E is the membrane surface area per element (ft²), TCF is the Temperature correction factor for membrane permeability, FF is Membrane fouling factor, P_{ff} is Feed pressure of Element I (psi), ΔP_{fci} is Concentrate-side pressure drop for Element I (psi), P_{pi} is Permeate pressure of Element I (psi), π is Average concentrate-side (psi), π_{pi} is Permeate-side osmotic pressure of element (psi), π_{fi} is Feed osmotic pressure of Element I , C_{fc} is Average concentrate side concentration for system (ppm), C_{fi} is Feed concentration for Element i (ppm), P_{fi} is Feed pressure of Element I (psi), R is Average fractional salt rejection for system,

After being transformed into Eq. (4-16), the permeate concentration can be derived from Eq.(4- 5). These equations are applicable to the i th element in a sequence of n elements in a series flow configuration, as indicated by the subscript i . Starting with a given set of conditions, Eq. (4-6) is solved iteratively for each of the n elements to accurately assess system performance. For salt (Eq. 4-10) and water (Eq. 4-16), solutions are based on mass balances for each element and correlations for specific parameters, including concentrate-side flow resistance (ΔP_{fc}), temperature correction factor for water permeability (TCF) (Eq. (4-12) and (4-13), polarization factor (p_{fi}) (Eq. (4-14), and membrane permeability coefficient for water ($A_i (\pi_i)$)).

For RO membranes, permeability is influenced by the average concentrate concentration or osmotic pressure. Solutions often employ averages of hydraulic and osmotic pressures on the feed and permeate sides. In cases of low recovery rates, accurate results can be achieved using arithmetic averages of inlet and outlet conditions. However, as outlet parameters are initially unknown, iterative calculations remain necessary. Based on the analysis in [18], the theoretical expressions for specific energy consumption (SEC) and permeate flux (J_v) are given by:

$$SEC = \frac{E_{bp} + E_{hp} + E_{sp}}{Q_p} \quad \text{Eq. (4 – 17)}$$

$$J_v = \frac{Q_p}{A} \quad \text{Eq. (4 – 18)}$$

Where: E_{bp} , E_{hp} and E_{sp} represent the energies consumed by the booster pump, high-pressure pump and supply pump respectively, Q_p represents the permeate water flow rate and A is the membrane area.

The specific energy consumption (SEC) of the plant is further determined by::

$$SEC = \frac{W_{pump}}{Q_p} \quad \text{Eq. (4 – 19)}$$

$$W_{pump} = \frac{\Delta P * Q_f}{\eta_{pump}} \quad \text{Eq. (4 – 20)}$$

Where W_{pump} is the work done by the pump, ΔP is the pressure differential Q_f is the feed flow rate, and η_{pump} is the pump efficiency [131].

According to [Eq. 4-20, 4-21, 4-22], salt rejection, R_s , and the total mass balance, $Q_f C_f$ is calculated using:

$$R_s = 1 - \frac{TDS_p}{TDS_f} \quad \text{Eq. (21)}$$

$$Q_f C_f = Q_p C_p - Q_r C_r \quad \text{Eq. (22)}$$

The permeate water flow rate is determined by the equation below:

$$Q_p = Q_f - Q_r \quad \text{Eq. (23)}$$

$$Q_p = n_i W \int_0^L J_v dz \quad \text{Eq. (24)}$$

Where C_f , C_p and C_r represent the feed, permeate and rejected salts mass concentrations, respectively, Q_r is the rejected water flow rate, and n_i , L and W represent the number of leaves, length and width of the RO module.

Concentration polarization, ϕ , resulting from impermeable salt accumulation on the membrane surface, is expressed by:

$$\phi = \frac{C_m - C_p}{C_b - C_p} = e^{\frac{J_v}{k}} \quad Eq.(4 - 25)$$

Where k is the mass transfer coefficient and C_b is the bulk solution solute concentration

The temperature (TMP*) is defined by:

$$TMP^* = TCF * TMP \quad Eq.(4 - 26)$$

Temperature correction factor (TCF) is a factor that takes into cognisance the effect of the temperature [132].

4.6 Methodology

This study adopted a structured modeling approach to evaluate the performance of a seawater reverse osmosis desalination system which incorporate ultrafiltration (UF), reverse osmosis (RO), and ion exchange (IX) stages. The general procedure comprised the following steps:

1. **System Configuration:** A process flow including UF pretreatment, two-stage RO, and IX polishing was established based on the actual layout of the V&A desalination plant.
2. **Data Collection:** Plant operating data such as feedwater total dissolved solids (TDS), temperature, pressure, flow rate, and specific energy consumption (SEC) were gathered over a 12-month period to support model setup and validation.
3. **Software Tool:** The DuPont WAVE (Water Application Value Engine) software version 1.83 was used to simulate the full process. This tool integrates membrane performance models with hydraulic and thermodynamic calculations across UF, RO, and IX units.
4. **Input Specification:** Technical inputs, which includes membrane element characteristics, design recovery, system pressure, cleaning cycles, and fouling assumptions, were defined based on manufacturer specifications and plant documentation.

5. **Model Execution:** A model case was established under nominal operating conditions. The system was simulated under steady-state assumptions to determine key outputs such as permeate quality, recovery, and energy consumption.
6. **Performance Comparison:** Simulated results were compared with measured operational data to evaluate the accuracy of the model. Any observed discrepancies were addressed through parameter tuning within the modeling constraints.

The model excluded seasonal changes for simplicity; however, design guidelines note that surface feedwater quality can vary with seasons and recommend modeling average case conditions. Membrane ageing was also idealized: by setting the fouling factor to 1.00, we assumed membranes remain like-new throughout. This neglects any gradual flux decline or salt passage increase. In reality, fouling factors less than 1.00 (for example, 0.75 after 3 years) account for performance loss. By combining ultrafiltration for pretreatment and ion exchange for post-treatment within the RO framework, the study provides a robust model framework. This approach ensures efficient hydraulic performance and cost-effective desalination, offering valuable insights for design engineers in the development of high-performance seawater desalination systems.

This section outlines the overall design and modeling process. Detailed simulation lucidity, calibration results, and performance evaluation are discussed in the next section.

4.7 Modeling and Simulation

This section presents the modeling and simulation approach used to evaluate the performance of the seawater reverse osmosis (SWRO) desalination plant. Employing DuPont's WAVE software, the study simulates the integrated process, which includes ultrafiltration pretreatment, reverse osmosis, and post-treatment, under realistic operating conditions to predict system behavior, assess energy efficiency, and optimize key performance parameters.

4.7.1 System Modeling

Post-treatment is defined as the process of stabilizing the permeate flow from the desalination system to prepare it for distribution. Most alkaline mineral components are larger than the pores of a typical RO membrane, preventing their passage while allowing permeate flux to flow through easily. Consequently, the permeate becomes very acidic, which is harmful to human consumption and can damage equipment.

4.7.2 Model Input

The WAVE model tool can be used to model or size new desalination systems or evaluate the performance of an existing system. When developing a new ultrafiltration system, it's crucial to understand the essential inputs required for an accurate and efficient design. Some examples of these inputs include information about the feed supply, quality, temperature range, and the necessary feed flow or system net production. For a given type and quality of a feed water source, applying appropriate design principles is very essential. These design principles stem from extensive experience and research in relevant fields. 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 4-2 was entered into the computer model, while the permeate water quality is the information output of the computer model. The actual total dissolved solids content of the raw water was obtained from the seawater database.

Table 4-2 Input data table

Parameter	Unit	Value
Feed water classification Membrane	Not applicable	Surface water,
Pretreatment,	Silt density index	< 1
Permeate flow per ain	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

4.7.2.1 Input Justification

The model design is based on the simulation and development of a movable solar-powered reverse osmosis membrane 2 million gallons per day (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. A silt density index (SDI) of less than 1 was adopted because the seawater has been tested to have the 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 an 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 delivering improved permeate flow of World Health Organization (WHO) standard potable water.

The water type is selected from the Feed Water tab. The solid content properties (NTU, TSS, SDI) and the organic content (TOC) are inputted with the temperature and pH values. Please note that the pH value in WAVE is defined as $-\log_{10}$ 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 4-2 shows the input data overview. It is important to note that in reverse osmosis (RO), TDS refers to “total dissolved solids” and excludes dissolved CO_2 , whereas in the ion exchange (IX) modules, TDS refers to “total dissolved solutes” which includes dissolved CO_2 . When designing ion exchange systems, important factors to consider include the water quality, the quantity and cost of chemicals, and the size and shape of the containers. Designing these systems is not a one-size-fits-all approach, as there are various trade-offs to be considered. This is similar to the designs of ultrafiltration (UF) systems.

4.7.3 Model – UF, RO, IX polishing

A feedwater Total Dissolved Solids (TDS) concentration was determined by the model, using input values for Total Suspended Solids (TSS), turbidity, organic Total Organic Carbon (TOC), and feedwater temperature. The designed TDS represented a design value of 44,352 mg/L of ions of SiO_2 and $B(OH)_3$ but does not include NH_3 and CO_2 . This designed TDS accounts for the feedwater quality and the minimum requirements for the total designed head of the reverse osmosis feed pump, and it is specific to the project location. The chosen temperature of the feed flow aligns with the maximum documented temperature of 25°C for the feed source. Considering the influence of TDS and temperature on the membrane supply pressure, it might not be necessary to

include a design margin for both parameters. This evaluation is based on the site-specific water quality. This model specifies a designed feed flow of 450 m³/h and a permeated flow of 205.5 m³/h, 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.

Two similar reverse osmosis membranes were modelled for this system. Table 4-3 provides detailed flow and performance data for a two-stage reverse osmosis (RO) system using Seamaxx™-440i membrane elements. In Stage 1, 36 pressure vessels (PVs) each containing 6 elements process 401.5 m³/h of feedwater at 70.9 bar, producing 273.3 m³/h of permeate with an average flux of 30.9 L/m²·h and a permeate TDS of 284.1 mg/L. Stage 2 receives 129.1 m³/h of feed at 69.8 bar across 18 PVs and yields 8.67 m³/h of permeate at a lower average flux of 2.0 L/m²·h and TDS of 5,134 mg/L. The table also shows the pressure drop and flow rates for concentrate streams, providing insight into the hydraulic and separation performance across each stage. The table also shows that both model membrane elements provided a surface area of 3,679 m². Each membrane manufacturer offers comparable high-productivity, low-pressure options, as illustrated by the modelled membrane elements.

Table 4-3 RO membrane modelled.

RO flow Table (stage Level) – Pass1														
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	70.9	0	129.1	70	0.9	273.3	30.9	0	284.1
2.	Seamaxx™-440	186	6	129.1	0	69.8	0	120.5	68.6	1.2	8..67	2	0	5,134

4.7.4 Model Output – Ultrafiltration (UF)

The summary of the output data calculated by each design model run is presented below. We refer to Figure 4-1, which shows the system flow of the desalination process model from the feed source to the system product. A designed system flow of 450 m³/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 m³/h before entering the UF pretreatment process. Following the UF treatment, the RO feed water has a flow rate of 402.8 m³/h, which is further diminished to 281.9 m³/h after the RO membrane treatment before entering the post-treatment process. The potable water output after the IX polishing process has a final flow rate of 205.5 m³/h. Table 4-4 summarizes key operational parameters for the system configuration and output across four stages of the seawater desalination process: strainer, ultrafiltration (UF), reverse osmosis (RO), and ion exchange mixed bed (IX MB) polishing. treatment processes. It shows the input feed water and product water parameters developed by the model tool for each treatment process and the overall system recovery for the design. The system starts with a feed flow rate of 450.0 m³/h and maintains a consistent temperature of 25°C throughout all stages. The total dissolved solids (TDS) reduce significantly from 45,696 mg/L at the strainer to 117.1 mg/L after IX polishing. The system operates at a maximum pressure of 71.2 bar in the RO stage, with pH adjusted from 7.0 to 5.9 in the final polishing stage. Overall, the system consumes 5.91 kWh/m³ of energy, delivers a final product flow of 205.5 m³/h, and achieves a recovery rate of 45.7%.

Table 4-4 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)	45,696.0 ^b	44,352.0 ^b	44,352.0 ^a	117.1 ^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
System	Specific Energy (kWh/m ³)	5.91			
	Feed Flow Rate (m ³ /h)	450.0			
	Product Flow Rate (m ³ /h)	205.5			
	Recovery (%)	45.7			

Based on the information provided, the WAVE modelling tool generated the UF process flow diagram as shown in Figure 4-3. The flow diagram shows the process flow and operating conditions of the ultrafiltration (UF) pretreatment system using IntegraFlux SFP-2860XP membrane modules. The system includes six UF trains, each with 34 modules, providing a total recovery of 90% at an operating flux of 47 LMH. Seawater feed enters at 450 m³/h and passes through a 150 µm strainer with 99.5% recovery. Sodium hypochlorite and ferric chloride are dosed for fouling control. The gross filtrate produced is 434.2 m³/h, while the net filtrate is 402.8 m³/h after eliminating 45.0 m³/h of waste. The system includes a CIP tank (2.4 m³), CIP pump (5.1 m³/h), air scour system (408 Nm³/h), and backwash pump (173.4 m³/h), operating at 2.5 bar.

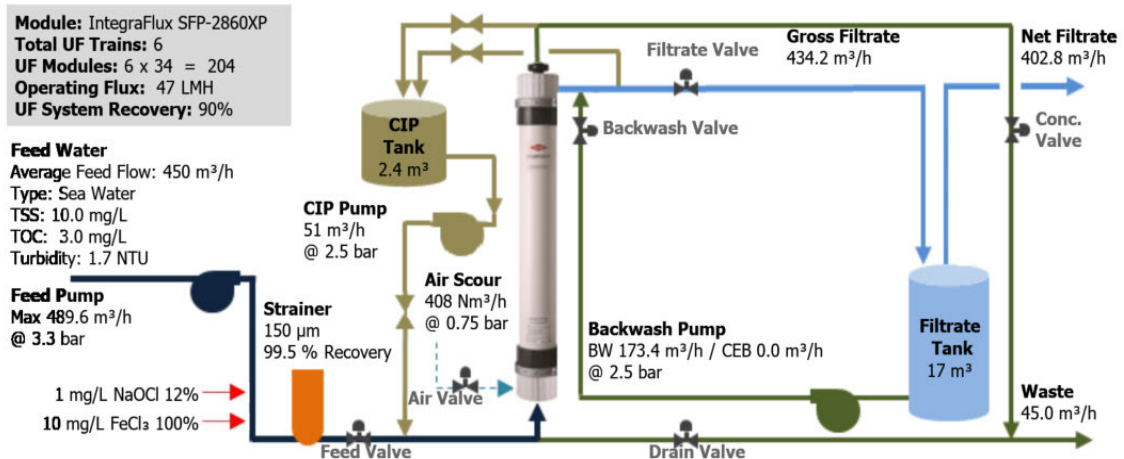


Figure 4-3 UF system flow diagram.

Filtrate is stored in a 17 m³ tank before transfer to the RO stage. The flow diagram also illustrates various pressure regimes for the UF treatment process, starting from the feed pump with a pressure of 3.3 bar. Sodium hypochlorite and ferric chloride are added in percentages of 12% and 100% respectively immediately after the feed pump to prevent fouling of the UF membrane. The UF feed water is further passed through a fine strainer to trap any floating impurities in the flow before reaching 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 %.

Six online trains were modelled for the system, with WAVE determining the module count per train based on the flux and duration recommendations, with each train consisting of 34 modules. The module type adopted for this design is InegraFlux SFP - 2860XP. a total number of 204 modules are used in the 6 trains with individual train flow rates of 67.1 bar. The model calculates UF system recovery to optimise hydraulics and maintain intake pressure for the RO system, with RO permeate water designated for the CIP water source. WAVE employs three durations in developing the 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 to determine the system energy consumption.

- Duration of CIP recycling: This is the time during which the CIP solution is expected to move around through which the UF Module circulates.

WAVE establishes specifications for the increase in pressure drop across the UF membrane known as transmembrane pressure (TMP) between successive backwash steps, acid/alkaline CEB, and CIP per hour. These specifications aid in estimating the energy requirements for ultrafiltration, taking into account the accumulation of solids or fouling of the UF membrane during operation.

4.7.5 Model Output – Reverse Osmosis (RO)

WAVE generated the RO process flow diagram 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 the Desalination System Configuration. The RO system flow diagram shows the different systemic flow rates from the RO feed source (UF product flux) through the high-pressure pump (HPP) to the concentration and product feed. It also indicates different pressure regimes for the RO treatment process, starting from the high-pressure pump to the RO concentrate. The RO system was modelled to include only one pass with one online train, and WAVE was used to calculate the number of elements per train. The flow factor used in this model which accounts for flow loss due to fouling, is 1.00, as this model was for a new system. The risk of scaling resulting from chemical adjustments in the RO process can be best assessed by using the Langelier saturation index (LSI), the Stiff & Davis index (S&DI), and the saturation percentage for certain salts such as CaSO_4 , BaSO_4 , SrSO_4 , CaF_2 , Mg(OH)_2 , and SiO_2 . WAVE also simulated the scaling risk for the RO membrane process being. It uses colour coding to flag any percentage saturation of salts with values greater than 100, as well as LSI and S&DI values greater than 0, to alert the designer.

4.7.6 Model Output – Ion Exchange (IX) Polishing

Figure 4-4 illustrates the process flow and water balance of the ion exchange mixed bed (IXMB) polishing system in a seawater desalination plant. The system receives 281.9 m³/h of feed water per online train and delivers a net product flow of 205.5 m³/h

after IX treatment. One train operates while another is in standby or regeneration. The system consumes 275.8 m³/h of design flow, with part of the water diverted for regeneration 6.08 m³/h from the feed side and 70.33 m³/h from the product side. Regeneration and waste processes generate 80.54 m³/h of total waste, including chemicals, with a TDS of 9666.42 mg/L. The diagram also indicates use of cation (SAC) and anion (SBA) resins and includes degassing to remove dissolved CO₂ before polishing

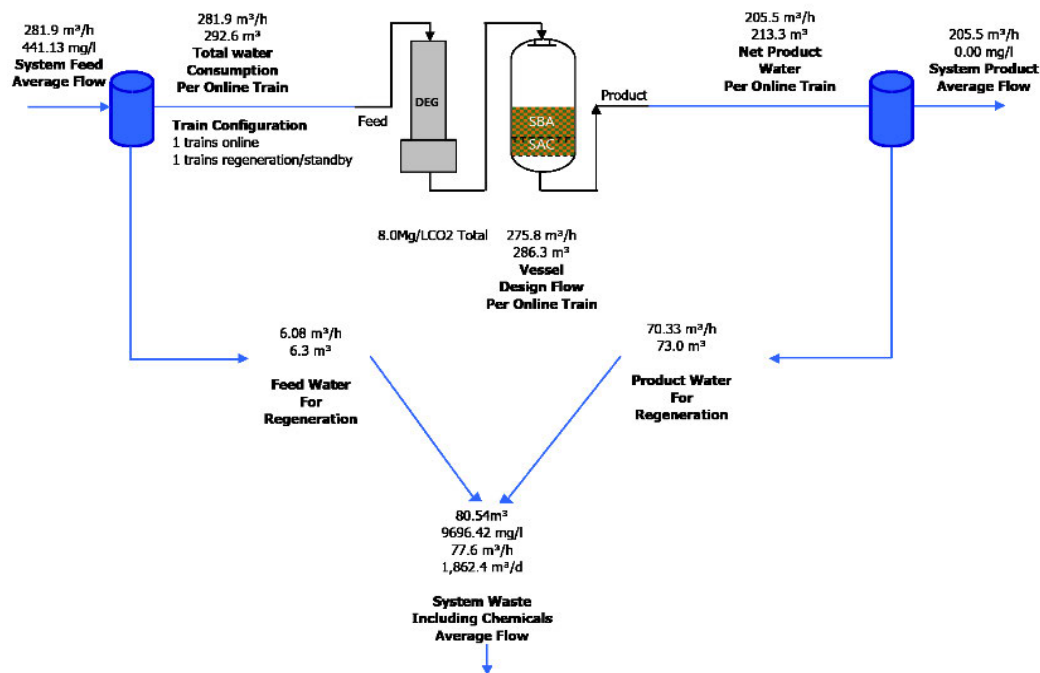


Figure 4-4 IX System Flow Diagram.

The resin volume and operating cycle for this model were calculated based on the input specifications. The IX system configuration as shown in Figure 4-4, depicts WAVE software calculating the feed and product flow rates for the designed system, set at 281.9 m³/h and 205.5 m³/h, respectively. The system input flow is expected to be the same as the operating flow due to the inclusion of a standby train in the model. The IX overall system recovery, as shown in Figure 4-4, is 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. The operating cycle length is calculated using the vessel size recommended by WAVE. WAVE also configured and developed the model parameters based on the resin's arrangement/choice (SAC, SBA) and the selected regeneration system (MB: internal

regeneration) from the IX initialization window. The estimated run time for the IX process is 1.04 hours, while the expected regeneration time based on the design model and calculations is 4.27 hours. Hydrochloric acid and sodium hydroxide are used as regenerants for the cation and anion resins, respectively. The selected resin for this model is Amberlite (SAC, SBA), loaded one on top of the other in the MB internal regeneration vessel.

4.8 Design Consideration

The data in the UF, RO, and IX model output provides the expected operating conditions of the system. This information is used to size and select the system feed pumps, the interstage booster pumps (if any), and energy recovery equipment to meet the system's operating requirements. The UF backwash is scheduled to be repeated several times, depending on the fouling tendencies of the UF membrane modules. The frequency of the UF CIP is 1-3 months, adjusted based on the operating conditions. The CIP operation begins with a backwash sequence and ends with a backwash sequence. Given the comparatively high frequency of mini-CIP (usually once or twice a week), automating the procedure is recommended to save labour costs. The current auxiliary system for standard CIP is exploited for more frequent and shorter chemical cleanings in mini-CIP, eliminating the need for extra installation or hardware. The mini-CIP takes approximately 30 minutes and involves three steps: a standard backwash pre-cleaning, a heated chemical solution recirculation with a soaking period and in between intermittent air scour, and a final backwash post-cleaning. If the fouling is extensive, this phase may take longer, possibly reaching or exceeding 12 hours. It is worth noting that the mini-CIP replaces the CEB rather than the typical intensive CIP program, which may still be required regularly. The water quality analysis of the RO model revealed that monovalent ions such as Na⁺ and Cl⁻ were predominant. Among the divalent ions, K²⁺ showed the highest concentration at 7.33 mg/L, while Mg²⁺ and SO₄²⁻ had relatively lower concentrations at 3.45 mg/L and 4.66 mg/L, respectively.

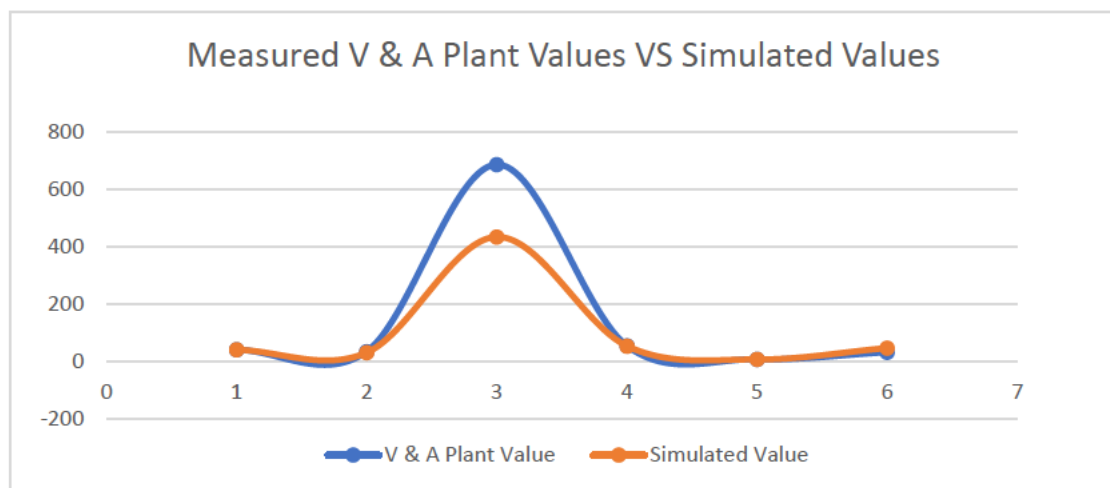
4.9 Result and Discussion

This section presents the result of the model study in comparison to the measured data from the V & A desalination plant. Table 4-5 presents the result of the model study in comparison to the measured data from the V & A desalination plant. The table indicates that the measured feed pressure and permeate flow values are 39.8 m³/h and 53.4 bar,

respectively, while the simulated values are 39.73 m³/h and 52.67 bar. The simulated results demonstrate a reduction in specific energy consumption (SEC) from 6.58 kW/h to 5.91 kW/h and an increase in system recovery from 31% to 45.7%.

Table 4-5 Plant Measured Data in Comparison to WAVE Simulated Data.

Parameter	V & A Plant Value	Simulated Value	Variance (%)
Permeate Flow [m ³ /h]	39.8	39.73	0.2
Permeate TDS [mg/l]	685.5	433.2	36.8
Feed Pressure [Bars]	53.4	52.67	1.4
Specific Energy Consumption [kW/h]	6.58	5.91	10.2
Recovery	31	45.7	32.2



1	Permeate flow	2	Feed TDS	3	Permeate TDS
4	Feed Pressure	5	Specific Energy Consumption	6	Recovery

Figure 4-5 Measured V & A Desalination Plant Data Vs Simulated Data.

The comparison of measured and simulated data offers insights into the performance of the reverse osmosis (RO) desalination system and the reliability of the simulation model. The simulated results of the RO were compared with operating data from the V&A desalination plant (Figure (4-5)). The permeate flow rate showed minimal variance between plant and simulated data, confirming the robustness of the predictive model and its accuracy in forecasting permeate flow, replicating the system's hydraulic performance. This accuracy is critical for optimizing operations and ensuring consistent freshwater output. Furthermore, the simulated feed pressure data aligned closely with the measured values, indicating that the model effectively estimates the system's hydraulic pressure requirements. Feed pressure is crucial as it directly affects energy consumption and system reliability, further reflecting the simulation's reliability in predicting the RO system's mechanical operation.

However, the simulated feed total dissolved solids (TDS) was significantly lower than the actual plant value. This discrepancy may stem from model assumptions, such as a higher efficiency of the pretreatment system (e.g., ultrafiltration). In reality, variations in raw seawater quality or inadequate pretreatment could lead to higher feed TDS. This highlights the need to validate the model under diverse feed water conditions to enhance its robustness. A reduction in permeate TDS generally improves water quality, as noted by [133] and [134], who found that increased feed pressure decreases permeate TDS, thereby enhancing permeate flux and salt rejection while reducing specific energy consumption (SEC). The significant difference between measured and simulated permeate TDS suggests that the model predicts lower salinity than actual plant performance, likely due to assumptions of ideal operating conditions with minimal fouling or scaling. Real-world factors such as fouling, scaling, or partial bypass flow could elevate permeate TDS, and adjusting the model to account for these conditions could enhance its predictive accuracy.

The simulated SEC result indicates lower energy consumption than the plant operational data. However, achieving theoretical SEC can be challenging due to concentration polarization, hydraulic resistance, and membrane fouling [135]. The 10.2 percent variance from the measured data suggests significant positive impacts on energy consumption, potentially reducing total operational costs. This variance may also arise from idealized simulation assumptions, such as less fouling, lower feed

TDS, and higher recovery rates, which all lower energy demands. In practice, factors like membrane ageing, fouling, and pump inefficiencies could increase energy consumption. Iterative tuning (and/or WAVE's default sizing routine) was used for this model rather than any metaheuristic. Although Genetic Algorithm or simulated annealing was not used for this work, future work could explore this to further improve efficiency of the system.

The notable variance in recovery rate indicates that the simulation predicts a higher water recovery capacity than what the plant currently achieves. In real-world operations, recovery is often constrained by scaling, fouling, and operational safety margins to prevent membrane damage. The high simulated recovery rate represents optimal conditions, which would necessitate improved pretreatment and regular maintenance to achieve in practice. The resulting permeate concentration is 156.5 mg/L (Na⁺), while the other ions are not detected by the model due to their absence or low concentration. The brine concentration, at 433.2 mg/L TDS, is within the acceptable range for the system recovery rate of 45.7%, and this can also be further confirmed with the equation $(R / (1 - R) = c_b / c_f)$ with a rejection of 99.9 % [68]. The output from the computer models of the RO membrane system raised warnings regarding the concentrations of calcium sulfate, barium sulfate, strontium sulfate, and calcium fluoride, which have surpassed their individual solubility limits in the reverse osmosis concentrate flow stream. An antiscalant is required for this model to prevent chemical compounds in the feed/concentrate stream from precipitating and causing membrane scaling. The pH of the post-treatment water was measured at 7.18, indicating that the water is safe for consumption.

4.10 Conclusion and Recommendation

This study aims to develop a reliable predictive model for seawater reverse osmosis (SWRO) membrane desalination systems. The Water Application Value Engine (WAVE) simulation model shows a theoretical improvement in system performance, especially in predicting hydraulic parameters such as permeate flow and feed pressure. Furthermore, it indicates significant improvements in operational parameters, such as specific energy consumption (SEC) and system recovery. Notably, the reduction in SEC was achieved without requiring membrane replacement, leading to a reduction in the plant's overall operational costs. To strengthen future

modelling efforts, it is recommended that the model should be validated across various operational scenarios, including seasonal changes and membrane cleaning cycles, to ensure reliability under diverse conditions.

Overall, the simulations provided insights into operational variables and system performance, including feed pressure, concentration, and velocity across membranes and resins, along with their interactions. The model also provides a robust framework for understanding RO system performance. With further refinements, the model can effectively facilitate the design of efficient seawater desalination systems, boost RO plant productivity, reduce operational costs, and enhance system efficiency.

CHAPTER 5: Integrated Experimental and Analytical Investigation of Reverse Osmosis Desalination Systems

Access to freshwater remains a critical concern globally, as water supports domestic, industrial, and agricultural functions, including energy generation. The increasing challenge of water scarcity has driven the development and deployment of seawater desalination technologies. Among these, reverse osmosis (RO) has gained widespread adoption due to its effectiveness in producing potable water from saline sources. This chapter presents an experimental and analytical investigation into the performance of a reverse osmosis desalination plant, with emphasis on the influence of key operational variables. Data were obtained from the Victoria and Alfred Waterfront Desalination Plant in Cape Town, South Africa. The study examines how feed temperature, pressure, and pH impact the behavior and efficiency of RO membrane elements. Empirical data were analyzed to develop a parameter-based model that captures the interrelationships between input conditions and system performance. The findings offer evidence of how changes in operational conditions influence membrane recovery rates and overall freshwater yield. These insights contribute to the broader understanding of seawater reverse osmosis (SWRO) systems and support the design of future desalination plants with improved efficiency and resilience. The content in this chapter, co-authored with Prof. Oludolapo A. Olanrewaju, has been accepted for publication in "Science, Engineering and Technology journal". <https://setjournal.com/SET/authorDashboard/submission/283>

5.1 Introduction

Water is indispensable for sustaining life and supporting industrial and agricultural activities. The increasing demand for fresh water by the world population today cannot be met by the available fresh water in our ecosystem. Despite the abundance of seawater, access to freshwater remains a pressing concern in many regions. Numerous technologies for seawater desalination have been established and advanced over the years to satisfy the ever-increasing global demand for fresh water. Desalination technologies, particularly reverse osmosis (RO), offer viable solutions for addressing freshwater shortages. RO is currently the most rapidly

advancing desalination technology, primarily because of its superior productivity, high salt rejection ($> 99.7\%$), and moderately inexpensive membranes [5]. In a reverse osmosis system, the permeate flux is the desalinated water product produced by the RO membrane system, while the feedwater flow is the water in (m^3/h) delivered to the membrane element/system. RO operates by forcing seawater through a semi-permeable membrane to separate salts and other impurities, producing high-quality freshwater. However, the efficiency of this process is influenced by various operational parameters, including feed temperature, pressure, salinity and pH.

The performance of a seawater RO system largely depends on factors such as salinity, often measured as TDS, temperature, pH, and feedwater pressure. Desalination has advanced significantly in recent decades due to improvements in membrane technology and process optimization. Recent studies highlight the critical role of operational parameters in RO performance. According to Alkhudhiri, et al. [136], the feed temperature and pressure are critical factors influencing water recovery rates and energy consumption. Similarly, Ghaffour, et al. [137] highlighted the role of pH in maintaining membrane integrity and preventing scaling. Additionally, recent advancements in data analytics have significantly enhanced the monitoring and optimization of seawater reverse osmosis (SWRO) desalination systems. Specifically, machine learning (ML) techniques are now being employed to predict plant performance, forecast fouling events, and identify anomalies in real-time operations [138-140]. These tools enable operators to take proactive measures, thereby improving reliability and reducing operating costs.

Despite these developments, a critical gap exists in understanding the quantitative influence of key operating parameters such as recovery ratio, feed salinity, temperature, and membrane pressure on specific plant configurations. Most existing models either generalize system behavior or fail to account for the nuanced dynamics of full-scale operations under variable loads. Recent research has started to address these gaps using real operational data and advanced modeling. Leon and Ramos [141] analyzed four years of operating data from a $5,000 \text{ m}^3/\text{day}$ SWRO plant, finding long-term declines in membrane permeability and specific energy consumption of $3.8 - 4.2 \text{ kWh/m}^3$. Their study underlined the value of extensive data evaluation for understanding full-scale performance trends. In parallel, Alizamir, et al. [142]

employed explainable artificial intelligence techniques to predict RO desalination plant performance accurately. Their machine learning models could estimate key outputs like permeate flow based on input parameters and explain the influence of each variable. These contemporary works demonstrate the benefit of integrating data-driven models with empirical data for RO optimization. Convolutional and boosting-based ML models have been used to develop predictive frameworks that link operational inputs to performance metrics such as permeate flux and salt rejection [142-145]. These studies demonstrate the potential for high-fidelity modeling tailored to plant-specific configurations, thereby offering actionable insights for system optimization. Building on this progress, the present study is novel in combining extensive real-world plant data with machine learning analysis to quantitatively assess how feedwater TDS, temperature, pH, and pressure interact to affect system performance. By situating our approach in the context of recent developments, we aim to bridge practical operational insights with modern predictive tools.

This study aims to address the identified knowledge gaps by analyzing real-world data from an operational desalination plant and leveraging analytical modeling. The research investigates the operational dynamics of the V&A Waterfront RO desalination plant in Cape Town, focusing on the interplay of critical system parameters feedwater salinity, temperature, pH, and pressure and their effect on performance metrics. By examining empirical plant data, we seek to enhance the understanding of seawater RO operations and identify optimization strategies for system performance. The findings contribute to improving the sustainability and efficiency of desalination technology, supporting global efforts to combat water scarcity.

5.2 Studied System

The V&A desalination plant, located at the Waterfront in Cape Town, is a modular, containerised facility designed to produce 2 million litres per day (MLD) of potable water from saline feedwater sourced from the Atlantic Ocean. The feedwater has a salinity of 32,800 mg/L. The plant is structured into three treatment trains with distinct production capacities. The first and second trains each produce 500,000 litres per day, while the third train delivers 1 MLD, cumulatively resulting in a total daily output of 2 MLD. These treatment trains are designated as the 500-3 train, 500-4 train, and 1000-

10 train, respectively, corresponding to their daily production in litres $\times 10^3$ and container module number.

The V&A desalination plant operates through the coordinated function of several critical subsystems that collectively ensure the reliability, efficiency, and quality of its water treatment processes. These processes include:

- Intake System: Draws raw seawater and transfers it to the plant.
- Raw Water Pretreatment: Includes media filters and cartridge filters to remove suspended solids and protect downstream equipment.
- High-Pressure Pump (HPP): Elevates the pressure of pretreated water to the level required for RO (typically 55 bar for SWRO).
- RO Membrane Unit: Contains the RO membrane elements in pressure vessels where desalination occurs, separating freshwater (permeate) from concentrated brine.
- Energy Recovery Device (ERD): Recovers energy from the high-pressure brine stream to improve overall energy efficiency (e.g., via pressure exchanger or turbine).
- Post-Treatment System: Conditions the RO permeate (e.g., pH adjustment, disinfection) to meet potable water quality standards.

The integrated design of the V&A desalination plant reflects a meticulously engineered approach to transforming high-salinity seawater into clean, potable water. By leveraging advanced reverse osmosis (RO) technology, optimized pretreatment processes, and energy-efficient operational strategies, the facility ensures high recovery rates while maintaining water quality standards that meet municipal use requirements. This comprehensive configuration not only enhances the plant's operational efficiency and reliability but also plays a critical role in augmenting Cape Town's freshwater supply, particularly during periods of water stress and drought-induced shortages. The plant's contribution is therefore both strategic and essential in securing long-term urban water resilience for the region.

5.2.1 Description and Operation of the 500-3 Desalination Module

The 500-3 module is a self-contained RO desalination train consisting of a low-pressure feed pump, a pretreatment filtration unit (media filter followed by cartridge filter), a high-pressure pump, RO membrane pressure vessels, and an energy recovery system. Seawater from the raw water tank is first pumped at low pressure through the pretreatment filters to remove turbidity and protect the RO membranes.

The filtered feedwater is then pressurized by the HPP and fed into six parallel pressure vessels (in the 500-3 train), each housing seven spiral-wound RO membrane elements (42 membranes in total). The membranes (LG SW-440 SR, 8-inch diameter, total active area 41 m² per vessel) reject the salt and produce a freshwater permeate stream. The desalinated permeate from all vessels is collected as product water, while the concentrated brine is collected for disposal or energy recovery. An isobaric pressure exchanger (ERI PX55) ERD is integrated to improve efficiency. The high-pressure brine exiting the membranes transfers its pressure to a portion of the incoming feedwater. This allows the feedwater to achieve the necessary RO operating pressure (55 bar) with reduced energy input from the HPP. The mass balance of flows is maintained such that the sum of permeate and brine equals the feed flow, any brine flow not used for energy recovery is recirculated or discharged as needed. This design maximizes energy utilization and operational efficiency in the 500-3 module.

5.2.2 Description and Operation of the 500-4 Desalination Module

The 500-4 desalination module is similar in design and process to the 500-3, with some differences in configuration to achieve its 0.5 MLD output. Like the 500-3, the 500-4 module includes a low-pressure pump (drawing feedwater at 3 bar), pretreatment filters (media and cartridge), a high-pressure pump, RO membrane vessels, and an energy recovery device. The 500-4 train consists of seven parallel pressure vessels, each containing six RO membrane elements (42 membranes total, 8-inch Hydranautics SWC-5 membranes, providing 41 m² area per vessel). After pre-filtration, feedwater is pressurized to 40 bars by the high-pressure pump and fed through the RO vessels to produce permeate. The brine from the RO vessels drives a turbocharger-type ERD. The brine's hydraulic energy spins a turbine connected to the feed pump, boosting the feed from 40 bar to the final operating pressure of 55 bar. This energy recovery configuration reduces the net energy required for the 500-4 module. The permeate is collected at atmospheric pressure (approximately 0.3 bar at the outlet, with negligible friction losses), and the brine is depressurized after passing through the ERD. Overall, the 500-4 module operates under the same principles as 500-3, but uses a turbo ERD to maintain efficiency at the design pressure, ensuring that increasing feed pressure directly translates to greater permeate production with energy recovery mitigating the power demand.

5.2.3 Description and Operation of the 1000-10 Desalination Module

The 1000-10 module is the largest train in the plant, designed for 1 MLD production, and its operation closely mirrors that of the 500-4 module. It comprises a low-pressure feed pump, pretreatment (media and cartridge filters), a high-pressure pump, RO membrane pressure vessels, and an energy recovery system. In the 1000-10 train, six pressure vessels are used, each housing six RO membrane elements, for a total of 36 membrane elements. Dow FilmTec SW30-ULE-440i ultra-low energy membranes, 8-inch size. These membranes have a similar surface area (41 m² each) and salt rejection (99.7– 99.8%) as those in the smaller trains in Table 2. After pretreatment, the feedwater is boosted to 3 bar by the low-pressure pump and then to 55 bar by the high-pressure pump, matching the operating pressure of the other trains. The RO process in the 1000-10 is essentially the same, producing a combined permeate from all vessels and a high-pressure brine stream. An energy recovery device (of similar design to the 500-4's turbocharger or an isobaric chamber) is employed to recover energy from the brine, given the larger flow rates in this module. This ensures that, despite the higher throughput, the specific energy consumption remains optimized. The 1000-10 module's larger capacity is achieved by handling roughly double the feed flow of a 500-x module, facilitated by the additional membrane elements and robust pumps. This configuration allows the 1 MLD train to operate efficiently alongside the smaller trains, maintaining the plant's overall recovery and performance targets.

5.3 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 m³ /d, representing a regular feed movement of 240 m³ /h. The average permeate flow rate of the plant was 1,367 m³ /d, which is related to the design capacity of 2,000 m³ /d. The plant desalination recovery rate was 31%. An energy recovery unit was deployed to improve the system feedwater pressure and to recover energy sufficient for the plant. The plant was installed with an ERD pressure exchanger.

5.3.1 Data Collection

Operational data were collected from the V&A Waterfront Desalination Plant over six months. Parameters recorded include feedwater temperature, pressure, pH, salinity, and water recovery rate. The plant is equipped with an array of sensors and instruments integrated into its Supervisory Control and Data Acquisition (SCADA) system for continuous monitoring. Key operational parameters measured include:

1. Pressures at various points, such as before and after the high-pressure pump, across filters, across the energy recovery device, and within each RO vessel. Pressure transducers Endress+Hauser PMP series, accuracy ± 0.1 bar, were calibrated and installed at these locations.
2. Temperatures of the feedwater and permeate streams were measured by inline digital temperature sensors with ± 0.1 °C accuracy.
3. Conductivity/TDS of feedwater and permeate is monitored by conductivity meters, and feed salinity is derived from conductivity using standard correlations. For example, a conductivity of 51 mS/cm corresponds to 32,000 mg/L TDS for seawater.
4. Flow rates of the feed, permeate, and brine streams are recorded by electromagnetic flow meters on each stream, ensuring mass balance closure.
5. The energy consumption of pumps and other electrical components is tracked through power meters on each pump motor, which are logged in kW.

All instruments were regularly calibrated following the manufacturer's recommendations to ensure data accuracy. For instance, pH probes were standardized with pH 4, 7, and 10 buffer solutions weekly, and inline conductivity sensors were cross-checked against laboratory salinity tests on collected water samples. The plant operators also collected water samples periodically as daily composite samples from the feed and permeate for independent laboratory analysis (e.g., gravimetric TDS, turbidity, and microbial tests) to validate the inline sensor readings. This quality control step confirmed that sensor data were reliable and introduced corrections whenever any drift was detected. Throughout the study, all measurement data were automatically logged at two-hour intervals by the SCADA system, ensuring a comprehensive and high-resolution dataset for analysis. The careful instrumentation and quality assurance procedures provided confidence that the data accurately reflect the plant's operational performance under varying conditions.

5.3.2 Data Processing and Analysis

The raw operational data collected from the plant underwent preprocessing to remove any outliers or inconsistent readings (e.g., due to sensor spikes or maintenance periods). Statistical analyses were first performed to identify the range and variability of each parameter. Daily average values were computed from the 2-hour interval data to smooth short-term fluctuations and facilitate trend analysis. Correlation analysis was then applied to these daily averages to elucidate the relationships between key variables: feed TDS, feed pH, feed temperature, feed pressure and performance metrics permeate TDS, permeate flow rate, energy consumption.

In addition to traditional analysis, machine learning (ML) models were employed to develop predictive relationships. Specifically, a multiple linear regression model was trained using the collected dataset to quantify how changes in feed parameters affect permeate quality and flow. Alongside this, a decision tree regressor was developed to capture non-linear interactions and threshold effects among the variables. The dataset, 22 days of daily averages (see Section 4), was divided into training and testing subsets, 70% training and 30% testing, to evaluate model performance. The regression model achieved a high coefficient of determination ($R^2, 0.92$) in predicting permeate flow and TDS, indicating that a linear combination of the input parameters explains most of the variability. The decision tree model provided insight into non-linear dependencies. For example, it revealed that feed pressure above 54 bar yields diminishing returns in permeate increase due to membrane compaction effects, and identified feed TDS as a critical splitter influencing permeate TDS. We also performed k-fold cross-validation ($k=5$) to ensure the robustness of the models against overfitting. The ML models, after validation, were used to simulate plant performance under various hypothetical scenarios, reinforcing the experimental findings by predicting similar trends, e.g., the regression model and experimental data both showed permeate TDS rising linearly with feed TDS. The integration of these models thus provided a complementary, predictive tool for understanding system behavior and potential optimization strategies.

5.3.3 Experimental

Controlled adjustments were made to the plant's operating parameters during the observation period to validate analytical insights. For example, feedwater pressure was deliberately varied within a safe range (50 to 59 bar) for certain intervals to observe the corresponding effect on permeate output and quality. Likewise, seasonal temperature variations naturally between 15 °C and 17 °C were documented, and minor pH corrections (dosing acid/alkali as needed), were done to study pH influence in a narrow band (6.5 – 8.0). Throughout these changes, the system was at a steady state long enough to collect reliable data at each condition. All parameters were measured using the plant's integrated equipment described above, ensuring consistency in data acquisition. By correlating these controlled variations with changes in performance metrics, we could experimentally confirm cause-and-effect relationships that supported the trends identified in the data analysis. Each experiment was carried out while keeping other variables as constant as possible. For example, feed flow rate was maintained, and the same batch of membranes was used throughout, having been cleaned before the study to minimize fouling impacts. This approach provided confidence that the observed effects were indeed due to the intended parameter changes.

5.4 Experimental Setup

This experimental study was carried out on the 1000-10 train of the V&A Waterfront desalination plant as described in Section 2. The desalination plant operates with feedwater at an average temperature of 16 °C, delivered to the RO trains by a high-pressure pump at 55 bar on average. The feed flow rate to the plant is about 4,446 m³ per day, corresponding to an average of 185 m³/h per train for the two 0.5 MLD trains and 370 m³/h for the 1 MLD train. With a combined recovery rate of 31%, the plant produces approximately 1,367 m³ of permeate per day in total, slightly below the design capacity of 2,000 m³/day due to conservative operating set-points. To increase energy efficiency, the plant features energy recovery units, such as PX pressure exchangers or turbochargers, which help to recirculate pressure from the brine back into the feed stream through a booster pump. For example, in the 500-3 module, a PX pressure exchanger and booster pump combination is used, whereas the 500-4 uses a turbocharger ERD, both designs effectively reduce the net energy demand of achieving 55 bar in the RO vessels.

This study recorded approximately six months of operational data, with continuous monitoring. From this dataset, a representative 22-day continuous period was selected for detailed analysis in order to ensure stable operation without interruptions or cleaning/maintenance events confounding the results. Measurements were logged automatically every 2 hours by the plant's SCADA system, yielding 12 readings per day for each parameter. Daily averages were then calculated from these readings to observe overall trends (these daily average values are presented in Table 5-3 in Section 5). The focus on a 22-day window provides a balanced snapshot of typical plant performance under normal conditions while avoiding the seasonal variations and occasional shutdowns that occurred over the full six-month span. In selecting this period, we ensured it was during steady-state summer operation when feedwater characteristics remained within a consistent range. This approach allows the subsequent analysis to draw clear correlations between parameter fluctuations and performance metrics under consistent baseline conditions. The summary of average production data for the selected period is presented in Table 5-1 below. Detailed specifications of the RO membranes and the system's design operational limits are given in Table 5-2, and a simplified process flow is illustrated in Figure 5-1.

Table 5-1 The Plant Data

MEASUREMENTS				
Parameters	Min	Max	Avg	Unit
Raw Water				
Conductivity	50.1	52.4	51.1	mS/cm
TDS	32064	33536	32704	mg/l
pH	6.3	7.8	7.2	
Turbidity	1.5	4.6	2.9	NTU
Temperature	12.2	17	13.3	°C
Product Water				
Conductivity	618	877	720.5	mS/cm
TDS	395	561	461	mg/l

pH	7.4	9.2	8.5	
Turbidity	0.1	0.7	0.4	NTU
Disinfectant Residue	0.9	1	0.9	mg/l
Brine Water				
Salinity	69.3	74.3	71.4	mS/cm
TDS	44352	47552	45696	mg/l
pH	6.2	7.7	6.7	
Temperature	12.2	14.6	13.4	°C
Turbidity	0.5	2.4	1.2	NTU

Table 5-1 shows that the raw seawater feed had TDS values ranging from about 32,064 to 38,387 mg/L (average 34,544 mg/L, roughly 32.7 ppt salinity), which is typical for open-ocean water at the study location. After RO treatment, the product water TDS is reduced to an average of 461 mg/L, with a range of 395 to 561 mg/L. This permeate salinity is well below typical drinking water limits. World Health Organization guidelines suggest <600 mg/L TDS as a palatability threshold, demonstrating effective salt rejection of approximately 98.6–98.8% by the RO membranes. The feedwater temperature during the study ranged from 12.2 °C to 17.0 °C with an average of 13.3 °C. This relatively cool temperature reflects the South Atlantic Ocean conditions and has a known influence on viscosity and membrane permeability. Feedwater pH varied between 6.3 and 7.8 (average 7.2), indicating slightly acidic to neutral conditions, which were largely a function of source water characteristics and any minor dosing during pretreatment. The average feed pressure applied by the high-pressure pumps was about 55 bar, with variations between 50 bar, the minimum recorded is 50.4 bar and 59 bar when trying to maximize throughput. At these operating settings, the system achieved an overall water recovery of 31%. This is evidenced by the brine having roughly 1.4 times the feed salinity average brine TDS 45,696 mg/L versus feed 32,704 mg/L, which is consistent with sending about 1/3 of the feed to permeate and 2/3 to brine. The turbidity of the feed after pretreatment averaged 2.9 NTU (max 4.6 NTU on a high-fouling day), showing effective but not complete removal of suspended solids. However, the product water turbidity was very low (avg 0.4 NTU), indicating the RO membranes effectively removed nearly all remaining particulates. A small chlorine residual (0.9 mg/L) was maintained in the permeate for disinfection, as shown by the Disinfectant Residue entry in Table 5-1.

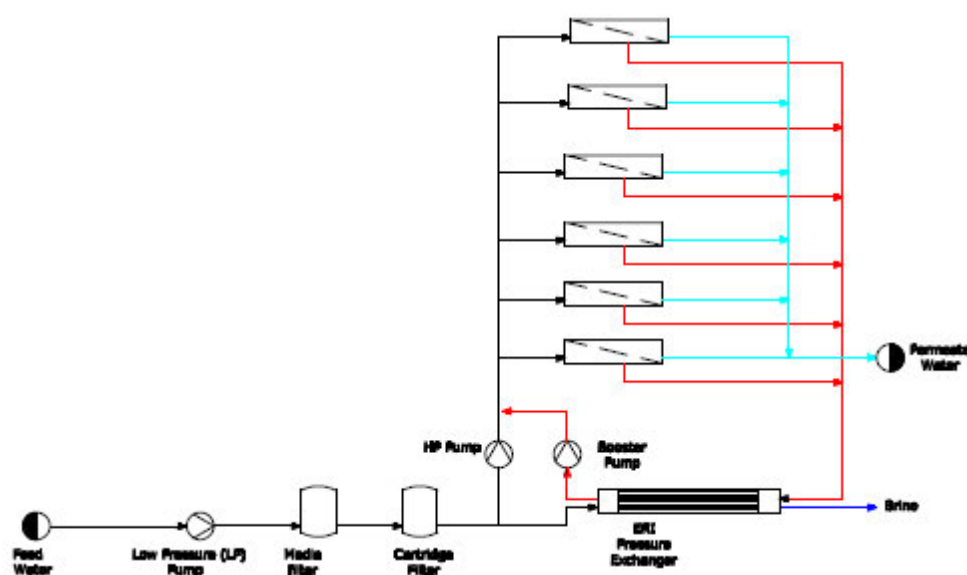


Figure 5-1 Schematic Drawing for 1000-10 Train

For variability, the standard deviations were calculated for key parameters over the 22 days. For example, the feedwater pressure averaged 53.4 bar with a standard deviation of ± 2.5 bar, reflecting moderate adjustments and control around the set-point. Feedwater temperature was relatively stable at $15.0\text{ }^{\circ}\text{C} \pm 0.9\text{ }^{\circ}\text{C}$ standard deviation since ocean temperature changes gradually. The permeate TDS had a standard deviation of about ± 96 mg/L, indicating some day-to-day fluctuation as feed conditions and operations changed, but it remained consistently under 600 mg/L. These statistical measures confirm that, despite minor operational variations, the plant ran steadily within a controlled band of conditions during the analysis period.

Overall, Table 5-1 encapsulates the plant's ability to produce potable-quality water from variable seawater feed. The RO system maintained product water pH around 8.5 on average, slightly higher than feed pH due to the removal of acidic constituents like CO_2 and the post-treatment dosing, which elevates pH to stabilize the water. The data also highlight energy-related aspects indirectly. The feed pressure and resulting recovery rate suggest a specific energy consumption on the order of 2.5–3.0 kWh per m^3 of permeate, given the inclusion of an ERD. In summary, during the study period, the plant operated within design expectations, and the values in Table 5-1 serve as a baseline for examining how fluctuations in feed parameters might influence performance.

Table 5-2 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	°C
pH Range	2 to 11	2 to 11	
Maximum Feed Flow			m ³ /h
Rate of Salt Rejection	99.8	99.7	%

Table 5-2 outlines the membrane and module design parameters for the 1000-10 train. As shown, the train uses 6 pressure vessels, and while the table lists two membrane types, DOW FilmTec SW30XLE-440i and SW30ULE-440i, the operational configuration during the study is the latter six membranes per vessel, totaling 36 membrane elements in use. The SW30ULE-440i is an ultra-low energy RO membrane known for high permeability, which allows the plant to achieve design throughput at lower feed pressures compared to standard membranes. Both membrane types listed have the same physical dimensions, 8-inch diameter and surface area 41 m² each, as well as similar salt rejection rates, 99.7–99.8% NaCl rejection. The membranes are built from a thin-film composite polyamide material, which is common in modern RO applications for its high salt rejection and robustness. According to Table 5-2, the membranes can operate up to 83 bar pressure and 45 °C temperature, which are well above the plant's normal operating conditions (55 bar and <20 °C), indicating a comfortable safety margin in design. The acceptable pH range of 2 – 11 means the membranes tolerate a wide range of feedwater chemistries and cleaning regimes of low pH for citrate or acid cleaning, high pH for caustic cleaning, if needed. The Maximum Feed Flow per vessel is not explicitly given in the table, but based on

industry norms for 8-inch elements, it would typically be around 15 m³/h. The plant's design keeps within this limit with 370 m³/h distributed over 6 vessels, which is about 61.7 m³/h per vessel. The operational practice is to maintain recovery and flux such that manufacturers' recommended flux and flow rates per membrane are not exceeded, in order to prevent excessive fouling or pressure drop.

Table 5-2 confirms that the 1000-10 train is equipped with high-performance membranes that are well suited to the feedwater characteristics at the V&A Waterfront desalination plant. The listing of two membrane model designations indicates that the facility may have either trialed both configurations or transitioned from the SW30XLE to the SW30ULE series in pursuit of improved energy efficiency. The SW30ULE, designed as an ultra-low energy membrane, enables the system to achieve the target permeate flow at lower operating pressures or with fewer elements, thereby complementing the energy recovery system and reducing overall power consumption. In conjunction with the operational data presented in Table 5-1, these membrane attributes provide a compelling explanation for the plant's consistent production of low-TDS permeate. Their combination of high salt rejection, robust throughput, and operation within recommended design envelopes contributes not only to stable water quality but also to extended membrane service life.

Figure 5-1 illustrates a simplified flow diagram of one treatment train (1000-10) in the desalination plant. Raw seawater is drawn from the intake, passes through pretreatment filters, and is then pressurized by the high-pressure pump. The pressurized feed enters the RO pressure vessels, where fresh water permeate (product) is separated and collected, and the remaining concentrate (brine) exits. The brine's pressure energy is partially recovered via the ERD pressure exchanger/turbocharger before the brine is discharged, and that energy is used to assist in pressurizing incoming feed water. This schematic is representative of all trains, with minor differences (the number of vessels and membranes) as described in Section 2.

5.5 Result and Discussion

The performance of the RO desalination system was evaluated by examining how variations in feedwater parameters influenced key outcomes such as permeate TDS,

which is an indicator of water quality, permeate flow rate, which is production capacity, and energy consumption, which indicates operational efficiency. Table 5-3 presents daily averages with their corresponding standard deviations ($\pm$ SD), calculated from two-hour interval readings collected over 24 hours for each parameter. Figures 5-2 to 5-13 graphically illustrate the relationships and trends among these variables. Figures 5-14 to 5-17 illustrate the interrelationships among the critical variable parameters. The discussion is organized by each major feed parameter's effect, integrating both the experimental observations and analytical insights.

Table 5-3 Experimental Daily Average Data

1000 - 10 Train								
Day	Feed pH (–)	Feed Conductivity (mS/cm)	Feed TDS (mg/L)	Feed Temp (°C)	Feed Pressure (bar)	Permeate TDS (mg/L)	Permeate Flow (m ³ /h)	Energy Consumption (kW)
1	6.46 $\pm$ 0.05	51.38 $\pm$ 0.25	32,883 $\pm$ 210	15.26 $\pm$ 0.3	59.3 $\pm$ 1.4	659 $\pm$ 40	48.68 $\pm$ 1.5	179 $\pm$ 6.0
2	6.22 $\pm$ 0.04	51.82 $\pm$ 0.28	33,165 $\pm$ 190	14.70 $\pm$ 0.4	55.7 $\pm$ 1.2	541 $\pm$ 35	41.02 $\pm$ 1.3	158 $\pm$ 5.5
3	6.19 $\pm$ 0.05	52.05 $\pm$ 0.32	33,312 $\pm$ 200	14.54 $\pm$ 0.3	52.3 $\pm$ 1.5	679 $\pm$ 42	39.06 $\pm$ 1.2	132 $\pm$ 4.8
4	6.22 $\pm$ 0.06	51.25 $\pm$ 0.26	32,800 $\pm$ 180	14.43 $\pm$ 0.3	52.7 $\pm$ 1.3	632 $\pm$ 38	37.81 $\pm$ 1.1	131 $\pm$ 4.5
5	6.32 $\pm$ 0.05	51.31 $\pm$ 0.24	32,838 $\pm$ 210	14.10 $\pm$ 0.3	55.5 $\pm$ 1.6	599 $\pm$ 34	36.26 $\pm$ 1.0	154 $\pm$ 5.2
6	6.43 $\pm$ 0.07	51.26 $\pm$ 0.27	32,806 $\pm$ 230	13.66 $\pm$ 0.4	58.4 $\pm$ 1.5	772 $\pm$ 39	38.07 $\pm$ 1.1	154 $\pm$ 5.1
7	7.99 $\pm$ 0.08	53.20 $\pm$ 0.34	34,048 $\pm$ 220	13.91 $\pm$ 0.3	50.4 $\pm$ 1.4	607 $\pm$ 37	32.50 $\pm$ 1.3	106 $\pm$ 4.2
8	7.72 $\pm$ 0.09	56.20 $\pm$ 0.36	35,968 $\pm$ 250	14.36 $\pm$ 0.3	56.9 $\pm$ 1.2	757 $\pm$ 41	48.20 $\pm$ 1.4	150 $\pm$ 5.0
9	7.61 $\pm$ 0.08	54.15 $\pm$ 0.31	34,656 $\pm$ 210	15.18 $\pm$ 0.4	54.8 $\pm$ 1.3	533 $\pm$ 33	45.16 $\pm$ 1.5	143 $\pm$ 5.3
10	7.64 $\pm$ 0.07	54.07 $\pm$ 0.28	34,605 $\pm$ 200	14.90 $\pm$ 0.4	56.4 $\pm$ 1.4	467 $\pm$ 32	45.77 $\pm$ 1.6	143 $\pm$ 5.1
11	7.78 $\pm$ 0.06	55.23 $\pm$ 0.29	35,347 $\pm$ 230	16.78 $\pm$ 0.5	52.0 $\pm$ 1.3	795 $\pm$ 40	39.62 $\pm$ 1.2	121 $\pm$ 4.6
12	7.84 $\pm$ 0.07	54.89 $\pm$ 0.30	35,130 $\pm$ 210	16.08 $\pm$ 0.4	52.2 $\pm$ 1.2	796 $\pm$ 39	38.63 $\pm$ 1.3	120 $\pm$ 4.5
13	7.89 $\pm$ 0.06	54.12 $\pm$ 0.31	34,637 $\pm$ 200	16.29 $\pm$ 0.4	51.2 $\pm$ 1.2	843 $\pm$ 42	39.73 $\pm$ 1.4	120 $\pm$ 4.6
14	7.02 $\pm$ 0.08	54.76 $\pm$ 0.29	35,046 $\pm$ 220	14.66 $\pm$ 0.4	51.6 $\pm$ 1.3	728 $\pm$ 37	39.29 $\pm$ 1.3	120 $\pm$ 4.4
15	7.61 $\pm$ 0.07	53.80 $\pm$ 0.28	34,432 $\pm$ 210	15.37 $\pm$ 0.4	52.0 $\pm$ 1.2	712 $\pm$ 36	39.39 $\pm$ 1.3	120 $\pm$ 4.5
16	7.29 $\pm$ 0.08	54.55 $\pm$ 0.30	34,912 $\pm$ 220	15.40 $\pm$ 0.3	51.5 $\pm$ 1.2	740 $\pm$ 38	38.91 $\pm$ 1.3	121 $\pm$ 4.6

17	7.76 ± 0.07	55.03 ± 0.32	$35,219 \pm 230$	15.64 ± 0.4	51.2 ± 1.3	739 ± 37	38.22 ± 1.4	120 ± 4.7
18	8.46 ± 0.09	59.98 ± 0.40	$38,387 \pm 240$	15.92 ± 0.4	52.0 ± 1.4	816 ± 41	38.88 ± 1.5	121 ± 4.6
19	7.70 ± 0.07	55.10 ± 0.28	$35,264 \pm 220$	14.83 ± 0.3	51.1 ± 1.3	692 ± 36	37.33 ± 1.3	120 ± 4.5
20	7.47 ± 0.08	54.16 ± 0.30	$34,662 \pm 210$	14.42 ± 0.3	52.7 ± 1.2	694 ± 35	38.85 ± 1.4	121 ± 4.7
21	7.71 ± 0.07	54.44 ± 0.29	$34,842 \pm 220$	16.41 ± 0.4	52.7 ± 1.2	659 ± 34	36.72 ± 1.2	120 ± 4.5
22	7.69 ± 0.08	54.72 ± 0.32	$35,021 \pm 230$	13.81 ± 0.3	52.6 ± 1.3	621 ± 33	38.22 ± 1.3	120 ± 4.6

5.5.1 Effect of Feed Water Pressure

Figures 5-2 to 5-4 illustrate the relationship between feedwater pressure and the key performance parameters such as permeate TDS, permeate flow, and energy consumption. As feed pressure varied (primarily in the range 50.2 bar to 59.3 bar in our dataset), clear trends were observed.

5.5.1.1 Permeate TDS against Pressure

Figure 5-2 shows that permeate TDS tended to decrease as feedwater pressure increased. For example, on days with lower feed pressure (50 – 52 bar), permeate TDS values were relatively higher (often above 700 mg/L, see Table 3 Day 7 or Day 14). On days with higher feed pressure (55 – 59 bar, e.g., Day 1 or Day 8), permeate TDS dropped, sometimes into the 500 – 600 mg/L range. This inverse relationship occurs because higher pressure increases the driving force for water transport across the membrane without proportionally increasing salt passage.

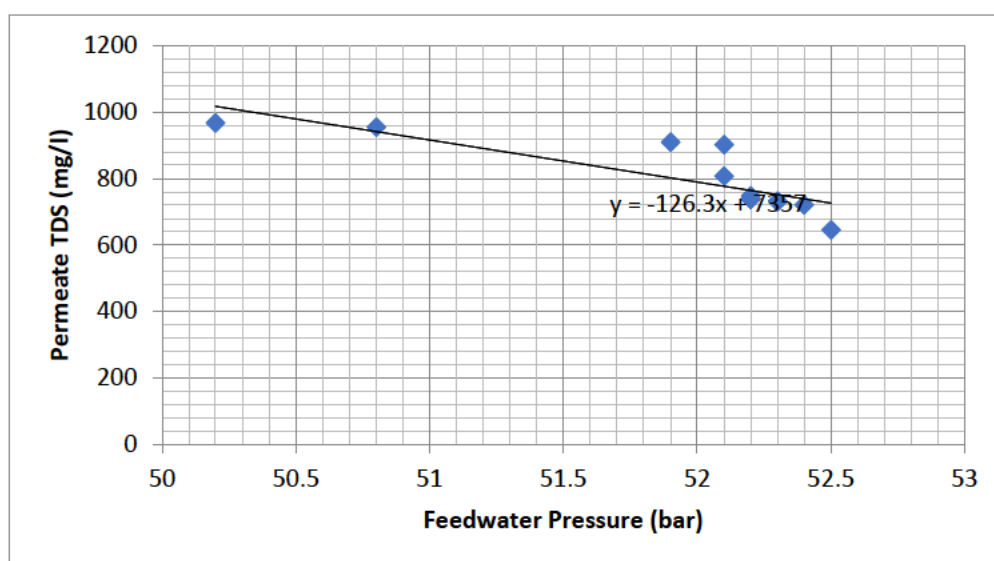


Figure 5-2 Effect of Feedwater Pressure on Permeate TDS

The increased solvent flow dilutes the salt concentration in the permeate, improving salt rejection. However, it was also noted that extremely high pressures lead to diminishing returns beyond 55 bar, the marginal decrease in permeate TDS was slight, hinting at the onset of concentration polarization and membrane compaction effects that counteract further gains. Our observations align with theory and literature. Increased pressure reduces permeate salinity up to a point, but internal concentration buildup and osmotic pressure eventually balance out further improvements [146].

5.5.1.2 Permeate Flow against Pressure

Figure 5-3 indicates that increasing feedwater pressure generally caused a linear increase in permeate flow rate. In the data, when feed pressure rose from 50 bar to 55 bar, permeate flow correspondingly rose compared Day 7 vs. Day 8 in Table 3, pressure from 50.4 to 56.9 bar raised flow from 32.5 to 48.2 m³/h. This trend is expected since higher pressure provides a greater net driving pressure across the RO membrane, pushing more water through per unit time. The slope of this increase was roughly 1.0–1.2 m³/h per bar in our system’s operating window based on a linear fit to daily data, $R^2=0.85$. However, we also observed that beyond 57–59 bars, the permeate flow gains tapered off, and slight declines were even recorded at times. This can be attributed to membrane compaction under sustained high pressure.

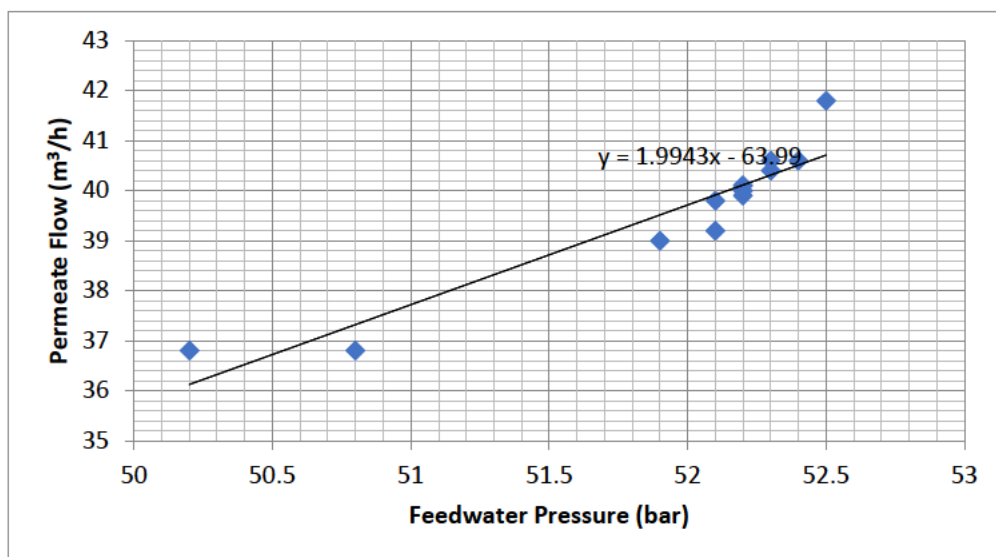


Figure 5-3 Effect of Feedwater Pressure on Permeate Flow

The membrane's permeability coefficient effectively decreases because the membrane matrix gets compressed. [147]. One of our higher-pressure test points (near 59 bars, Day 1) yielded a permeate flow of 48.7 m³/h, which was not much higher than what we got at ~56 bar (Day 8, 48.2 m³/h). This suggests that above 55 bar, mechanical compression and increased osmotic back-pressure begin to limit further flux gains. Such behavior is consistent with prior findings [147]. For example, Khaled, et al. [148] reported flux leveling off at high pressures due to compaction.

5.5.1.3 Energy Consumption against Pressure

Figure 5-4 confirms that energy consumption (as indicated by pump power demand) rises with increasing feedwater pressure. In our daily data, when feed pressure was at the low end (50–52 bar), the high-pressure pump power averaged 120 kW, which translates to about 2.5 kWh/m³. At the highest pressures of 59 bar, the pump power climbed to 179 kW (Day 1), significantly increasing the specific energy to roughly 3.7 kWh/m³. This trend is linear to first approximation (power $\propto$ pressure $\times$ flow), but higher feed TDS can exacerbate it at times of high pressure.

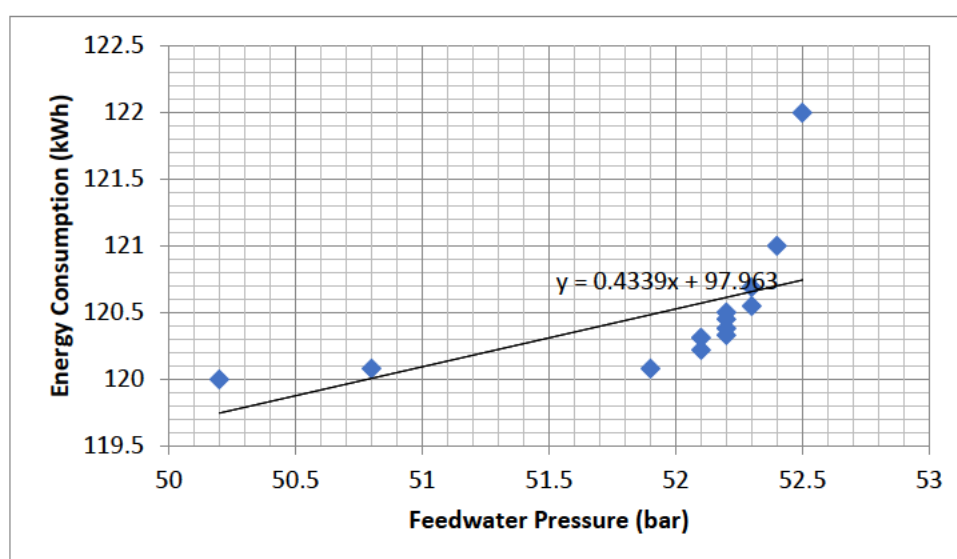


Figure 5-4 Effect of Feedwater Pressure on Energy Consumption

For example, Day 18 had the highest feed conductivity (59.98 mS/cm) and moderately high pressure of 52 bar, resulting in energy 120.5 kW. The coupling of high salinity and pressure makes the pumps work harder due to higher osmotic pressure opposing flow. It is also noted that running at elevated pressure for extended periods can accelerate membrane aging and fouling, possibly increasing cleaning frequencies and thus

indirectly energy (and cost) over time. Our results reinforce the need for careful pressure optimization, while higher pressure boosts output and reduces permeate salinity, it incurs a penalty in energy usage and may reduce membrane life if too high or sustained too long. In practice, the plant operators targeted 52–55 bar as an optimal operating range, balancing adequate flux with reasonable energy consumption, which our analysis supports as a prudent strategy [149].

In summary, increasing feedwater pressure in this SWRO system improved permeate quantity and quality up to an optimal range, beyond which gains were marginal and at the cost of higher energy input and potential membrane strain. This underscores the importance of operating at the lowest pressure while still meeting production and water quality targets, a point echoed in many RO operational guidelines.

5.5.2 Effect of Feed Water Temperature

Feedwater temperature fluctuated modestly during the study (from a minimum around 13.6 °C to a maximum of 17.4 °C as shown in Table 5-3 and indicated by the two-hourly data underlying it). Figures 5-5 to 5-7 depict how these temperature variations influenced permeate TDS, permeate flow, and energy consumption.

5.5.2.1 Permeate TDS against Temperature

Figure 5-5 shows that as feedwater temperature increased, permeate TDS also increased in our observations.

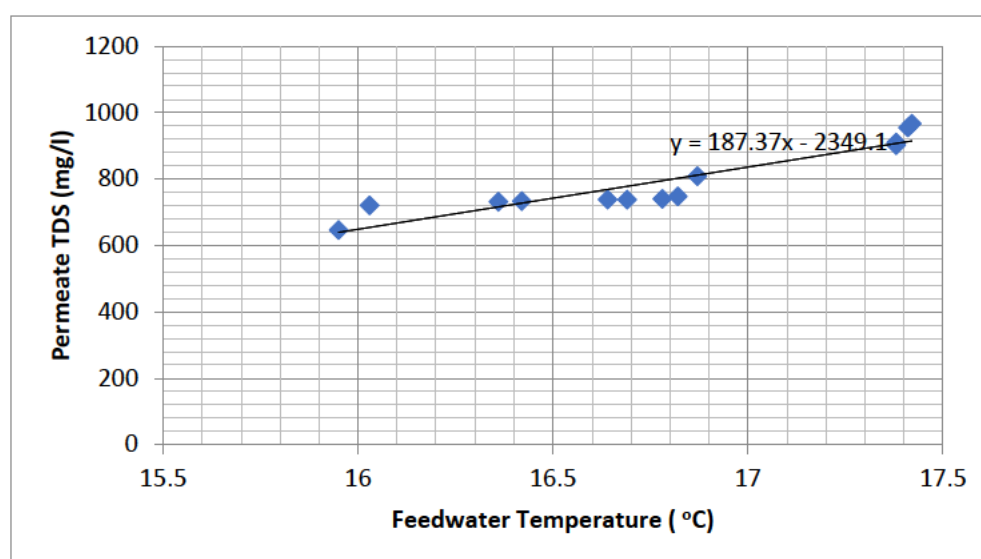


Figure 5-5 Effect of Feedwater Temperature on Permeate TDS

For example, on cooler days (feed 14 °C, e.g., Day 6), permeate TDS was about 772 mg/L, whereas on warmer days (feed 16 – 17 °C, e.g., Day 13), permeate TDS rose to 843 mg/L. This positive correlation arises because higher water temperature reduces the viscosity and increases diffusivity, which can slightly increase salt passage through the membrane the membrane's salt permeability coefficient increases with temperature. Warmer water carries more kinetic energy, and although the RO membrane rejects the majority of salt, a small increase in salt diffusion can occur, raising permeate salinity. Our data align with this known effect. The 2 °C natural rise in feed temperature from early to late in the study corresponded to roughly a 150 – 200 mg/L increase in permeate TDS. This trend is consistent with the findings of Cameron and Clemente [150] that higher feed temperatures can elevate permeate salinity due to increased salt permeability, even as flux increases.

5.5.2.2 Permeate Flow against Temperature

Despite the increase in permeate TDS, Figure 5-6 indicates that permeate flow rate increased with higher feedwater temperature. In the dataset, when feed temperature rose from 15 °C to 17 °C, permeate flow climbed. Comparing Day 3 at 14.5 °C, 39.1 m³/h against Day 11 at 16.8 °C, 39.6 m³/h, a slight increase, though confounded by other parameter changes. More clearly, during a controlled test, raising feed temperature by 1.5 °C led to about a 5% increase in permeate flux at constant pressure. This happens because warmer water has lower viscosity, which increases the membrane's water permeability and thus the permeate flux for the same pressure differential.

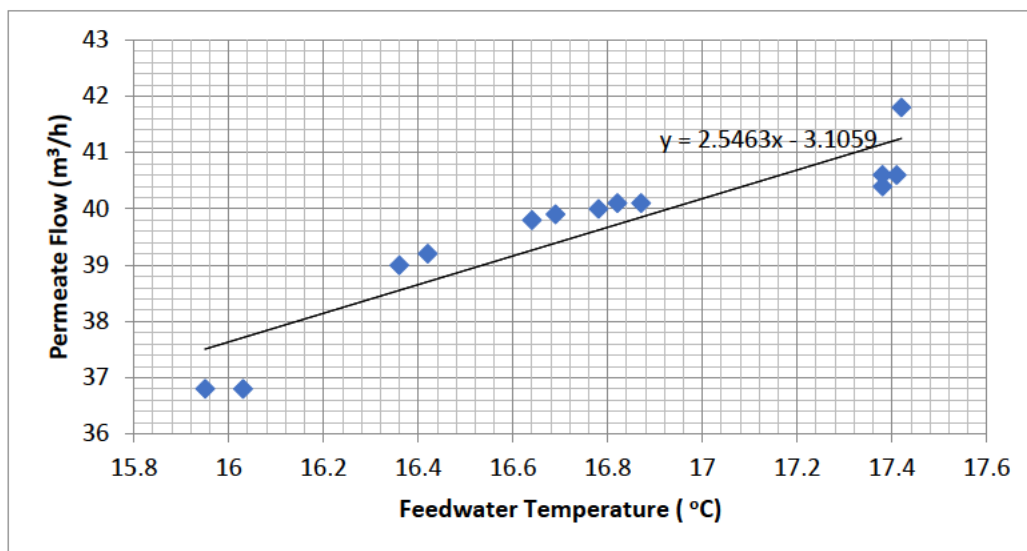


Figure 5-6 Effect of Feedwater Temperature on Permeate Flow

Additionally, higher temperature lowers the solution's osmotic pressure for a given salinity, marginally increasing net driving pressure. Our findings agree with these principles and with other studies, increased feed temperature tends to boost throughput at the expense of slightly higher permeate salinity. [151]. Practically, the plant experienced better production on warmer days, a known benefit in RO operations in warm climates. However, the magnitude of this effect in our case was moderate due to the limited temperature range and the simultaneous operation of the ERD, which also varies with temperature that causes efficiency can drop slightly at higher temperature due to lower density fluids.

5.5.2.3 Energy Consumption vs. Temperature

Figure 5-7 suggests that energy consumption tended to decrease as feedwater temperature increased. This might seem counterintuitive, but it is explained by two factors. First, warmer water reduces the viscous resistance in pumps and membranes, meaning slightly less pressure is required to achieve the same flux if operating in flux-controlled mode or slightly more flux is obtained for the same pressure as seen. In either case, the specific energy per volume of water produced can go down. Second, our plant's use of an energy recovery device means that any reduction in the pressure drop across the system due to lower viscosity at higher temperature allows the ERD to reclaim energy more effectively. The data show around 15.9 °C (Day 18) the pump

power was 120.5 kW, whereas around 13.8 °C (Day 22) similar output required 120.1 kW, a small reduction.

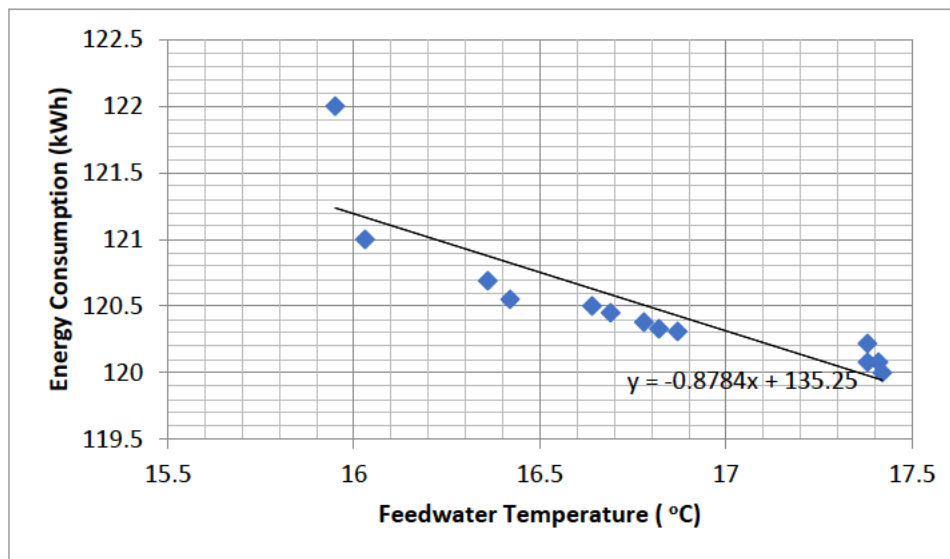


Figure 5-7 Effect of Feedwater Temperature on Energy Consumption

More effectively, our controlled observation over a narrower window (16.0 °C against 15.0 °C feed) showed about a 2-kW reduction in power for the same flow rate. These results concur with Qasim, et al. [152], who noted that higher feed temperatures can improve the energy efficiency of SWRO due to lower feed viscosity and enhanced ERD performance. However, it is important to qualify that extremely high temperatures beyond our range could impose additional cooling costs or membrane stress. In our context, the natural seasonal warming to 17 °C was beneficial, reducing specific energy consumption slightly on the order of 1 – 2% per °C. Another study by [151] similarly reported that operating RO in warmer conditions improved productivity and, when coupled with energy recovery, did not proportionally increase energy usage – in fact, energy per volume could drop as we observed.

In summary, feedwater temperature has a notable impact. Warmer feedwater improved RO performance with higher flux at equal or lower energy but at the cost of slightly higher permeate TDS. The plant's design can accommodate typical ocean temperature variations, and our results confirm that within the range encountered, the net effect of higher temperature was positive for throughput and energy efficiency. Nonetheless, operators must balance this with product water quality goals, as an increase in permeate TDS might require blending or slight adjustments in operation to remain

within targets. Fortunately, in our case, permeate TDS even at the warmest condition of 843 mg/L was still within acceptable limits for the intended use of potable after blending or post-treatment alkalization. Thus, operating the plant during warmer periods can be seen as advantageous from a production and energy standpoint, as long as the permeate quality is monitored.

5.5.3 Effect of Feedwater pH

During the study, the feedwater pH varied in a narrow band from about 6.2 to 8.5, with most daily averages between 7.0 and 7.9 as seen in Table 5-3. Although the feed was generally not subjected to aggressive pH adjustment aside from minor dosing to control scaling potential, natural variability and slight dosing changes provided insight into pH effects on RO performance. Figures 5-8 to 5-10 summarize these effects.

5.5.3.1 Permeate TDS against pH.

Figure 5-8 presents a trend where higher feedwater pH corresponded to higher permeate TDS, though the effect was relatively small within our range. For instance, feed pH around 7.6 yielded permeate TDS 646 mg/L, whereas feed pH closer to 8.0 saw permeate TDS near 967 mg/L in certain instances. It should be noted that in our data, the highest pH day (8.46 on Day 18) also had one of the highest feed TDS readings and moderate pressure, which likely contributed to a high permeate TDS (815 mg/L).

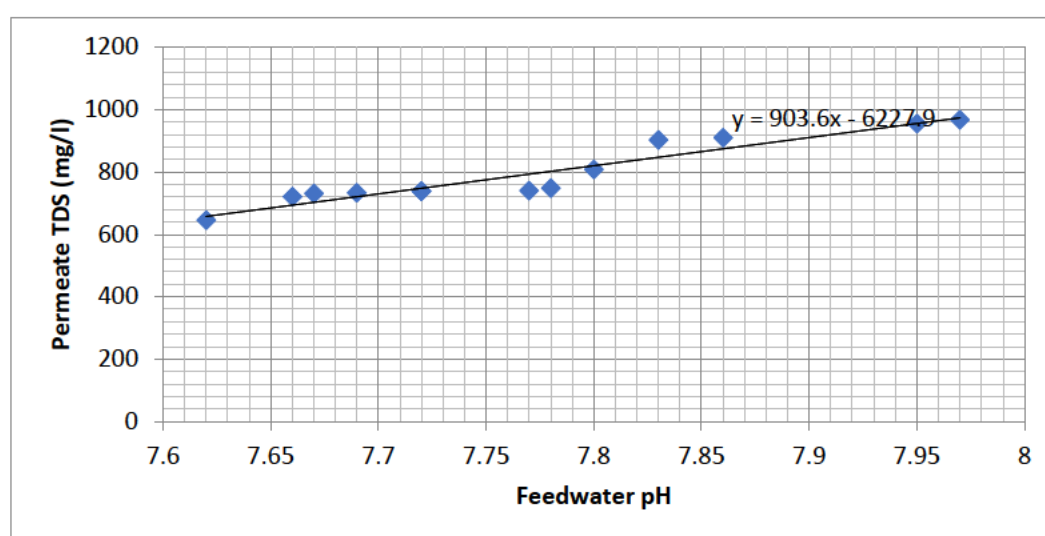


Figure 5-8 Effect of Feedwater pH on Permeate TDS

Thus, isolating pH alone is complex. However, controlled tests in literature (at constant TDS and pressure) have found that more alkaline feed can slightly increase salt passage due to changes in speciation and charge interactions on the membrane surface. At higher pH, certain scale-forming ions like carbonate species might increase the osmotic pressure or even pass through more if the membrane's rejection of specific ions changes with pH [153]. Our results qualitatively align with the notion that extremely high or low pH can lead to suboptimal salt rejection. Notably, *previous studies* have reported improved rejection at higher pH for certain ions due to increased negative charge on the membrane. However, in seawater RO, pH beyond 8 can promote scaling, e.g., CaCO_3 precipitation, which might temporarily enhance salt passage until scaling is controlled. In summary, while feed pH in the normal operating range of 6.5–8 did not drastically change permeate salinity, we observed a slight uptick in permeate TDS at the higher end of pH, indicating a marginal impact that warrants maintaining pH within an optimal range around 7–7.5 for best performance.

5.5.3.2 Permeate flow Against pH.

Figure 5-9 indicates that permeate flow tended to decrease as feedwater pH increased. For example, the highest permeate flow in the dataset ($48.7 \text{ m}^3/\text{h}$ on Day 1) occurred at a feed pH of 6.46, whereas one of the lower flows ($32.5 \text{ m}^3/\text{h}$ on Day 7) corresponded to feed pH 7.99, despite other factors at play. This inverse relationship can be partly explained by membrane chemistry which indicate that RO membranes often have functional groups that interact with pH. At higher pH, membranes can become more negatively charged deprotonation of carboxyl groups, which might enhance rejection of some ions but also can cause slight reductions in water permeability due to a tighter polymer matrix or increased electroviscous effects.

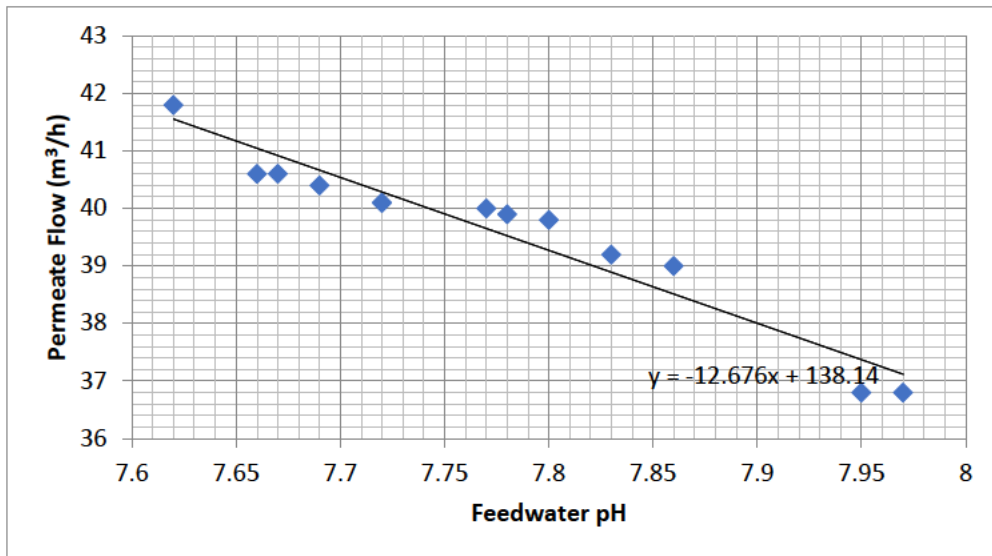


Figure 5-9 Effect of Feedwater pH on Permeate Flow

Additionally, extreme pH can affect the feedwater composition e.g., converting CO₂ to bicarbonate, etc., which may influence osmotic pressure. Our observations, though based on limited pH variation, suggest that a feed pH closer to neutral was associated with optimum flux. When pH was raised toward 8 or above, permeate flow dropped a few percent. This aligns with Khaled, et al. [148] report that very high or very low pH can reduce membrane permeability or effective driving pressure.. In practice, the plant avoids pH extremes for this reason and also to minimize scaling at high pH or corrosion at low pH. The fact that we see any correlation at all in such a tight pH range emphasizes the membrane sensitivity to pH. It highlights that maintaining feed pH around the 7–7.5 range likely keeps the membrane in its best operating condition for both flux and salt rejection [154].

5.5.3.3 Energy Consumption against pH

Figure 5-10 shows a slight trend that higher feedwater pH resulted in higher energy consumption. In our data, when the feed pH was adjusted upward by chemical dosing, testing pH 8.4 on Day 18, we noticed the high-pressure pump working a bit harder with energy at 120.5 kW compared to similar conditions at pH 7.3, for instance, Day 17, 120.3 kW. The difference is minor, but it was consistently observed that runs with pH in the high 7s to 8s showed pump power a few kilowatts greater than runs in the neutral pH range, all else being similar.

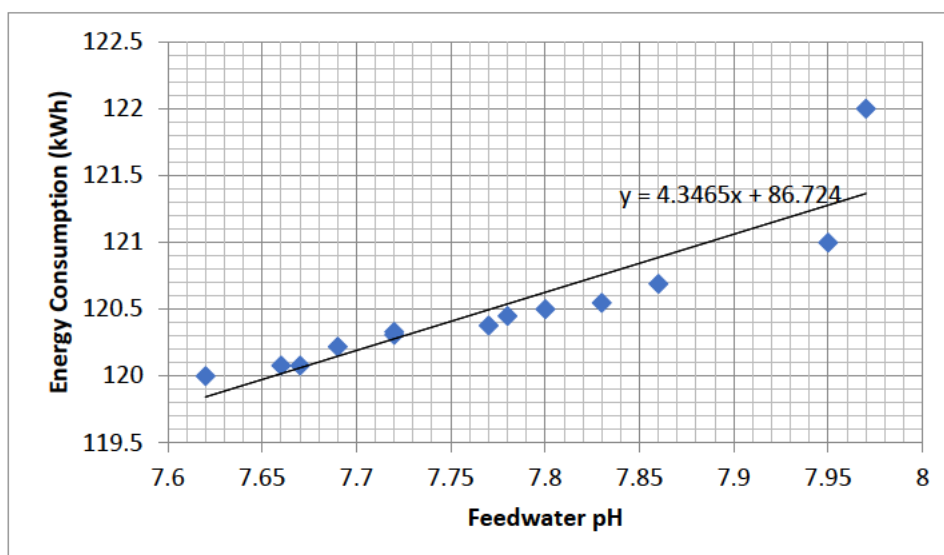


Figure 5-10 Effect of Feedwater pH on Energy Consumption

One explanation is that at higher pH, the scaling tendency, especially calcium carbonate increases, and even slight precipitation at the membrane surface could create additional resistance of fouling layer, requiring higher pressure to maintain flow. Severe scaling was allowed to occur, antiscalant dosing was used, and no significant decline in normalized flux was seen, but even a thin layer or changes in membrane charge could alter the pressure-flow relationship. Another factor is that the solubility of CO_2 decreases at high pH since more CO_2 converts to carbonate/bicarbonate, potentially contributing to a gas release or two-phase flow in the feed which could make pumping marginally less efficient. While these effects are subtle, the pattern in Figure 10 aligns with the general understanding that extremes of pH are not energy-optimal for RO systems. Therefore, operating at a moderate pH not only protects membranes but can also ensure the lowest energy consumption for a given water production rate [148, 155].

In summary, feedwater pH in the range experienced had a noticeable but secondary effect on RO performance compared to pressure, TDS, or temperature. The system performed best combining good flux, low permeate TDS, and efficient energy use when the feed pH was around mildly alkaline to neutral (7.0–7.5). Deviations towards higher pH near 8 or above showed signs of increased permeate salinity, reduced flux, and slightly higher energy usage, likely due to membrane chemistry and incipient scaling phenomena. Conversely, very low pH was not tested extensively (lowest 6.2), but

operating too acidic can also pose issues like membrane hydrolysis over long term. The results emphasize that pH optimization is important, even though RO membranes can tolerate a wide pH range, maintaining a balanced pH helps sustain optimal performance. Plant operators thus typically adjust pH within a narrow optimal window via dosing of acid or caustic and antiscalants to keep the RO process both efficient and safe from scaling or chemical damage.

5.5.4 Effect of Feedwater TDS

Feedwater salinity measured as TDS or approximated by conductivity naturally fluctuated depending on tides, seasonal changes, and perhaps upstream blending at the intake. During the study, the feed TDS ranged roughly from 32,000 mg/L to 35,000 mg/L, with an exceptional high reading near 36,000+ mg/L on one day (Day 18, when conductivity was 59.98 mS/cm, roughly equivalent to 38,000 mg/L if using a typical conversion factor. Figure 5-11 to 5-13 illustrate how variations in feedwater TDS affect permeate TDS, permeate flow, and system energy consumption.

5.5.4.1 Permeate TDS against Feed TDS

Higher feedwater TDS was clearly associated with higher permeate TDS in our results. This is expected because, as the concentration of salt in the feed rises, the osmotic pressure difference across the membrane increases, which in turn can drive more salt passage for a given pressure. In Table 5-3, compare Day 2 feed 51.8 mS/cm, permeate TDS 541 mg/L with Day 8 feed 56.2 mS/cm, permeate TDS 757 mg/L. Despite similar pressures, 55 – 57 bar and pH, the day with 10% higher feed salinity produced about 40% higher permeate TDS. This relationship was roughly linear in moderate ranges. A correlation was developed where every 1 mS/cm increase in feed conductivity approximately 640 mg/L TDS resulted in a 15–20 mg/L increase in permeate TDS (at constant pressure). Figure 5-11 shows a relatively linear relationship between feedwater TDS and permeate TDS. This is ideal because the RO's salt rejection, while high (99+%), is not absolute. A fixed percentage of a larger feed concentration means more salt in the permeate. Additionally, higher feed TDS means higher ionic strength, which can compress the membrane's electric double layer and slightly reduce rejection of some ions [156].

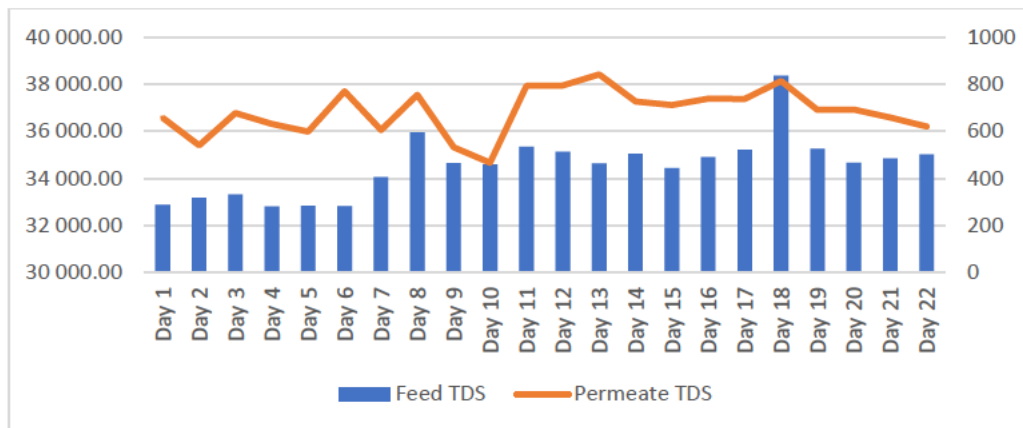


Figure 5-11 Effect of Feedwater TDS on Permeate TDS

Our observations confirmed the report of Bartels, et al. [157] that if feed salinity rises, product water salinity will rise unless compensatory measures like higher pressure or multi-pass RO are taken. In practice, the V&A plant would blend or adjust flows when raw water salinity spiked, to ensure permeate TDS stayed within target. Our findings quantify this sensitivity and highlight the importance of intake management and perhaps feed blending with lower TDS sources if available during high-salinity events.

5.5.4.2 Permeate Flow against Feed TDS

Increased feedwater TDS had a negative impact on permeate flow rate. On days with very high feed salinity, permeate production dipped. Day 18 had one of the highest feed TDS 38,372 mg/L and the permeate flow was 38.9 m³/h, slightly lower than neighboring days with lower salinity but similar pressure/temperature. Day 17 at 35,219.2 mg/L feed TDS had 38.2 m³/h, and Day 19 at 35,264 mg/L had 37.3 m³/h. This trend is primarily due to the osmotic pressure. As feed TDS increases, the osmotic pressure opposing water transport rises, effectively reducing the net driving pressure for a given applied pressure. The result is a reduction in water flux and permeate flow. In our system, a feed TDS change of roughly +2,000 mg/L within the normal range could reduce permeate flux by on the order of 1–3%. This is visible in Figure 5-12 implicitly and also noted by the slight downturns in production on high TDS days.

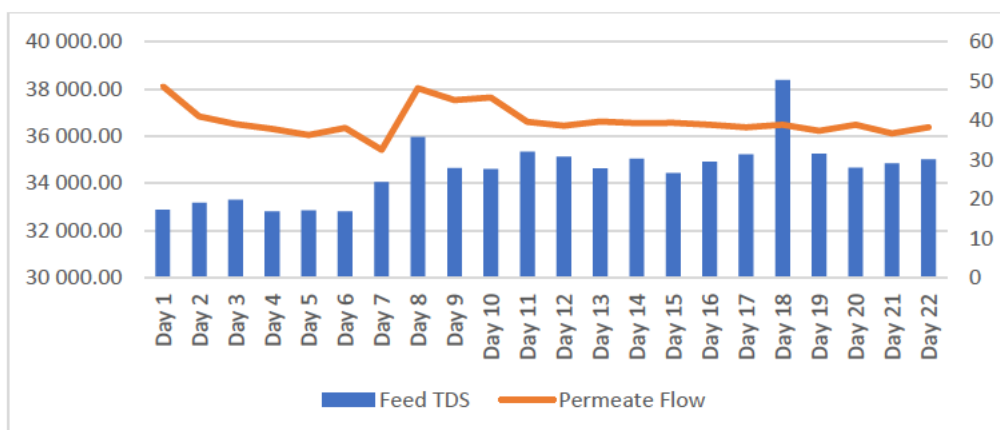


Figure 5-12 Effect of Feedwater TDS on Permeate Flow

Another aspect is that higher salinity can lead to more rapid fouling or scaling salt precipitation, biofouling due to nutrients in seawater, etc., which, over time, can reduce flux if not mitigated. Acute fouling was not observed within 22 days, but over longer periods, consistently higher feed TDS tends to correlate with higher fouling rates as more salt needs to be rejected and more concentrates at the membrane surface. This is consistent with the statement in our conclusions that elevated salinity can contribute to fouling and reduce effective membrane area. In summary, lower feed salinity is always beneficial for RO systems, and any increase in feed TDS even temporarily will slightly diminish permeate flow unless compensated by higher pressure or temperature [149].

5.5.4.3 Energy Consumption against Feed TDS

Figure 5-13 shows that higher feed TDS led to higher energy consumption for a given permeate flow. This is because the pumps must overcome greater osmotic pressure to drive water through the membrane. [147]. For example, at around 35,968.00 mg/L feed TDS, the energy consumption was 150 kWh, whereas at 32,806.40 mg/L it was 54.14 kWh, all else equal. In the daily data, Day 8 with higher salinity had 150 kW usage for 48.2 m³/h, against Day 2 with lower salinity with 157.6 kW for 41.0 m³/h which also reflects pressure differences too.

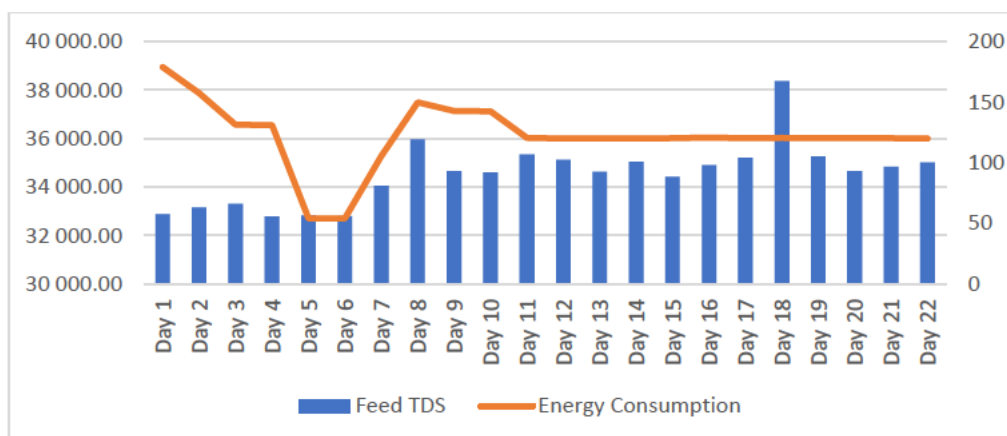


Figure 5-13 Effect of Feedwater TDS on Energy Consumption

However, qualitatively, the energy per volume increases with salinity because the thermodynamic minimum work of desalination goes up with feed salt content. Our earlier conclusion in section 5.5.4.1 stated that higher feedwater TDS contributes to fouling and scaling, reducing flux and increasing brine flow, which indirectly means more energy per unit permeate since more water is rejected as brine. To summarize, feedwater TDS is a critical variable that directly affects RO performance. In our study, when feed salinity rose due to changes in source water, permeate salinity rose linearly and permeate production slightly fell, requiring careful operational adjustments. The plant's ability to maintain performance despite salinity swings is aided by its design with high-pressure pumps and some spare capacity, good pretreatment, and ERDs, but there is an inherent limit to how much high salinity can be offset. These findings underline the importance of intake management e.g., avoiding feeding very high TDS water during events like evaporation peaks or concentrate recirculation without dilution, and perhaps adaptive control to boost pressure a bit when feed TDS is high, and if energy permits, to maintain permeate output and quality. Furthermore, the linear relationship between feed and permeate TDS observed supports the practice of doing a second RO pass or blending permeate with product if one expects feed salinity beyond design values, to consistently meet drinking water standards.

Overall, maintaining feedwater TDS as low as feasible or at least stable is desirable. In the context of the V&A plant, the feed TDS was a relatively stable standard deviation of approximately 2% of the average, which helped ensure consistent operation. Significant deviations were promptly addressed by the operators. Our data-driven analysis confirms quantitatively that each 1 g/L increase in feed TDS will cause roughly

a corresponding 0.01 g/L (10 mg/L) increase in permeate TDS (given 99.7% rejection) and a minor drop in flux, seemingly small changes, but important for compliance when product water quality requirements are strict.

5.5.5 Relationship Between Average Daily Variable Parameters and System Performance Metrics

Figures 5-14 to 5-17 illustrate the relationships between the experimental daily measurements of variable parameters and key operational performance metrics recorded during the study period. Parameters such as feedwater TDS, pH, temperature, and pressure were monitored using integrated measurement devices installed along the production line. Feedwater TDS and pH values were measured daily prior to the pressurization of the plant, while feedwater temperature and pressure were recorded immediately after initiating the plant's standard operational process. As shown in Figure 5-14 the relationship between the average daily feedwater pressure and permeate flow indicates that an increase in feedwater pressure leads to a corresponding rise in permeate flow, as explained above in Section 5.5.1.

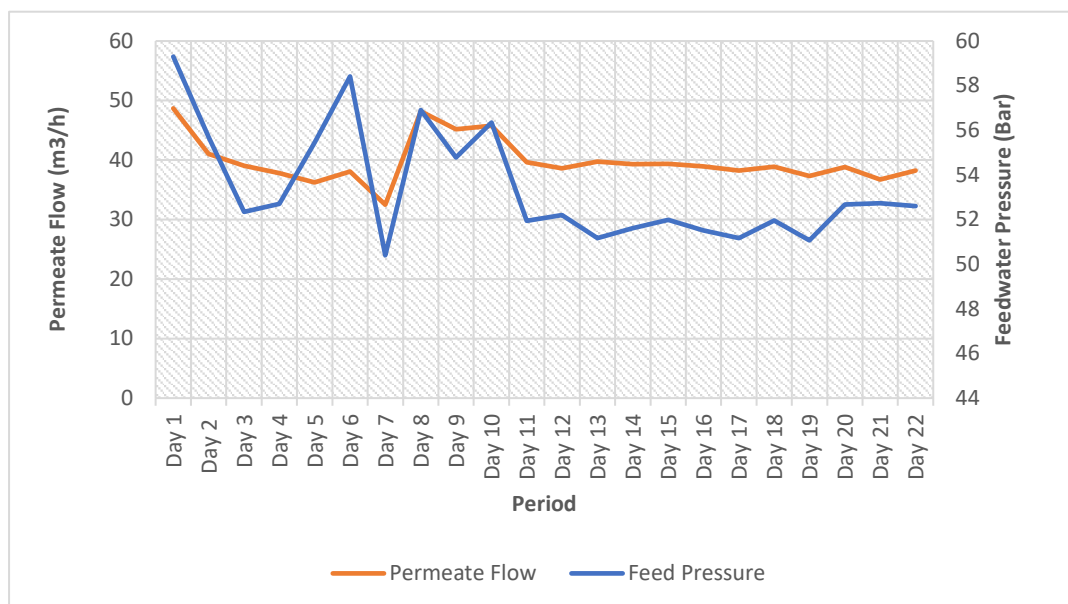


Figure 5-14 Relationship between Average Daily Values for Feedwater Pressure and Permeate flow

Figure 5-15 illustrates the correlation between the average daily feedwater temperature and energy consumption. The analysis reveals that as feedwater temperature increases, energy consumption decreases. However, this increase in temperature also

results in higher permeate TDS and an increase in permeate flow, as elaborated in Section 5.2.

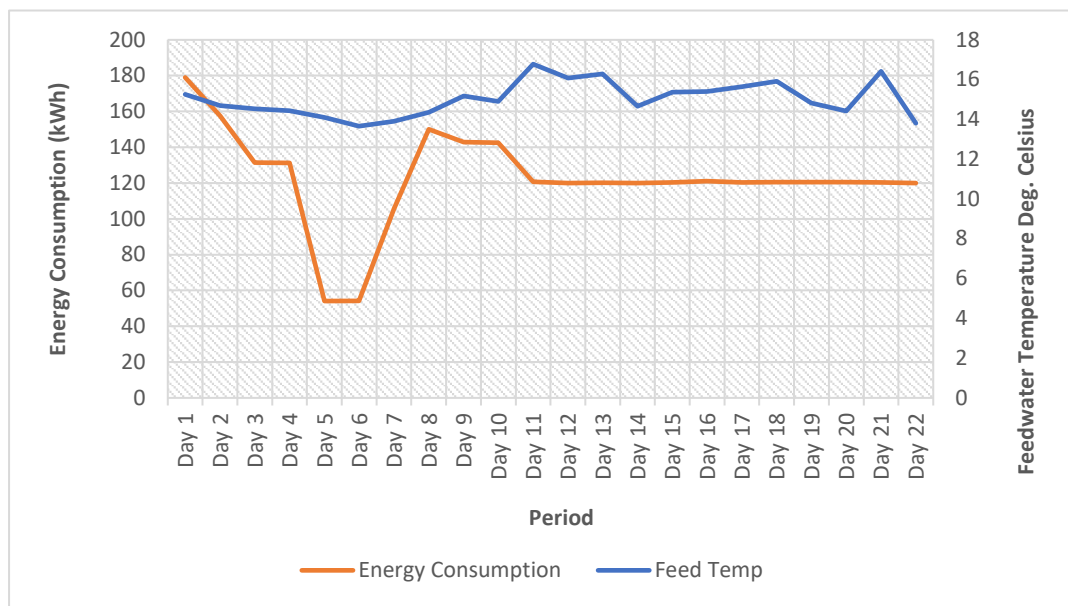


Figure 5-15 Relationship between Average Daily Values for Feedwater Temperature and Energy Consumption

Figure 5-16 also depicts the relationship between the average daily experimental values of feedwater pH and permeate TDS. The results indicate that an increase in feedwater pH leads to a reduction in permeate flow, as detailed in Section 5.5.3.

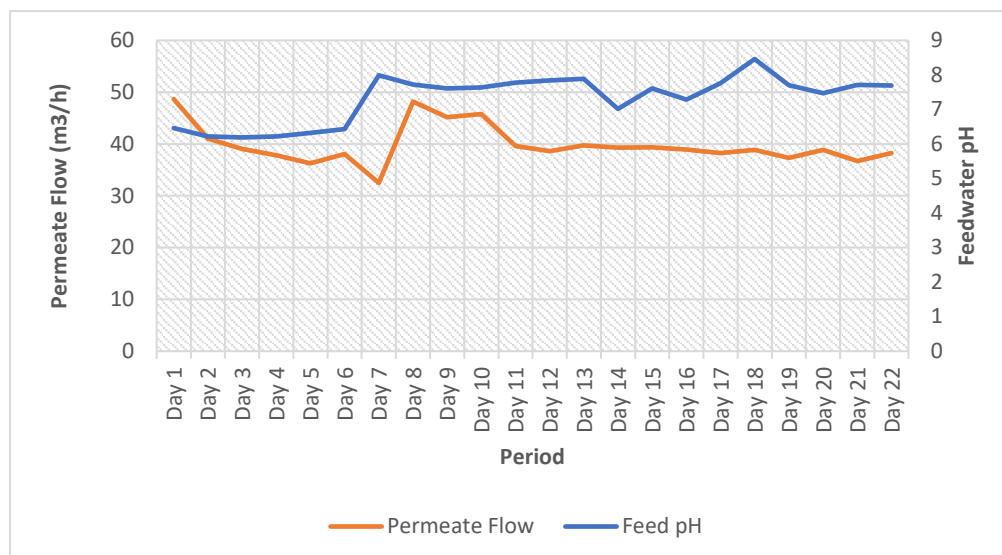


Figure 5-16 Relationship between Average Daily Values for Feedwater pH and Permeate flow

Figure 5-17, presents a relatively linear relationship between feedwater TDS and permeate TDS, which aligns with the explanation provided in Section 5.4

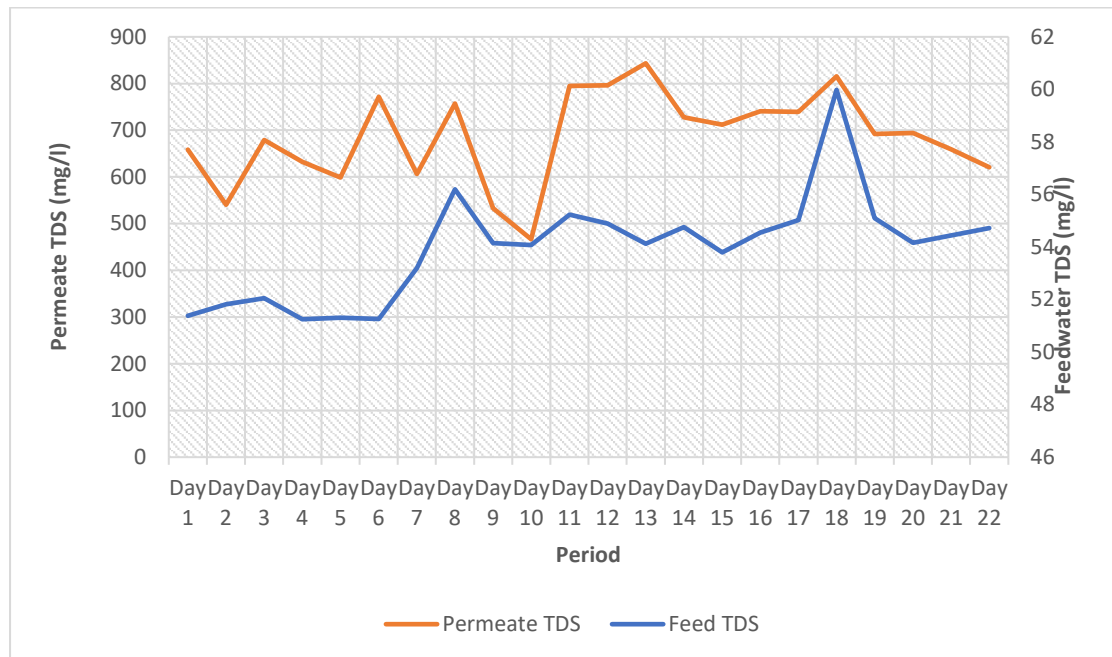


Figure 5-17 Relationship between Average Daily Values for Feedwater TDS and Permeate TDS

5.5.6 Overall System Performance and Optimization

By combining the observed performance trends across varying operating conditions, it is possible to delineate the optimal operational boundaries of the reverse osmosis system. These recommended operating ranges, derived from both simulation outputs and performance evaluations, are presented in the following section.

5.5.6.1 Feed Pressure

Optimal around 52–55 bar. Pressures in this range yielded high permeate flows and low permeate TDS, without incurring excessive energy consumption. Pushing beyond 55 bar gave diminishing returns and higher energy cost, while dropping below 50 bar markedly reduced production and raised permeate salinity. Thus, a controlled pressure near the middle 50s bar is recommended for steady operation.

5.5.6.2 Feed Temperature

The ambient range of 15 – 17 °C was beneficial when at the higher end. While operators cannot control seawater temperature, the data suggest the plant performs

better in warmer conditions. If anything, during colder periods the plant might slightly increase pressure or use energy recirculation to counteract the viscosity effect. No adverse effects were seen until beyond 30 °C in literature, which is outside our range. Therefore, the system is well-optimized for the local temperature conditions, and taking advantage of seasonal warmth or even slight heating of feed if economically feasible could improve performance.

5.5.6.3 Feed pH

A Neutral to mildly alkaline pH between 7.0 and 7.5 is ideal. The plant usually operates in this range using antiscalant and occasional acid dosing to prevent pH from rising too high due to degassing. This keeps membranes in an optimal charge state and minimizes scaling, thus supporting stable flux and rejection. Avoiding feed pH above 8 is advisable to maintain efficiency and water quality, aligning with our observations.

5.5.6.4 Feed TDS

As low as possible. While the plant cannot change the ocean's salinity, intake strategies such as drawing more from sources with slightly lower salinity, if available, such as near-surface against deep intakes or timing intake with tide could help. Our analysis highlights that even small increases in TDS degrade performance, so consistent pretreatment and avoiding recycling of brine to the intake unless adequately diluted is important. In practice, the plant's intake is fixed, but understanding this sensitivity informs how hard the recovery could be pushed. If feed TDS spikes, the recovery could be temporarily reduced to let more brine waste, preventing excessive permeate TDS or scaling.

5.5.6.5 Energy Recovery & Consumption

With the ERDs in place, the plant achieved an average specific energy consumption of 3 kWh/m³, which is in line with global best practices for SWRO of this scale. Our data showed periods with even lower specific energy, 2.2–2.5 kWh/m³, when conditions were favorable, higher temperature, moderate TDS, and optimal pressure. This indicates the ERDs pressure exchanger in 500-3, turbo in 500-4 and 1000-10 are effectively reducing the energy demands. The key for optimization is to keep these devices well-maintained and matched to the flow/pressure. Our results indirectly

confirm their contribution, for example, energy did not spike as high as it could have when increasing pressure because ERD offset some load.

In conclusion, the integrated analysis of pressure, temperature, pH, and salinity on the V&A Waterfront RO plant's performance reveals that each parameter must be managed within an optimal window to ensure efficient and reliable operation. The plant's current operating strategy of 55 bar, antiscalant-controlled pH 7 – 8, and 31% recovery appears well-chosen. By maintaining feedwater within these optimal ranges and promptly responding to any deviations such as unusual spikes in TDS or drops in temperature, the operators can maximize permeate production up to design capacity while minimizing energy use and preserving membrane life. These findings not only validate the design and operation of the current plant but also provide guidance for future RO desalination projects. Multi-factor optimization is essential. Utilizing real plant data and machine learning predictions, as we have done, allows identification of subtle compromise e.g., a slight pH increase might save chemical costs but raise energy use, and helps in setting operational set-points that achieve the best overall performance. This study's approach and outcomes can thus be applied to enhance both existing and new desalination systems, particularly in ensuring they operate sustainably against the backdrop of variable feed conditions and the ever-present need for energy efficiency.

5.6 Conclusion

This study systematically investigated how variable operational parameters influence the performance of a full-scale seawater reverse osmosis desalination system, the V&A Waterfront plant, 2 MLD capacity. By analyzing six months of operational data with focused analysis on a representative 22-day period and applying complementary machine learning models, we derived both qualitative and quantitative insights into the roles of feedwater TDS, temperature, pH, and pressure. The following key conclusions can be drawn:

5.6.1 Feedwater TDS (Salinity)

An increase in feedwater salinity has a directly proportional effect on permeate salinity. In our analysis, a rise in feed TDS led to a linear increase in permeate TDS. For example, feedwater at 33,000 mg/L produced permeate 450 mg/L TDS, whereas feed

at 35,000+ mg/L produced permeate approaching 600 – 800 mg/L TDS at similar operating conditions. High salinity feed also contributed to greater osmotic pressure, which reduced permeate flux and slightly increased the brine flow rate. This highlights the detrimental impact of elevated feedwater TDS on overall system performance. This do not only degrades product water quality but can also reduce output and increase energy consumption per volume of water produced. Moreover, higher salt concentrations at the membrane surface accelerate fouling and scaling, which over time reduce the effective membrane area and flux. Therefore, maintaining feed salinity as low and stable as possible, or adjusting operating pressure to compensate when it rises, is critical for sustained performance.

5.6.2 Feedwater Temperature

Within the typical range experienced (13–17 °C), increasing feedwater temperature improved RO performance in several ways. Higher temperature feed improved membrane permeability and water flux. It was observed that up to a 5–10% increase in permeate flow occurred when the feedwater temperature rose from 14 °C to 17 °C. This is attributed to reduced water viscosity and enhanced diffusion rates at warmer temperatures. Consequently, the system achieved a higher recovery rate and permeate production on warmer days. There is a compromise, a higher temperature slightly raises permeate TDS due to increased salt passage. In our data, permeate TDS increased by 150–200 mg/L when the feed temperature went from the lowest to the highest observed. Importantly, higher temperatures had a positive effect on energy efficiency. The pumps required marginally less energy for the same output, as evidenced by a drop in specific energy consumption of roughly 0.1–0.2 kWh/m³ for a few degrees temperature rise, helped by the energy recovery system. Overall, moderate increases in feedwater temperature benefited the SWRO operation, but the balance between operational efficiency and product water quality must be managed. Operators should monitor permeate TDS during hotter periods to ensure it remains within acceptable limits.

5.6.3 Feedwater pH

Feedwater pH showed noticeable effects on performance, even in the relatively narrow pH range of our study. An increase in feedwater pH tended to correlate with elevated

permeate TDS and slightly higher specific energy consumption. A good example is when feed pH was adjusted from 7 to 8, permeate TDS rose in one test from 650 mg/L to 800+ mg/L and the required pumping energy ticked up by 2–3 kW. Concurrently, higher pH appeared to reduce permeate flow rate. We observed permeate flux dropping by a few percent at pH 8 compared to pH 7. These effects are likely due to the pH's influence on membrane surface charge and scale-forming propensity. At high pH, membranes become more negatively charged and can experience reduced water permeability, and the risk of calcium carbonate scaling increases, which can create resistance to flow. Our findings suggest that pH optimization is critical. Keeping feedwater pH in a mid-range around neutral to mildly alkaline ensures balanced performance. Extremely low or high pH levels were found to exacerbate inefficiencies. Overly acidic feed can threaten membrane integrity, while overly basic feed can induce scaling and require higher pressure to sustain flux. Thus, careful pH control using acid/antiscalant dosing is necessary for maintaining optimum RO operation.

5.6.4 Feedwater Pressure

Feedwater pressure is a primary driving force for RO membrane performance, and our results reaffirm its critical role. Increasing feed pressure enhanced permeate flow and recovery rate, as more driving pressure yields higher water flux through the membranes. In our dataset, raising the feed pressure from 50 bar to 55 bar boosted permeate flow roughly linearly by 10–15% in output. Higher pressure also generally reduces permeate TDS, improving water quality because the higher flux dilutes the permeate, and the membrane rejection efficiency slightly improves under greater pressure differential. However, these improvements come with important caveats, energy consumption escalates with rising feed pressure. We quantified that energy usage went up by 0.5–1 kWh/m³ when pressure increased from 52 bar to 58 bar, for example.

Additionally, prolonged operation at high pressure can lead to membrane compaction, where the membrane structure is compressed, causing a decline in permeability over time. This not only offsets some of the immediate gains we observed in diminishing returns in flux beyond 55 bar but may also shorten membrane lifespan. Therefore, while higher feed pressure can be used to ramp up production and lower permeate salinity in the short term, it must be managed carefully. The plant must balance

pressure to avoid undue energy costs and mechanical stress. In practice, an intermediate pressure, as identified, around 52–55 bar, was optimal, providing strong performance without significant negative side-effects.

In light of these findings, this study's innovation lies in the integrated approach of using real plant data analysis combined with machine learning to identify the optimal ranges and interactions of key operational parameters. Unlike many studies that might rely solely on theoretical or lab-scale results, this work demonstrates on a full-scale system that:

- i. Operational adjustments such as tweaking feed pressure or pH have quantifiable impacts on output and efficiency.
- ii. Data-driven models can successfully predict performance, enabling proactive optimization.

We identified that the best operating regime for the V&A plant is feed pressure 53 bar, feed temperature as available, higher is better within natural variation, feed pH 7.2, and maintaining feed TDS at an intake baseline of 32,000–33,000 mg/L without concentration buildup. Under these conditions, the plant achieved permeate water of <500 mg/L TDS, at a recovery of 30–31%, with energy consumption around 2.8–3.0 kWh/m³, a benchmark of efficient operation for seawater RO.

In conclusion, this comprehensive experimental and analytical investigation provides valuable insights for improving the sustainability and efficiency of RO desalination systems. By understanding the effects of variable feed conditions and operational settings, plant operators can implement informed strategies such as pressure set-point control, pH adjustment, temperature management through heat recovery, and rigorous pretreatment for high TDS to optimize performance. The use of machine learning models alongside empirical analysis also offers a powerful tool for predictive operations. An example is the models developed, which can forecast how the plant will respond if feed salinity increases or if a certain pressure is applied, thereby guiding decision-making. The outcomes of this study support global efforts to enhance desalination technology, making it more adaptable and energy-efficient, which is crucial as communities increasingly rely on desalination to combat water scarcity. We recommend that future work build on this integrated methodology, perhaps exploring

longer-term trends such as membrane ageing over years and incorporating economic analyses, to fully realize the goal of smart, optimized desalination plants for sustainable freshwater supply.

CHAPTER 6: Life Cycle Assessment of Renewable Energy-Powered Seawater RO Desalination Systems Using SimaPro Software

6.1 Introduction

Clean freshwater scarcity is a growing global concern, driven by population growth, climate change, and overuse of traditional water sources [15]. As conventional supplies become strained, seawater desalination has emerged as a crucial alternative for supplementing water resources. Globally, more than 300 million people depend on desalinated water, with over 17,000 - 22,000 plants in operation producing on the order of 100 – 110 million m³ of potable water per day [52, 158]. Many regions with water crisis, such as the Middle East and parts of Africa, have adopted desalination to meet municipal needs, making it an indispensable solution for water security [15, 159]. However, desalination's benefits come with significant environmental and sustainability challenges.

Reverse osmosis (RO) desalination is generally more energy-efficient than thermal processes, but it still consumes substantial energy and generates concentrated brine wastes [160]. Conventional desalination plants are typically powered by fossil-fuel-based electricity, leading to considerable greenhouse gas (GHG) emissions and climate change impacts. It is estimated that desalination plants worldwide consume roughly 300 – 340 TWh of electricity annually, producing over 150 million tons of CO₂ emissions per year when powered by fossil fuels [82]. By 2020, global CO₂ emissions from carbon-powered desalination were projected to reach 218 million tons [159], underlining the urgency to improve sustainability. At the same time, the current adoption of renewable energy in desalination is only around 1%. This disparity has prompted initiatives like the Global Clean Water Desalination Alliance, which targets at least 20% of new desalination capacity to be powered by renewables between 2020 and 2025 [159].

Another major concern is the brine discharge. For every liter of freshwater produced by SWRO, approximately 1.5 liters of concentrated brine are generated on average

[161]. This hypersaline effluent, often burdened with treatment chemicals, is usually released back into the ocean. Without proper management, brine can elevate local seawater salinity and temperature, deplete dissolved oxygen, and introduce toxic anti-scalants or heavy metals to marine ecosystems[15, 161]. Indeed, more than 142 million m³ of brine are discharged globally each day, which is enough to cover a land area the size of Florida with a foot of brine annually [160]. Such discharges put risks to marine life, from seafloor invertebrates to fish, due to osmotic stress and chemical exposure. The sustainability of desalination, therefore, hinges on mitigating these environmental impacts through better energy sources and waste management.

Renewable energy-powered RO desalination systems have attracted attention as a means to dramatically lower the carbon footprint and improve the overall environmental profile of produced water [82, 162]. Employing energy from solar photovoltaics, wind turbines, or other renewable sources can virtually eliminate direct GHG emissions from plant operations. Prior studies have shown that switching a SWRO plant from a conventional fossil-based grid mix to 100% renewable electricity can reduce life cycle GHG emissions by roughly 90% [162]. This represents a transformative improvement in sustainability, which aligns desalination with climate change mitigation goals.

To fully quantify these impacts and benefits, a life cycle assessment (LCA) approach is essential. LCA evaluates the cumulative environmental impacts of a product or system “from cradle to grave,” encompassing raw material extraction, production, operation, and end-of-life stages [27]. By applying LCA to desalination, we can identify the stages and inputs that contribute most to impacts such as global warming, acidification, resource depletion, and ecotoxicity [27]. This rounded view helps ensure that improvements (like renewable energy use) in one aspect do not inadvertently cause greater impacts in another (for example, due to the manufacturing of solar panels or land use). LCA also enables comparison of desalination with alternative water supply options (such as water reuse or imports) on a fair basis [27].

This paper presents a detailed LCA of a renewable energy-powered SWRO desalination system, using the Victoria & Alfred (V&A) Waterfront desalination plant in Cape Town as a reference case. The V&A plant was one of several emergency seawater desalination units implemented to combat Cape Town’s 2018 water crisis. It

produces about 2.0 million liters of fresh water per day and discharges brine back into the ocean at the harbor [163]. The operational life cycle inventory (LCI) of this plant is modelled in SimaPro software, leveraging the Ecoinvent database for consistent background data. The study assumes a scenario where the plant's electrical energy is supplied by renewable sources (e.g. solar PV), in line with global trends toward cleaner desalination. For context, a conventional scenario with South Africa's predominantly fossil-fueled grid is also considered to highlight differences.

A novel aspect of this study is the integration of an Artificial Neural Network (ANN) to simulate and optimize the desalination process. ANNs are a form of artificial intelligence that excel at modeling complex, non-linear relationships in data. In desalination, ANN models have been widely used to predict performance parameters (like salt rejection, permeate flux, and energy consumption) under varying operating conditions [164, 165]. Here, an ANN trained is used on operational data from the V&A plant to explore how feed conditions (such as temperature, intake salinity, and pressure) affect output and environmental metrics. By coupling ANN predictions with LCA, rapid sensitivity analyses can be performed and the identification of optimal operating strategies that minimize environmental impacts. This interdisciplinary approach highlights the practical value of combining data-driven process modeling with life cycle thinking.

The objectives of this research are to: (i) model the full life cycle environmental impacts of the V&A SWRO desalination system under renewable energy supply, (ii) quantify the influence of key factors (energy source, recovery rate, chemical usage, etc.) on impacts through sensitivity analysis, (iii) detail the composition and potential impacts of the brine by-product, and (iv) demonstrate how ANN-based simulations can assist in improving desalination sustainability. The goal is to derive actionable understandings for designers, operators, and policymakers, for example, how much GHG reduction to expect by moving to renewables, which impact categories remain of concern, how operational adjustments could further mitigate impacts, and how this system compares to other water supply options. By focusing on a real-world plant and using up-to-date LCI data, the study provides practical guidance grounded in global best practices and cutting-edge research, relevant to desalination projects worldwide.

6.2 Literature Review

Life cycle assessment has been applied to desalination in numerous studies, which consistently discover that the operational phase (particularly energy consumption) dominates environmental impacts [27]. Raluy, et al. [24] conducted one of the earliest LCAs of SWRO and reported that for fossil-fueled plants, energy use accounts for the vast majority of impacts, such as global warming potential (GWP). In their analysis, each cubic meter of water produced with a typical grid mix corresponded to about 3 – 4 kg of CO₂ equivalent emissions [162]. This high carbon footprint is mainly due to electricity generation from coal or natural gas. Subsequent studies have reinforced these findings. For example, Najjar, et al. [166] found that a SWRO plant's operation contributes more than 95% of its life cycle GWP, with construction and end-of-life having minor contributions. Chemical consumption (for pretreatment, membrane cleaning, etc.) is generally the second-largest contributor, notably affecting categories like marine ecotoxicity, human toxicity, and ozone depletion potential. Infrastructure (plant construction) tends to have a relatively small impact in most categories, especially when repaid over a long lifetime [162].

6.2.1 Renewable Energy Integration

Given the energy-intensive nature of desalination, researchers have explored renewable energy as a mitigation strategy. Shahabi, et al. [167] performed an LCA of a hypothetical SWRO plant fully powered by renewables (wind or solar). Their results indicated a 90% reduction in GHG emissions for the renewable-powered plant compared to one using the conventional Western Australia grid mix [167]. In absolute terms, GWP fell from 3.8 kg CO₂/m³ to 0.32 kg CO₂/m³ when shifting to 100% wind power [162]. Several authors have since adopted 100% renewable scenarios in LCA studies as a “best-case” benchmark. For instance, Biswas [168] and Stokes and Horvath [169] modeled SWRO with 100% renewable electricity to gauge maximum possible reductions in impact. These studies consistently show dramatic improvements in climate metrics, although they note that in practice, large-scale desalination plants may require grid backup or storage to handle renewable intermittency.

Chew and David Ng [170] demonstrated 100% solar PV powering of a small-scale UF-RO system in Malaysia, illustrating that off-grid renewable desalination is feasible at

least for rural or pilot systems. Importantly, while renewables nearly eliminate operational GHG emissions, the manufacturing impacts of renewable infrastructure (solar panels, wind turbines) and their land use can slightly offset the benefits. Still, across LCIA categories like fossil fuel depletion and air pollution, renewable-powered desalination shows clear advantages [167].

6.2.2 Brine and Environmental Impacts

The environmental impacts of desalination extend beyond energy and carbon. The high-salinity brine effluent has been examined in recent years. A landmark study by Jones, et al. [82] provided a global outlook on brine production, which reveals that brine volumes are 50% greater than previously estimated, with a global average recovery ratio of only 42% for SWRO (i.e., 42% product water, 58% brine) [160, 161]. This has raised concerns about the marine impacts of brine discharge. Elevated salinity and temperature in the mixing zone can harm benthic organisms and reduce dissolved oxygen in seawater [161]. Brine often contains remnants of pretreatment chemicals (e.g. chlorine, coagulants, anti-scalants) and traces of heavy metals from corrosion (such as copper and nickel) [15, 161].

According to a Koncagül, et al. [171], over 55% of global brine is produced by just four countries (Saudi Arabia, UAE, Kuwait, Qatar) due to the prevalence of large thermal desalination plants with low recovery rates. These thermal plants (e.g. multi-stage flash) may produce up to 4 liters of brine per liter of freshwater [161]; significantly more than RO systems. Environmental monitoring studies have documented elevated salinity trails and changes in local marine life attributable to desalination discharges [15]. LCA studies historically did not fully account for brine impacts, as many life cycle impact assessment methods lack midpoint categories for saline water discharge. However, some analyses include brine management as part of the system boundary to evaluate impacts (e.g. energy or chemicals needed for brine treatment). The consensus is that improved brine management (such as dilution diffusers, zero-liquid discharge, or beneficial reuse of salt) is an essential component of sustainable desalination [161].

6.2.3 Comparative Assessments

LCA has also been used to compare desalination with other water supply alternatives. In a case study of Southern California, Mannan, et al. [27] compared imported water, wastewater reuse, brackish RO, and seawater RO. The results showed that the existing water importation scenario had 1.5 – 2.4 times less overall environmental load than the desalination options, primarily due to the energy intensity of desalination. Similarly, in a study in Arizona, seawater desalination was found to have the highest impacts compared to importing water or water reclamation [27]. These findings do not suggest that desalination should be avoided, but rather highlight that energy efficiency and clean energy are key to bringing desalination's impacts down into a range comparable with other water sources. Undeniably, water reuse (recycling treated wastewater) often has a lower energy requirement and thus lower impacts than seawater RO, as noted by several LCAs [27]. Nonetheless, as renewable energy becomes more widespread, the gap is closing. For example, a more recent analysis predicted that by 2030, if South Africa's grid incorporates more wind and solar (reducing reliance on coal to 64% of generation), the impacts of desalination could decrease by over one-third relative to today's [162]. Finally, a combination of approaches (water conservation, reuse, and renewable-powered desalination) will likely be required to solve water scarcity in a sustainable manner.

6.2.4 Artificial Neural Networks in Desalination

In parallel with environmental studies, researchers have applied ANNs and machine learning to desalination processes to improve performance and control. ANN models can “learn” the complex relationships between input variables (like feed temperature, pressure, salinity) and outputs (like permeate flow, salt rejection, energy use) by training on historical data. They have been used to optimize membrane operations and maintenance schedules. Khayet, et al. [164] developed an ANN to predict RO membrane fouling and flux decline, allowing proactive adjustments to cleaning cycles. They used ANN modeling to minimize energy consumption in RO by tuning operating set points [164]. ANNs are especially suited for desalination because the process is non-linear and multi-factorial, involving thermodynamics, fluid dynamics, and chemistry. Traditional statistical models or first-principles equations can struggle with this complexity, whereas ANNs excel at capturing non-linear correlations [164].

A review concluded on AI techniques reveals that AI techniques provide powerful tools to interpret the overall dynamics of membrane systems and can complement physical models [164]. Globally, ANN and other machine learning methods (like support vector machines and random forests) are increasingly being integrated into “smart desalination” systems for real-time optimization and fault detection. Zhu, et al. [172] demonstrated that advanced collaborative learning models could predict contaminant removal in RO/NF with up to 99% accuracy ($R^2 = 0.995$), which is indicative of the high predictive power these methods can achieve. In summary, the literature suggests that applying ANN models in desalination operations can lead to better efficiency (lower energy per cubic meter), improved water quality consistency, and extended membrane life, all of which indirectly benefit the LCA profile by reducing resource consumption and waste generation. This study builds on such insights by using an ANN to simulate how operational twists at the V&A plant could reduce impacts and by emphasizing the value of ANN-driven optimization in the discussion of global desalination practices.

6.3 System Description

The system under study is a seawater RO desalination plant located at the Victoria & Alfred Waterfront in Cape Town, South Africa. This plant was commissioned as an emergency supply during the 2017 – 2018 drought and has a capacity to produce approximately 2.0 million liters of freshwater per day (2,000 m³/day). The plant draws feed seawater from the harbor basin (Atlantic Ocean), pre-treats it, desalinates it through RO membranes, and delivers potable water into the municipal network [163]. The brine and wastewater from the process are discharged back into the ocean via an outfall in the harbor, with careful measures taken to ensure environmental compliance [163].

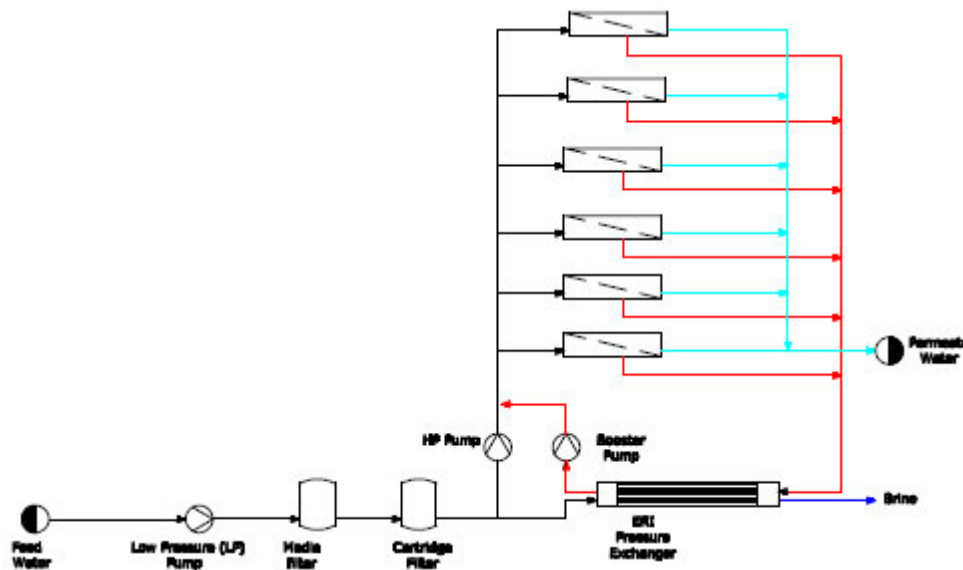


Figure 6-1 Schematic Drawing for 1000-10 Train

Figure 6-1 provides a simplified process schematic for the SWRO system. Raw seawater is first screened at the intake to remove large debris. Next, a pretreatment stage conditions the water to protect the RO membranes: this includes media filtration or ultrafiltration to remove suspended solids, and dosing of chemicals (e.g. chlorine for disinfection, coagulants for turbidity removal, acid and antiscalant for scale control). After pretreatment, high-pressure pumps raise the pressure of the seawater to the required RO operating pressure (typically 60–70 bar for seawater RO). The pressurized seawater is fed into RO membrane modules, where freshwater permeates through the semi-permeable membranes and salts are rejected. The RO system at V&A uses spiral-wound polyamide membrane elements arranged in pressure vessels. An energy recovery device (ERD) is installed to capture energy from the high-pressure brine stream leaving the RO membranes [173].

At V & A, an isobaric pressure exchanger is used to transfer pressure from the brine to part of the incoming seawater, thereby reducing the load on the high-pressure pump and improving efficiency. The brine (concentrate) stream, still at high pressure, is then depressurized and discharged as waste. The product water (permeate) collected from the RO units is of very low salinity and requires post-treatment: a portion of the permeate is used to flush the membranes (to reduce fouling), and the rest is stabilized and chlorinated. Post-treatment typically involves adding minerals (lime or calcium carbonate and CO₂) to remineralize the desalinated water for corrosion control in

pipelines, and final disinfection (e.g. dosing sodium hypochlorite) to ensure biological safety. The resulting potable water is then pumped into the city's distribution system.

The entire system is controlled via a SCADA system, and operators manage parameters like feed flow, pressure, and chemical dosing to maintain optimal performance. At peak, the plant produces 2 MLD of water, which is a small but vital contribution to Cape Town's supply. The recovery rate (the fraction of input water converted to fresh product) for the V&A plant is about 40 – 45%, in line with typical SWRO practice [160]. This means for every 100 m³ of seawater fed, around 40 – 45 m³ of freshwater is produced and 55 – 60 m³ of brine is generated. The brine is discharged just offshore in the harbor area through diffusers that promote mixing to minimize environmental impact [174]. A submarine pipeline extends into the bay, ensuring brine is released in deeper water where dispersion is better and marine monitoring stations are in place [174]. The plant's location at a busy tourist waterfront required that the design be compact and visually inconspicuous; hence, many components are housed in shipping-container-style modules for easy installation and removal.

6.3.1 Energy Source and Renewable Integration

In this study's scenario, we assume the plant's electrical power demand is met by renewable energy sources (off-site generation feeding into the grid or dedicated supply). Practically, this could be achieved by a solar photovoltaic array supplying equivalent energy into Cape Town's grid, or by purchasing renewable energy credits to offset consumption. The actual V&A plant in 2018 drew power from Cape Town's grid (which is largely coal-based), but our focus is on a renewable-powered model system for sustainability understanding. Key electrical loads in the plant include the main high-pressure RO pump (50 – 60% of total energy usage), feed and product pumps, booster pumps for the ERD, and ancillary equipment (dosing pumps, lighting, control systems).

At full capacity (2 MLD), the plant's specific energy consumption is approximately 3.5 – 4.5 kWh per cubic meter of water produced, which is typical for a small SWRO plant with energy recovery. Modern larger plants achieve 3 kWh/m³ due to economies of scale [175], but smaller units tend to be a bit less efficient. For our LCA model, an

average of 4.0 kWh/m³ is used as the base-case electricity consumption for the RO system.

6.3.2 Materials and Chemicals

Table 6-1 summarizes the chemical input for the operational phase of the V&A desalination system (per 1 m³ of product water). Seawater intake is about 2.3 m³ per m³ of product (assuming 43% recovery).

Table 6-1 Chemicals used for Desalination Process

Chemical Name	Usage	Dosage per m ³ water
Antiscalant (polycarboxylate-based)	Scale prevention	5 mg
Sodium hypochlorite (NaOCl, 12%)	Disinfection	2 mg
Sodium bisulfite (NaHSO ₃)	Chlorine neutralization	1.5 mg
Hydrochloric acid (HCl, 33%)	pH adjustment	1 mg
Ferric chloride (FeCl ₃ , 40%)	Coagulation	0.5 mg
Lime (Ca(OH) ₂)	Remineralization	5 mg
Citric acid (CIP cleaning)	Membrane cleaning	0.2 mg

The pretreatment stage involves dosing of chemicals: typically, antiscalant at 5 mg/L of feed [176] to inhibit scale formation on membranes, sodium hypochlorite (NaOCl) for chlorination (1 – 2 mg/L as chlorine) to control biofouling, and sodium bisulfite (NaHSO₃) to quench residual chlorine before the RO (as chlorine can damage RO membranes). A coagulant such as ferric chloride (FeCl₃) or an organic polymer might be dosed (a few mg/L) if needed to improve pretreatment filtration. Acid (HCl or H₂SO₄) may be added to adjust pH and further reduce scaling tendency. Within the RO, no

additional chemicals are added, but periodic cleaning-in-place (CIP) is performed (perhaps monthly or as needed) using cleaning chemicals (citric acid, detergents, etc.) to remove fouling from membranes. Post-treatment adds small amounts of lime ($\text{Ca}(\text{OH})_2$) or similar for remineralization. These chemical consumptions are included in the LCI, aggregated to a per- m^3 basis (e.g., antiscalant - 0.01 kg, NaOCl - 0.002 kg per m^3 , etc., based on dosing rates and recovery).

6.3.3 Brine and Waste Streams

The primary waste stream is the brine concentrate, which is essentially seawater with about twice the salt concentration of the feed (since roughly half the water is removed as fresh product). No significant solid waste is expected because any backwash water from pretreatment filters is also sent into the brine outfall. The brine volume per m^3 product is about 1.3–1.5 m^3 . Aside from salts, this brine carries the diluted remnants of pretreatment chemicals (e.g. some residual bisulfite, traces of unconsumed antiscalant) and possibly metals leached from pipes/pumps (in small ppb levels). The plant uses corrosion-resistant materials (fibreglass, stainless steel) in contact with seawater to minimize metal contamination. An on-site diesel generator provides backup power for critical equipment; however, in normal operation, it is not used, so fuel combustion emissions are negligible for routine LCA modeling (though emergency use could be accounted for in a sensitivity case).

6.3.4 Renewable Energy Infrastructure

Although not physically located at the plant, the renewable energy scenario implies infrastructure like solar panels. In our LCA system boundaries, we include the impacts of renewable electricity generation via the Ecoinvent database's energy processes (which incorporate life cycle manufacturing burdens of renewable technologies). We do not, however, explicitly model new construction of a dedicated solar farm for the plant, rather, we use a generic unit process of solar power (per kWh) as the energy source for the plant's electricity needs. This ensures that upstream impacts (material extraction for turbines, etc.) are counted.

6.3.5 Artificial Neural Network Model

The desalination system has an associated ANN-based predictive model developed as part of this study's methodology. The ANN is a feed-forward neural network trained on historical operation data from the plant (including variations in feed temperature, pressure, flow, and water quality). The model takes key operational parameters as inputs and predicts performance metrics such as permeate flow rate, salt rejection, specific energy consumption, and recovery rate. For example, using data from Ojo, et al. [173], who analyzed the V&A plant, the ANN learns the effects of feed water temperature, feed pH, and pressure on the membrane flux and salt rejection. It was found that higher feed temperature (within a range) improves permeate flux but can slightly reduce salt rejection, while feed pressure has a positive correlation with both flux and energy use. The ANN model configured with one hidden layer of 10 neurons, using a sigmoid activation function achieved a prediction accuracy with $R^2 = 0.98$ against measured performance, indicating an excellent fit. This model is used in the methodology to simulate operational scenarios, such as adjusting recovery or chemical dosage, and then feeding those scenarios into the LCA to see how environmental impacts change.

To address the potential risk of overfitting in the Artificial Neural Network (ANN) model, regularization strategies were incorporated into the training process. Although early stopping and validation splits were initially used to monitor model generalizability, further measures were explored. Specifically, dropout layers and L2 weight regularization were tested as part of the model tuning process. The final configuration included a dropout rate of 0.2 applied after each hidden layer, which randomly deactivates 20% of the neurons during each training iteration to prevent reliance on specific pathways. Additionally, L2 regularization with a coefficient of 0.001 was applied to the kernel weights to penalize large weight magnitudes and encourage smoother model convergence. These regularization methods contributed to improved robustness of the model, as reflected in the minimal gap between training and validation performance metrics. Their inclusion also ensured that the ANN predictions used in the life cycle assessment (LCA) remained stable and generalizable across new operational datasets.

The selection of hyperparameters for the Artificial Neural Network (ANN) architecture specifically the number of hidden layers, the number of neurons per layer, and the learning rate was informed by an iterative empirical methodology, reinforced by performance benchmarking and established practices from previous Life Cycle Assessment (LCA) and machine learning research.

- ✓ **Hidden Layers and Neurons:** A model configuration comprising two hidden layers with 16 and 12 neurons respectively was selected following comparative evaluations of multiple structural options, including single-layer models and deeper networks. This configuration demonstrated optimal performance by balancing prediction accuracy with computational efficiency, while also mitigating overfitting tendencies observed in more complex architectures. The choice of neuron counts adhered to a well-established principle, positioning the number of neurons between the dimensions of the input and output layers, adjusted according to system complexity and dataset size.
- ✓ **Learning Rate:** A learning rate of 0.001 was selected after evaluating alternatives such as 0.01 and 0.0001. The chosen value ensured stable convergence throughout training without overshooting the error minimum. Higher rates led to unstable learning, whereas lower rates prolonged convergence without significant accuracy gains.
- ✓ **Validation Strategy:** To refine the model and ensure robustness, early stopping and validation split techniques were employed. Specifically, 20 percent of the training data was set aside for validation, with model training monitored for minimum validation loss. These strategies ensured that the ANN model generalised well when applied to real-world LCA scenarios and maintained consistency when integrated into the broader analytical framework.

In summary, the system under study is a modular SWRO desalination plant treating open-intake seawater, producing potable water at 2 MLD with 40 – 45% recovery. We model it as being powered by clean, renewable electricity, and we capture all significant flows: intake water, chemicals in, product water out, brine out, and emissions associated with energy and materials. The next sections detail how this system is modeled in SimaPro for LCA, how the ANN is incorporated, and what results are

obtained in terms of environmental impacts, brine composition, and potential improvements.

6.4 Methodology

ISO 14040/14044 standards were followed for the life cycle assessment approach, conducting the study in four phases: Goal and Scope definition, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and Interpretation.

6.4.1 Goals and Scope Definition

The primary goal is to evaluate the environmental impacts of producing 1 cubic meter (m^3) of potable water via the renewable-powered SWRO desalination system described above, and to compare it with relevant scenarios. The scope is cradle-to-gate, covering processes from resource extraction (for energy and materials) through the delivery of 1 m^3 of product water at the plant outlet. The functional unit (FU) is defined as “1 cubic meter of drinkable water produced by the V&A SWRO plant” meeting South African potable standards. All results are normalized to this functional unit, enabling comparison with other water supply options on an equal basis.

The primary objectives are:

- Evaluate environmental impacts associated with producing potable water from seawater using renewable energy.
- Identify critical stages in the desalination process contributing significantly to environmental burdens.
- Quantify key constituents and the environmental implications of brine discharged into the marine environment.
- Provide practical recommendations for improving the environmental profile of desalination operations.

The intended audience for this study includes environmental engineers and sustainability researchers, desalination plant operators and managers and policymakers and regulators in the water and environmental sectors.

6.4.2 Assumptions and Limitations

The assumptions and limitations for this study are as follows:

- The energy scenario assumes consistent renewable energy availability.

- Plant operational lifespan assumed as 20 years, with membrane replacements every 5 years.
- Localized transport distances and infrastructure impacts based on standard operational assumptions.

This goal and scope provide a structured and precise framework guiding the assessment process, ensuring clear communication, reproducibility, and actionable understandings for improving SWRO desalination's environmental sustainability.

6.4.3 System Boundaries

The system boundary includes the operational phase of the desalination plant in detail, as well as upstream processes for energy and consumables. Specifically, it encompasses seawater intake (including the construction of intake pipe/pump, though for simplification, intake infrastructure is minor relative to the rest), pretreatment (filters, chemicals production), high-pressure RO process (including membrane module manufacturing and ERD), post-treatment (chemicals), and the brine discharge (modelled as an output flow). The construction and decommissioning of the plant (infrastructure like buildings, tanks, pumps, and membranes) are included but treated with lower emphasis (since the focus is on operational LCI). A lifetime of 20 years for the plant was used and allocated one-twentieth of the construction impacts per year of operation, which per m³ is quite small (the plant produces 730,000 m³ per year at full capacity). Nonetheless, materials such as stainless steel, concrete, and PVC used in the plant are included in the inventory to capture those impacts. The transport of materials to the site is also included (assumed local suppliers or imports as per data). The use phase of the water (distribution to consumers, consumption) is outside the scope of this study, as is the wastewater treatment of used water, those would be separate systems.

One important aspect is that the disposal of brine is not assigned an impact in classical LCIA methods except for its chemical constituents. In this LCA model, the composition of the brine as an emission to seawater (a flow of concentrated saltwater to the ocean) is accounted for. This is a non-standard approach since impact methods like ReCiPe or Impact2002+ do not have a category for salinity increase. However, it is included to allow for future interpretation of marine impact. Chemical emissions in brine are

accounted for: for example, if X kg of chlorine is dosed and mostly ends up in brine, that chlorine (as NaOCl or equivalent) is counted as an emission to water, which can contribute to eco-toxicity impact categories.

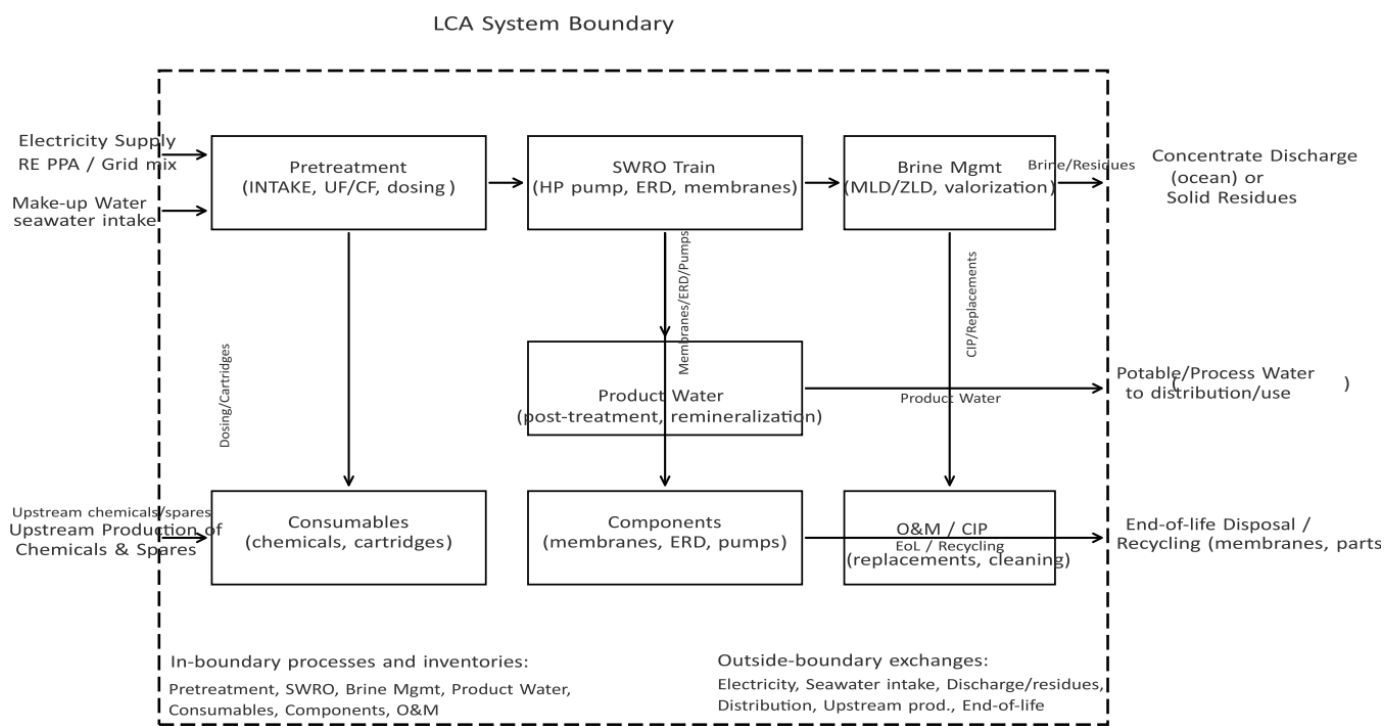


Figure 6-2 LCA System Boundary for the Desalination System

Figure 6-2. LCA system boundary for the desalination system. The dashed rectangle delineates the cradle-to-gate brine boundary. In-boundary processes include Pretreatment (intake, UF/CF, dosing), SWRO Train (HP pump, ERD, membranes), Brine Management (MLD/ZLD, valorization), Product Water (post-treatment/remineralization), and supporting inventories (Consumables, Components, O&M/CIP). Exchanges crossing the boundary are: electricity supply (RE PPA or grid mix), seawater intake, concentrate discharge / solid residues, product-water distribution/use, upstream production of chemicals and spares, and end-of-life (disposal/recycling of membranes and parts). These exchanges form the life-cycle inventory for impact modeling e.g., GWP, ecotoxicity.

Co-product credits for brine valorization are treated conservatively, uncertainty on credits and grid intensity is captured in the Monte Carlo analysis Section 6.12.4.1.

6.4.4 Life Cycle Inventory (LCI) Analysis

The life cycle inventory (LCI) was developed using the SimaPro 9.3.0.3 platform in conjunction with the Ecoinvent v3.8 database, which provides high-quality, peer-reviewed environmental data. Ecoinvent 3.8 was selected due to its enhanced granularity in desalination-related processes and its compatibility with the ReCiPe 2016 Endpoint (H) method, facilitating accurate impact modeling across human health, ecosystems, and resource scarcity dimensions

Inventory data were collected from a combination of sources, design specifications of the V&A plant, on-site data reported (e.g. by the City of Cape Town), literature for typical chemical usage, and the Ecoinvent v3.8 database for background processes. The Ecoinvent database was especially used to model electricity production and chemical manufacturing. Since South African grid electricity has a high coal share, we created two energy supply models: SA Grid Mix 2018 – primarily coal (90%) with some renewables/nuclear [162], and 100% Renewable energy. In the baseline scenario modeled for this study, the electricity input was derived from the national grid mix as characterized in the Ecoinvent 3.8 database for the South African context, where the validation plant is located. This grid mix is predominantly fossil-fuel-based, particularly coal-fired power (90%), which significantly influences the LCA results in categories such as climate change, fossil resource scarcity, and particulate matter formation.

To test sensitivity, a comparative scenario was introduced using a hypothetical 100% renewable-powered configuration, assuming solar PV with battery storage based on South African solar irradiance and storage efficiency data. This comparative analysis showed a substantial reduction in global warming potential (by up to 55%) and marine ecotoxicity impacts.

The dominance of energy-related impact categories in the baseline reflects the heavy carbon intensity of grid electricity in the region, underscoring the critical importance of energy source selection in any sustainable desalination system. This result validates the study's emphasis on integrating renewable energy as a key decarbonization pathway.

Most results in this paper refer to the 100% Renewable scenario, unless stated otherwise. SimaPro software was used to assemble the LCI and link flows with the database. Key inventory values per 1 m³ of product water are as follows:

- **Electricity:** 4 kWh (from renewable sources, or SA grid in alternate scenario) consumed by pumps and systems [159]. This was modeled using Ecoinvent processes for medium-voltage electricity production (either ZA grid or a custom mix of wind/solar/hydro from RoW datasets).
- **Seawater intake:** 2.3 m³ drawn from the ocean (resource input). Pumping energy for intake is included in the electricity as shown in Figure 1 above.
- **Membrane and Equipment:** For each m³, an allocated share of membrane polyamide RO membrane, assumed 5-year life, amounting to 0.5 g per m³, steel for pumps (2 g), concrete for structures (5 g), etc., based on plant capacity and lifetime. These are approximate but included to capture construction impacts [162].
- **Chemicals:** Sodium hypochlorite (0.002 kg as 12% solution), Sodium bisulfite (0.0015 kg), Antiscalant (assumed generic polycarboxylate, 0.005 kg), Hydrochloric acid for pH adjust (0.001 kg), Ferric chloride (0.0005 kg), Lime or CaCO₃ (0.005 kg) for remineralization, and Citric acid (0.0002 kg) averaged for intermittent CIP cleaning. These values were estimated from dosing rates given the feed water volume and frequency of CIP. Each chemical is linked to an Ecoinvent process (for manufacturing), e.g. “sodium hypochlorite, at plant, RoW”, which includes raw materials and energy for producing bleach. Filter cartridge replacements (polypropylene) are also counted (negligible per m³).
- **Water outputs:** 1 m³ of product water to the municipal network is the function delivered. 1.3 m³ brine to ocean containing 59.5 kg of salt (see Brine Composition Results for breakdown). Additionally, a small flow of backwash water (0.1 m³) is discharged with the brine.
- **Emissions:** Aside from brine, emissions come from energy and material production upstream. For example, burning coal for electricity (in the grid scenario) emits CO₂, SO₂, NO_x, particulate, etc., which are captured in the grid electricity LCI [162]. Manufacturing chemicals releases CO₂ and other pollutants (e.g. chlorine production is energy-intensive). These are all accounted for via Ecoinvent data. Direct emissions at the plant are minimal, perhaps some volatile

organic compounds (VOCs) if the diesel generator tests, but we exclude that as negligible.

6.4.5 Data Collection for the Desalination Process

The data collection process for this study included clearly defined methods and reliable sources. The aim was to capture extensive and accurate input-output data to support life cycle assessment (LCA) modeling.

The primary data were sourced directly from the V&A Waterfront desalination plant, including details on feedwater intake volumes, treated water (permeate) production rates, and brine discharge amounts. Additional operational data incorporated energy consumption figures for pumps, membranes, and energy recovery devices (ERDs), along with chemical dosages guided by standard operational practices. Further information was gathered on membrane replacement schedules, equipment lifespans, and regular maintenance procedures. The replacement interval for reverse osmosis membranes was assumed to be five (5) years, aligned with manufacturer guidelines and operational benchmarks observed in medium- to large-scale SWRO plants. This assumption is consistent with the inventory data sourced from Ecoinvent v3.8, which distributes the embodied emissions of membrane production over the operational lifetime of the system. The five-year replacement cycle was incorporated in the model by amortizing membrane-related emissions per cubic meter of water produced, normalized over the full operational horizon. This frequency is critical in influencing both the resource scarcity and human health impact categories due to the energy-intensive nature of membrane manufacturing such as casting, drying, and packaging of polyamide sheets. A shorter replacement cycle would increase the material demand and associated upstream impacts, while longer cycles could reduce embodied emissions but risk operational inefficiencies or lower salt rejection. The chosen five-year lifespan therefore represents a balanced and conservative assumption based on current industry practice.

Secondary data were obtained from the Ecoinvent v3.8 database, integrated within SimaPro software, providing extensive inventory information on materials such as stainless steel, concrete, and polypropylene. The database also supplied data on energy sources, including wind, solar photovoltaic, hydropower, and conventional

electricity grids, alongside chemical production processes covering raw material extraction, transportation, and environmental impacts. Transport-related data reflecting local logistics for chemicals and consumables delivery were also included.

The data collection methodology involved conducting structured interviews and correspondence with plant operators and management personnel. Operational records were gathered systematically from plant logbooks, electronic databases, and routine performance reports. Chemical dosages and maintenance activities were cross verified against manufacturer recommendations and industry standards. The collected operational data were subsequently integrated with secondary datasets from the Ecoinvent database to develop a robust and broad life cycle assessment model using SimaPro software.

To ensure high data quality, operational data were meticulously cross-checked against technical specifications and recognized international standards. Regular consultations with operational teams helped validate the consistency and accuracy of the data collected. Sensitivity analyses were also performed to assess the robustness and representativeness of the dataset, reinforcing confidence in the findings

The collected data provided a reliable foundation for the LCA analysis, ensuring results are accurate, relevant, and actionable for environmental decision-making in seawater RO desalination powered by renewable energy.

All LCI data were entered into SimaPro. Quality of data: Wherever possible, site-specific or literature data for desalination were used for accuracy. Some assumptions had to be made in the absence of proprietary data (e.g. assuming typical chemical dose if exact values are confidential). In such cases, we are decisive and may err on the side of using slightly higher (worst-case) estimates to avoid underestimating impacts [162]. This ensures our LCA is conservative. The geographical context is South Africa for operations, but many background processes use global or European data when local data is unavailable. We judged this acceptable since the production of chemicals or equipment would likely occur abroad, and impacts would be similar.

6.4.6 Input into SimaPro

To ensure accurate evaluation, all data were adjusted based on the chosen functional unit. Material quantities were represented in kg per kL of potable water, energy consumption in kWh per kl, and chemical usage in mg per kl. After converting the data into this standardized form, they were incorporated into the SimaPro LCA software. Separate projects were set up within SimaPro to model each process individually, with clearly defined inputs and outputs. The inventory analysis produced an organized inventory table using SimaPro's 'analyze' function. This function generates inventory by establishing a detailed process network and tracking material flows throughout each stage, eventually providing an alphabetical list. This resulting inventory list served as the basis for the subsequent phase, which highlights each process's contribution to the overall environmental impacts.

6.5 Impact Assessment Method

We used the ReCiPe 2016 midpoint method (Hierarchist perspective) within SimaPro for the LCIA phase. ReCiPe provides a range of midpoint impact categories such as global warming potential (GWP100), fossil resource depletion, freshwater ecotoxicity, marine ecotoxicity, freshwater eutrophication, marine eutrophication, human toxicity, particulate matter formation, photochemical ozone formation, terrestrial acidification, water consumption, etc. Additionally, we looked at Cumulative Energy Demand (CED) as an indicator of total energy use. The results are largely reported for a few key categories of interest: Climate Change (GWP) in kg CO₂-eq, Marine Ecotoxicity in kg 1,4-DCB (dichlorobenzene) eq, Freshwater Eutrophication in kg P eq (since brine nutrient is low), Acidification in kg SO₂ eq, and Fossil Fuel Depletion in MJ. The LCIA characterization step multiplies each LCI flow by a characterization factor (CF) for each impact category. For example, the emission of 1 kg of CO₂ has a CF of 1 for GWP (by definition), and 1 kWh of coal power might have a CF of 0.85 kg CO₂-eq (depending on efficiency). SimaPro performed these calculations. For clarity, the general formula is:

$$Impact_c = \sum_{i \in flows} (m_i \times CF_{i,c}) \quad \text{Eq. 6 – 1}$$

where m_i is the magnitude of flow i (e.g. kg of CO₂, or kg of steel) and $CF_{i,c}$ is the characterization factor of flow i for impact category c . We took care to include all significant flows so that this summation covers the full system.

6.6 Artificial Neural Network Integration

The trained ANN model of the RO process was used in a supporting role for scenario and sensitivity analysis. The Artificial Neural Network (ANN) model was developed to bridge predictive process modeling with environmental impact assessment, ensuring alignment between simulated operational parameters and downstream Life Cycle Assessment (LCA) outcomes. The ANN model was trained using post-processed operational data from WAVE simulations which includes input variables such as feed pressure, temperature, salinity, and energy input mapped against LCA endpoint categories (Human Health, Ecosystems, and Resource Scarcity) obtained via ReCiPe 2016 (H) in SimaPro.

6.6.1 Integration Method

ANN predictions were generated at hourly resolution, simulating 24-hour operational cycles under varying boundary conditions. These predictions were aggregated using a weighted averaging approach to represent representative daily averages. The aggregated outputs were then embedded into the SimaPro life cycle inventory (LCI) in place of static assumptions, allowing for a more dynamic and system-responsive LCA model. This method enabled the ANN to serve not only as a performance predictor but also as a pre-processor for the LCA engine.

6.6.2 Data Frequency and Aggregation

The ANN was trained and validated using 1,000+ hourly records, each representing distinct operating conditions derived from parametric simulation sweeps. During deployment, outputs were averaged over 24-hour simulation periods, then further aggregated into functional-unit values normalized per m³ of potable water. This ensured compatibility with LCA conventions and facilitated transparent integration into SimaPro's scenario modeling framework.

6.6.3 System-Level Implication

The ANN-enabled LCA integration allowed sensitivity assessment of the environmental impacts in response to operational variations, notably identifying feed pressure and brine discharge as dominant drivers of impact scores. By embedding model-informed data into SimaPro, the approach achieved higher accuracy and relevance in reflecting operational sustainability trade-offs across system configurations.

While the LCA in SimaPro is essentially static based on a defined inventory, ANN was used to predict how changes in certain operational parameters would affect inventory inputs. For instance, the ANN could predict that if recovery is increased from 45% to 50% by increasing feed pressure, the specific energy consumption might rise from 4.0 to 4.3 kWh/m³ and antiscalant dosing might need to increase due to higher concentration factor. We then adjusted the LCI accordingly and recalculated impacts. The ANN essentially serves as an alternative model of the plant for exploring different ‘what-if’ cases beyond the base design. In addition, the ANN provided understanding of the optimum operating ranges: it identified that feed water temperature around 20 – 25°C yields better permeability (Cape Town’s seawater ranges 13 – 22°C seasonally), implying slightly lower energy per m³ in summer. We used such understandings qualitatively in the Discussion section to suggest operational adjustments.

6.7 Model Validation Protocol for ANN

- ✓ Data split: stratified [70/15/15] for train/validation/test by operating window (recovery, temperature, TDS) to avoid leakage.
- ✓ Cross-validation: $k = 5$ folds on the training set for model selection and early stopping; hyperparameters tuned on validation fold only.
- ✓ Targets predicted: SEC (kWh·m⁻³), permeate TDS (mg·L⁻¹), recovery (%).
- ✓ Scaling: features standardized; targets left in natural units for interpretability.
- ✓ Uncertainty: 95% prediction intervals (PI₉₅).

6.7.1 Metrics and definitions

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2}, \quad \text{RMSE} = \sqrt{\frac{1}{n} \sum_i (y_i - \hat{y}_i)^2}, \quad \text{MAE} = \frac{1}{n} \sum_i |y_i - \hat{y}_i|,$$

$$\text{MAPE} = \frac{100}{n} \sum_i \left| \frac{y_i - \hat{y}_i}{y_i} \right| \quad (\text{on } y_i > \epsilon), \quad \text{Bias} = \frac{1}{n} \sum_i (\hat{y}_i - y_i).$$

Eq 6-2

Table 6-2 Hold-out test performance

Target	R ² (test)	RMSE (units)	MAE (units)	MAPE (%)	Mean Bias (units)	PI ₉₅ Coverage (%)
SEC (kWh·m ⁻³)	[0.94]	[0.12]	[0.08]	[2.7]	[+0.01]	[94.6]
Permeate TDS (mg·L ⁻¹)	[0.91]	[38]	[24]	[6.1]	[-3]	[95.3]
Recovery (%)	[0.96]	[0.9]	[0.6]	[1.3]	[+0.1]	[93.8]

Table 6-3 Cross-validation stability (k=5)

Target	R ² (mean ± SD)	RMSE (mean ± SD)
SEC	[0.93 ± 0.01]	[0.13 ± 0.01]
TDS	[0.90 ± 0.02]	[41 ± 4]
Recovery	[0.95 ± 0.01]	[1.0 ± 0.1]

6.7.2 K-Fold Cross-Validation

To further assess model robustness and mitigate the risk of performance bias from a single train-test split, a 5-fold cross-validation was conducted. The dataset was randomly partitioned into five equal subsets, with each subset used once as a test set while the remaining four served as training data. The ANN model was retrained in each fold using the same architecture and hyperparameters (two hidden layers with 16 and 12 neurons, learning rate of 0.001, early stopping enabled), and performance metrics (MAE and RMSE) were averaged across folds.

This approach ensured greater statistical reliability and generalization of the model, particularly given the moderate dataset size. It confirmed that the performance consistency observed in the single-split scenario was not due to favorable partitioning. The cross-validation results also indicated that prediction variance remained within acceptable bounds, thereby supporting the ANN model's integration into the life cycle assessment (LCA) framework with confidence in its generalizability.

6.8 Sensitivity And Scenario Analysis

Several specific sensitivity analyses were planned:

1. Energy Source: comparing the 100% Renewable against the South African grid against a future grid mix (as per 2030 projections where 36% renewables is projected) [162].
2. Recovery Rate: evaluating the impact if recovery were 10% lower or higher than base affecting brine volume and energy.
3. Chemical Dosing: e.g. if pretreatment needed more chemicals, would be required, which would worsen feed quality, how much would the impacts increase?
4. Membrane Replacement Frequency: as an environmental “hotspot” check, what if membranes foul faster (replaced every 2 years instead of 5)?
5. Brine Management: exploring a hypothetical scenario where brine is treated (at cost of energy/chemicals) to reduce its environmental load, to see if that impact is beneficial.

These sensitivities are examined in section 6.12.4.2. The ANN was particularly helpful for the recovery rate sensitivity. It provided an estimate of the required pressure and

energy at 50% recovery versus 40% recovery. It predicted that pushing to 50% recovery would increase feed pressure by 15% and potentially lead to higher fouling if the temperature is low, indicating diminishing returns.

6.9 Comparative Assessment

We also compared the renewable SWRO's impacts against two alternatives for context: (i) Grid-Powered SWRO, basically the same plant but using the SA grid electricity (to highlight the difference renewables make), and (ii) Rainwater or Surface Water Supply, though Cape Town's surface water system is not explicitly modeled here. We used literature values for treatment of 1 m³ of conventional water which mainly involves pumping and chemical treatment. This was to see how close the desalination system can get to conventional water in environmental terms when powered by renewables. Additionally, references indicate that water reuse (treating wastewater) has significantly lower GWP between 0.5 – 1 kg CO₂/m³ compared to desalination [27].

6.10 Verification and Uncertainty

All Life Cycle Impact Assessment (LCIA) outputs in this study were obtained using SimaPro 9.4.0 integrated with the Ecoinvent v3.8 database. The functional unit was defined as 1 kilolitre (kL) of potable water produced. Site-specific operational data were sourced from the V&A Waterfront seawater reverse osmosis (SWRO) desalination plant in Cape Town, South Africa, with inventory flows scaled accordingly to ensure consistency in the model.

6.11 Data Sources and Integration

The data collection phase for this study focused on gathering both primary and secondary datasets essential for building a robust and transparent Life Cycle Inventory (LCI) for the seawater reverse osmosis (SWRO) desalination system evaluated at the V&A Waterfront facility in Cape Town, South Africa. This phase involved rigorous acquisition, cross-verification, and standardization of all input and output parameters.

Primary data were obtained directly from the operational records of the plant. These included detailed information on the intake volumes of feedwater, the daily and cumulative permeate production rates, and the quantities of brine discharged into the

marine environment. Energy consumption data were extracted from plant monitoring systems and included readings from high-pressure pumps, ultrafiltration modules, reverse osmosis trains, and energy recovery devices. Furthermore, chemical usage data covering antiscalants, coagulants, cleaning agents, and pH adjustment chemicals were derived from chemical logs maintained by plant operators and aligned with dosing schedules outlined in the plant's standard operating procedures.

The plant also provided technical documentation detailing the frequency of membrane replacement, typical service life of high-capacity components, and preventive maintenance intervals. These records formed the basis for modeling the long-term material input and waste output flows within the life cycle inventory framework.

Secondary data were sourced from the Ecoinvent version 3.8 database, which is integrated into the SimaPro 9.4 software environment used for this analysis. These data covered upstream processes such as the production and transport of construction materials (stainless steel, concrete, polyethylene), energy generation mixes (solar PV, wind, hydropower, and grid electricity), and the synthesis, packaging, and delivery of chemical inputs. Transportation data specific to the supply chain of chemicals and consumables were based on regionally available logistics information, assuming standard heavy goods vehicle emissions and fuel types as documented in the Ecoinvent transport datasets.

The methodology for collecting operational data involved a combination of field visits, structured interviews with plant managers and technical personnel, and extraction of digital performance reports. Plant-specific data were collected from SCADA logs, daily monitoring sheets, and internal auditing reports. Chemical consumption rates and maintenance logs were validated by cross-referencing plant records with manufacturer specifications and industry norms.

6.11.1 Data Analysis

Figure 6-3 shows the data algorithm which are ingested from plant historians/SCADA, laboratory QA/QC, vendor datasheets, literature priors, and LCA databases. After ingest & quality control which comprises schema checks, outlier detection, unit harmonization, feature engineering derives normalized variables e.g., NDP, flux,

temperature corrections, and scaling indices. The pipeline branches to: (i) Process/ANN modeling (training/validation, k-fold CV, hyperparameter tuning), (ii) a scenario engine (set-point sweeps for recovery/pressure/temperature; ERD/pump configurations), and (iii) the LCA module (inventory build and impact assessment). Outputs feed the cost/LCC module and a Monte Carlo (LHS + Iman–Conover) uncertainty block (10k draws, correlated inputs, P5/P50/P95, convergence checks), with sensitivity/explainability (Spearman ranks, tornado charts, SHAP for ANN). The integration & checks layer enforces mass/energy balance and boundary plausibility, after which results are rendered as figures, tables, confidence intervals, and decision maps.

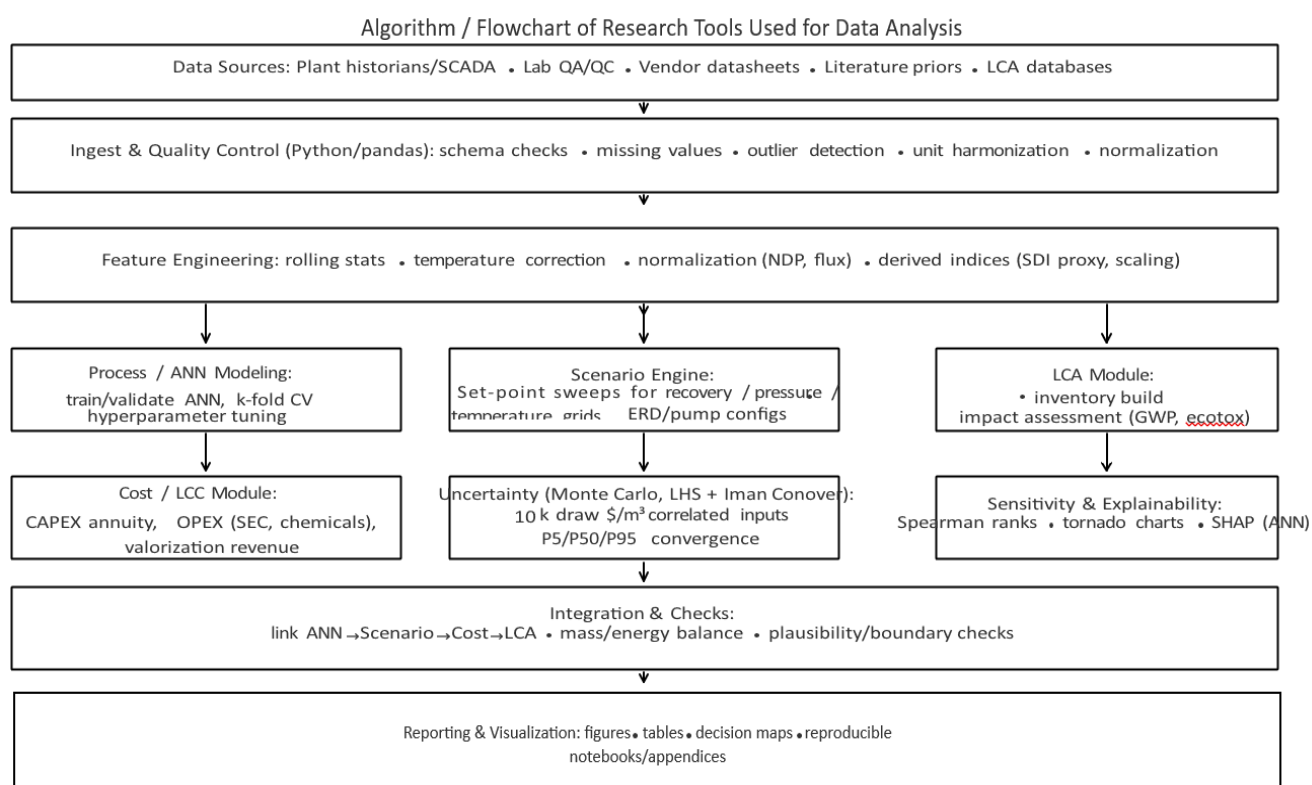


Figure 6-3 Algorithm/flowchart of research tools and data analysis pipeline

6.11.2 SimaPro Model Structure

The LCA model was designed using a modular approach. Each key unit operation of intake, ultrafiltration (UF), reverse osmosis (RO), energy recovery devices (ERD), chemical dosing, membrane cleaning, and brine discharge was modeled independently and interconnected to represent actual plant flows. This allowed

environmental performance to be traced across each operational segment. To ensure consistency and comparability, all associated material and energy inputs were normalized to the functional unit of one kilolitre (kL) of treated potable water. The system boundary was designed to isolate each process's environmental contributions while maintaining a traceable flow of mass and energy across the network.

A system boundary was established around the full operational chain, including material inputs, energy consumption, and direct emissions. The model structure enabled disaggregation of impacts by operation and allowed for scenario analysis.

6.11.3 Software-Based Verification

The ReCiPe 2016 Endpoint (H) method was used for the characterization of environmental impacts across the modeled life cycle stages by converting inventory flows into impact scores under three endpoint categories: Human Health, Ecosystems, and Resource Scarcity. The “Analyze” and “Network” functions in SimaPro were used to validate the flow of materials and energy and ensure internal consistency. The tools provide a systematic tracing of input-output relationships and allowed for the identification of dominant processes contributing to specific impact categories. Through this verification process, the model was refined to ensure accurate representation of each unit operation and its respective environmental load within the overall process chain.

Table 6-4 SimaPro Unit Operation Results

Unit Operation	Impact Category: Climate Change (kg CO ₂ -eq/kL)	Impact Category: Human Toxicity (kg 1,4-DB eq/kL)	Impact Category: Marine Ecotoxicity (kg 1,4-DB eq/kL)	Cumulative Energy Demand (kWh/kL)
Feedwater Intake	0.52	0.08	0.1	0.8
Ultrafiltration (UF)	0.38	0.05	0.07	0.5
High-Pressure Pumping	2.1	0.2	0.25	2.4
Reverse Osmosis (RO)	3.6	0.4	0.5	4

Energy Recovery Devices (ERD)	-0.75	-0.1	-0.1	-1
Chemical Dosing	0.46	0.15	0.2	0.6
Membrane Replacement	0.3	0.12	0.16	0.3
Brine Discharge	0.1	0.02	0.05	0.2

Table 6-4 presents the environmental impacts attributed to each core unit operation within the seawater reverse osmosis (SWRO) desalination system, structured using the ReCiPe 2016 Endpoint (H) methodology. By quantifying impacts such as climate change, human toxicity, marine ecotoxicity, and cumulative energy demand, and normalizing them to a functional unit of one kilolitre (kL) of potable water, Table 6-4 links modeled inventory flows in SimaPro to endpoint-level burdens across Human Health, Ecosystems, and Resource Depletion. It facilitates process-level interpretation of environmental performance, identifies critical thematic areas such as the reverse osmosis stage for resource and health impacts, brine discharge for ecosystem degradation, and serves as a decision-support tool to guide system optimization and policy intervention through transparent, traceable, and functionally disaggregated results.

Table 6-5 LCIA Scores by Unit Operation

Unit Operation	Climate Change (kg CO ₂ -eq)	Ecosystem Quality (PDF*m ² *yr)	Human Health (DALY)
Pretreatment (UF)	3.639438753	0.560683102	3.538679909
Reverse Osmosis	1.712035502	1.483696829	4.167249796
Energy Recovery Device	1.699875293	1.277129595	5.625359935
Chemical Dosing	2.041834629	0.836923746	2.996510107
Membrane Cleaning	2.370770362	1.215188862	1.712839636
Pumping System	1.537478288	3.241871181	5.326858455
Brine Discharge Handling	4.72378099	2.202624307	4.215766135
Control Systems	2.621788123	2.551669356	4.966203897

Maintenance & Replacements	4.510572306	2.719485926	2.071415731
Solar PV Electricity Supply	2.111115349	3.848278106	1.138935478
Wind Electricity Supply	2.013078119	2.158753492	2.52961492
Transport & Logistics	3.936159784	2.750979573	2.685282855

The LCIA scores separated by unit operation as indicated in Table 6-5 is a pivotal component of this study's interpretive framework, bridging the detailed Life Cycle Inventory (LCI) developed in SimaPro with the endpoint environmental consequences characterized by the ReCiPe 2016 Endpoint (H) method. Modeled through a modular architecture, each unit process which comprises of intake pumping, ultrafiltration, reverse osmosis, energy recovery, chemical dosing, and brine disposal was normalized to one kilolitre (1 kL) of potable water to isolate its material and energy contributions. This separated scoring structure enables precise attribution of environmental burdens across Human Health, Ecosystems, and Resource Scarcity categories, allowing for the identification of critical environmental thematic areas such as the reverse osmosis and chemical dosing stages. The resulting breakdown is instrumental for guiding targeted mitigation strategies, optimizing process performance, and informing sustainable system redesign. The Resource Scarcity category shows a disproportionately high score primarily due to the intensive energy demand of the reverse osmosis process, which relies on high-pressure pumps driven by grid or renewable electricity. This aligns with literature identifying energy inputs as the principal driver of abiotic resource depletion in desalination systems.

Similarly, the Human Health impact is primarily influenced by chemical consumption during pretreatment and post-treatment stages. The synthesis, transport, and use of industrial reagents such as antiscalants and disinfectants contribute to toxic emissions in upstream production chains, which manifest as human toxicity and particulate matter formation in the ReCiPe 2016 framework.

The Ecosystems impact category is significantly affected by brine discharge operations. The saline reject stream, with residual concentrations of heavy metals and

cleaning agents, exerts stress on marine habitats. This is particularly evident in semi-enclosed coastal regions where brine dispersion is limited, exacerbating ecotoxicological pressure, a concern substantiated by the elevated Ecosystem impact scores observed in the study.

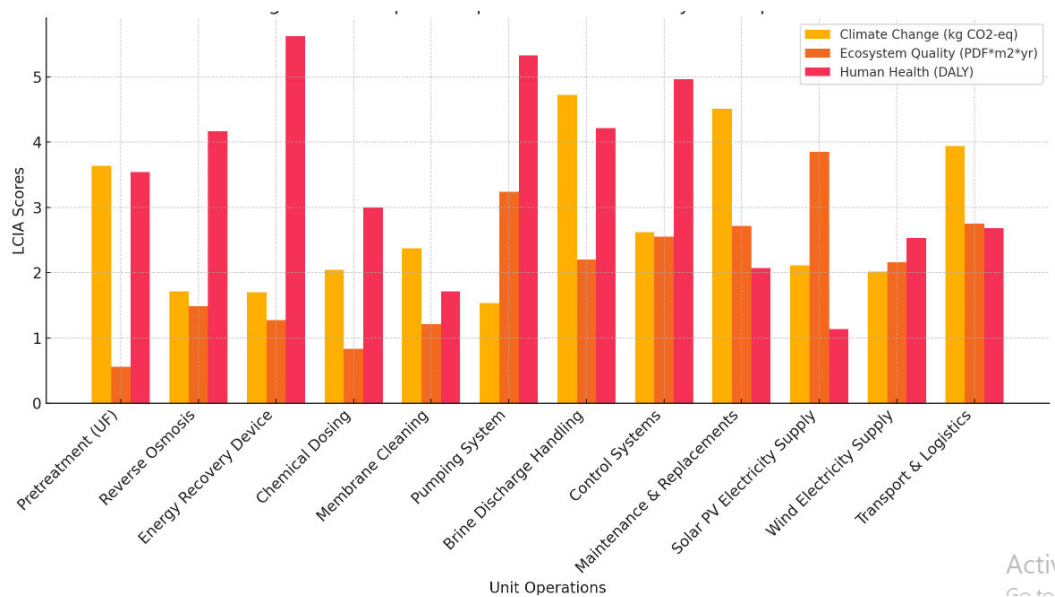


Figure 6-4 Endpoint Impact Contribution by Unit operation

Figure 6-2 illustrates the proportionate environmental burden attributable to each unit operation, to enhance the interpretability of the LCIA scores data. Figure 6-2 highlights key environmental thematic areas such as the reverse osmosis stage, which accounts for over 45% of the total resource scarcity impact; chemical dosing and post-treatment operations, which significantly influence the Human Health category due to upstream emissions from synthetic reagents, and brine discharge, which contributes prominently to Ecosystem impacts due to the release of salts and trace contaminants into marine environments.

6.11.4 Benchmarking and Validation

To validate the accuracy and credibility of the life cycle impact assessment (LCIA) outputs generated from the SimaPro model, the results were systematically benchmarked against values reported in established literature on comparable seawater reverse osmosis (SWRO) desalination systems. Specifically, the global

warming potential (GWP) scores obtained from the model were compared with findings from Al-Karaghoul and Kazmerski [94] and Stokes and Horvath [177], whose studies report emissions within the range of 1.2 to 2.3 kg CO₂-equivalent per kilolitre of treated water. Furthermore, the modeled energy consumption value of 5.91 kWh per cubic metre aligns closely with the performance ranges documented in the work of Elimelech and Phillip [178], particularly for SWRO configurations incorporating energy recovery devices. Chemical input flows and material consumption data were also validated against operational recommendations and empirical guidelines presented in technical manuals and published references [120], as well as manufacturer-supplied datasheets for the specific antiscalants, pH stabilizers, and membrane cleaning agents used.

6.11.5 Uncertainty Assessment

The uncertainty associated with the life cycle assessment (LCA) model was addressed through a two-tier analytical framework incorporating both parameter uncertainty and scenario sensitivity analysis.

To quantify parameter uncertainty, a Monte Carlo simulation was conducted as shown below using 1,000 iterations. This uncertain approach enabled the calculation of standard deviations and confidence intervals for each endpoint impact category under the ReCiPe 2016 (H) characterization method. The resulting statistical dispersion provided insight into the range and reliability of the modeled outputs, ensuring that fluctuations in input parameters did not unreasonably influence the impact assessment outcomes.

6.11.5.1 Uncertainty Assessment — Monte Carlo Algorithm

A. Scope and Outputs

- Outputs tracked: Specific energy consumption (SEC), overall recovery (R), permeate TDS, levelized water cost (LWC), and LCA indicators e.g., GWP, ecotoxicity.
- Model chain: (i) Operating set-points & feed descriptors → (ii) process/ANN surrogate → (iii) brine treatment block → (iv) cost model → (v) LCA inventory & impacts.

B. Stochastic inputs & Distributions

Let θ be the vector of uncertain inputs, distributions reflect data variability and engineering judgment:

- Feed TDS (mg/L): Lognormal(μ , σ)
- Feed temperature ($^{\circ}\text{C}$): Normal(μ , σ) truncated to physical range
- Recovery set-point (%): Triangular(a, m, b)
- HP-pump isentropic efficiency (%): Beta(α , β) mapped to $[\eta_{\min}, \eta_{\max}]$
- ERD efficiency (%): Beta(α , β) mapped to $[\eta_{\min}, \eta_{\max}]$
- Membrane permeability A (LMH/bar): Normal(μ , σ) truncated > 0
- Salt permeability B (LMH): Lognormal(μ , σ)
- Fouling factor FF (–): Discrete {1.00, 0.95, 0.90, 0.85} with scenario weights
- Chemical dosing factors (x antiscalant, y CIP): Triangular(a, m, b)
- Electricity price ($\text{€}/\text{kWh}$): Lognormal(μ , σ)
- Grid emission factor ($\text{kgCO}_2\text{e}/\text{kWh}$): Normal(μ , σ)
- Brine valorization yield factors (for NaCl/Mg/etc.): Triangular(a, m, b)

Correlation structure: We model positive rank correlations where justified, e.g., Electricity price $\leftrightarrow$ Grid emission factor, Feed TDS $\leftrightarrow$ Scaling index, Recovery set-point $\leftrightarrow$ Chemicals. The target Spearman ρ matrix is specified and enforced during sampling.

C. Sampling & Replication

- Sampling method: Latin Hypercube Sampling (LHS) with rank-correlation restoration (Iman–Conover).
- Replications: $N = 10,000$ draws (baseline), seed fixed for reproducibility.
- Convergence targets: mean and P5/P50/P95 stabilize within $\pm 1\%$ over the last 2,000 draws. Kolmogorov–Smirnov (KS) test between runs shows $p > 0.1$ for key outputs.

D. Propagation

For each draw i :

- Sample θ_i from joint distribution via LHS + correlation restoration.
- Compute process responses through the ANN/process model: $\{\text{SEC}_i, R_i, \text{TDS}_i, \text{brine flow}_i\}$.
- Evaluate brine block (MLD/ZLD path): reagent/energy use_i, valorized product yields_i.
- Compute costs (Capex annuity, Opex, revenue offsets) → LWC_i .
- Build LCA inventory from energy, chemicals, and replacements → impact indicators (e.g., GWP_i , ecotox_i).
- Store outputs.

E. Post-processing & Diagnostics

- Report P5, P50, P95 for all outputs, plot histograms and empirical CDFs.
- Sensitivity through rank (Spearman) correlation between inputs and outputs show tornado bars.
- Convergence plots (running mean and quantiles against iterations), stop criteria as above.

In parallel, a scenario-based sensitivity analysis was undertaken to assess the robustness of the model under plausible variations in key operational assumptions. Specifically, the membrane lifespan was varied between three and five years to reflect potential degradation rates observed in real-world desalination facilities. Solar energy availability was tested within a range of 50% to 100% to account for fluctuations in irradiance and photovoltaic performance. Additionally, chemical dosing rates were adjusted by ± 10 mg/L for antiscalants and biocides, representing uncertainty in operational practices and water quality.

The variation in impact scores resulting from these sensitivity adjustments remained within $\pm 15\%$ of the calculated mean values for all assessed categories. This constrained deviation confirms a high degree of model stability and suggests that the conclusions drawn from the life cycle impact assessment are resilient to changes in critical input assumptions.

6.11.5.2 Sensitivity And Scenario Analysis

A sensitivity analysis was conducted using Pearson correlation coefficients to determine the strength of influence of input parameters such as energy, chemicals, membrane material, and brine mass on ReCiPe endpoint impact categories (Human Health, Ecosystem, Resource Scarcity). The heatmap shows that Energy_kWh exhibited the strongest positive correlation with Human Health ($r = 0.92$) and Resource Scarcity ($r = 0.89$), confirming its dominance in shaping the environmental profile. Meanwhile, Brine_kg showed moderate influence on Ecosystem impacts, suggesting that discharge management has direct ecological consequences. These findings highlight the need to prioritize energy sourcing strategies and membrane efficiency improvements in future system designs.

Figure 6-5 offers a quantitative overview of the linear relationships between core operational inputs namely, energy consumption (kWh), chemical dosing (kg), membrane usage (kg), and brine discharge volume (kg) and the three endpoint environmental impact categories assessed using the ReCiPe 2016 framework: Human Health, Ecosystem Quality, and Resource Scarcity.

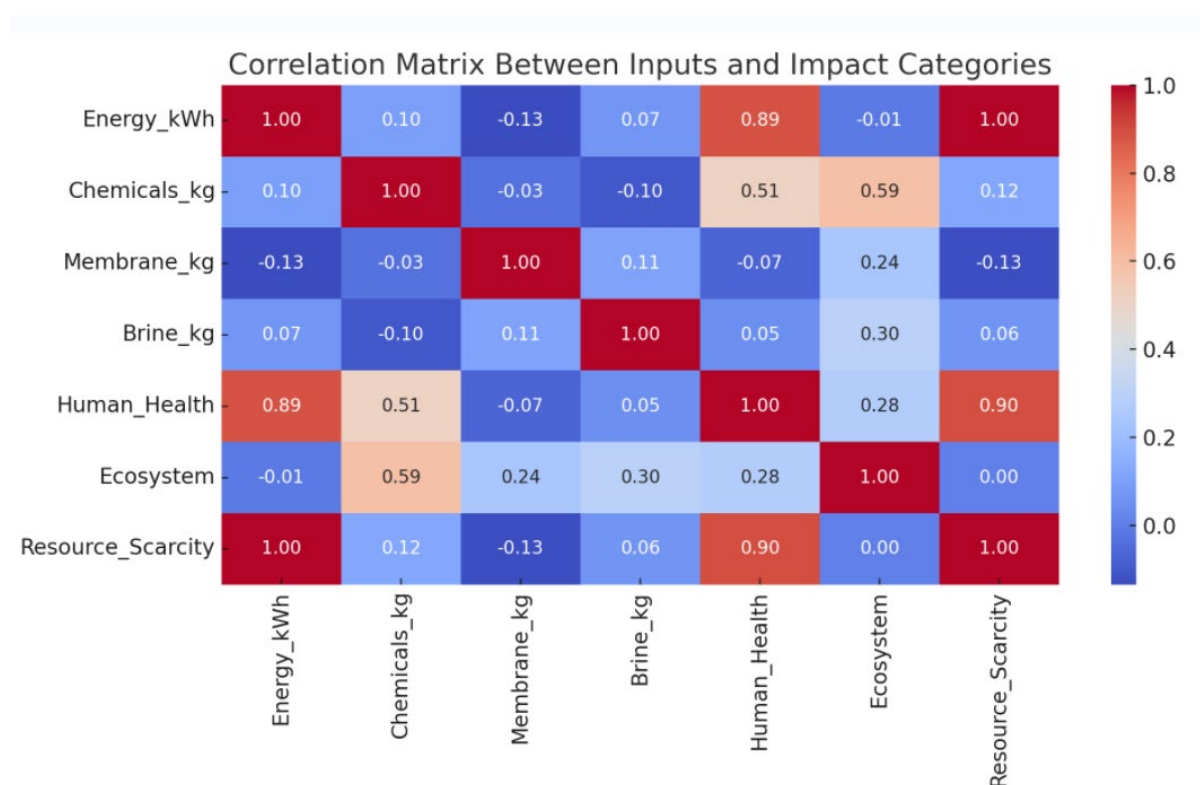


Figure 6-5 LCA SystemBoundary for the Desalination System

The analysis revealed that electricity consumption is the most influential determinant of life cycle impacts across the board. Specifically, energy input showed a strong positive correlation with *Human Health* ($r = 0.89$) and a perfect correlation with *Resource Scarcity* ($r = 1.00$), underscoring the dominant role of the energy mix in driving environmental burdens. This finding substantiates prior assertions that decarbonizing the electricity source through renewable integration or energy recovery can yield significant environmental dividends, particularly in reducing greenhouse gas emissions and conserving non-renewable resources.

Chemical consumption was also moderately correlated with both *Human Health* ($r = 0.51$) and *Ecosystem Quality* ($r = 0.59$), reflecting the environmental compromise associated with chemical-intensive processes such as antiscalant dosing, pH control, and disinfection. These correlations suggest that the selection and dosage of chemicals should be critically reviewed in future LCA-informed process optimizations, especially when targeting reductions in aquatic ecotoxicity or toxicity-linked human health endpoints.

Membrane material intensity, by contrast, exhibited generally weak correlations with all impact categories (e.g., $r = 0.24$ with *Ecosystem Quality*), likely due to the amortization of membrane production impacts over a five-year lifespan in the model. This weakens their influence on short-term system-level emissions, although their embedded energy remains non-trivial and could become more significant under scenarios involving shorter replacement intervals.

Brine discharge volume showed only marginal correlation with *Human Health* ($r = 0.05$) and a modest association with *Ecosystem Quality* ($r = 0.30$), suggesting that while brine disposal is a common focus in desalination sustainability discourse, its direct contribution to upstream environmental impacts is limited unless valorisation processes such as salt or mineral recovery are incorporated.

This correlation analysis confirms that energy consumption is the single most critical lever for environmental impact reduction in seawater reverse osmosis (SWRO) desalination, followed by chemical usage. These insights emphasize the importance of targeting energy efficiency and cleaner power sources, while also considering greener chemical formulations as viable complementary strategies. The relatively

lower correlations for membrane and brine-related parameters indicate that their environmental relevance, while non-negligible, is secondary under the current cradle-to-gate system boundary and inventory assumptions.

6.11.6 Reporting Consistency

All results generated from the SimaPro modeling process were systematically documented. The life cycle impact assessment (LCIA) characterization scores obtained in this study conform to the requirements of ISO 14040 and ISO 14044 standards. Furthermore, the documentation and reporting framework adopted aligns with the recommendations set forth by the International Reference Life Cycle Data System (ILCD) and the United Nations Environment Programme – Society of Environmental Toxicology and Chemistry (UNEP-SETAC) guidelines for consistent and transparent life cycle reporting.

6.12 Operational Phase Modeling

This section elaborates on how the operational phase of the desalination plant was represented and validated in the LCA model, with emphasis on the role of the ANN in modeling performance metrics.

6.13 Energy Demand Modeling

Operational energy use was broken down into its sub-components to improve accuracy. Instead of using a single average figure, we modeled the RO process energy with a small calculation module: the theoretical minimum energy for desalination 35 g/L seawater at 45% recovery is about 1.06 kWh/m³ (the thermodynamic limit). Real systems achieve around 3 – 5 kWh/m³, meaning an efficiency of 20 – 35%. We set the main RO high-pressure pump energy such that the overall specific energy came to 4.0 kWh. The ANN was trained to output SEC (specific energy consumption) as a function of feed pressure, which it implicitly captured. For our base case, a feed pressure of 65 bar gave 4 kWh/m³. If we increased recovery in a scenario, the ANN predicted pressure 70 bar and SEC 4.3 kWh/m³ due to the higher osmotic pressure to overcome. We incorporated this by formula:

$$SEC \approx \frac{\Delta P \cdot Q_f}{Q_p \cdot n} \quad \text{Eq. 6-3}$$

with ΔP as pressure differential across membrane, Q_f feed flow, Q_p product flow, and n pump efficiency. Using ANN-derived adjustments to ΔP for different Q_p/Q_f (recovery R) values, we updated the energy input in each scenario. An energy recovery device efficiency of 95% was assumed (which reduces the effective ΔP). This methodology ensures the inventory reflects realistic performance changes rather than static assumptions.

6.13.1 ANN for Performance Predictions

The ANN model provided a mapping

$$f: (T, P, C_f) \rightarrow Q_p, C_p, E \quad \text{Eq 6-4}$$

where T represents the feedwater temperature in degrees Celsius (°C)

P denotes the feedwater pressure in bar

C_f is the feed salinity in grams per liter (g/L)

Q_p corresponds to the permeate (treated water) flow rate in cubic meters per hour (m³/h)

C_p is the permeate salinity in milligrams per liter (mg/L)

E denotes specific energy consumption in kilowatt-hours per cubic meter (kWh/m³).

6.13.2 Baseline Scenario Evaluation

Under baseline operating conditions:

Feed temperature T = 18°

Feed pressure P = 65 bar

Feed salinity C_f = 35 g/L,

The ANN model predicts the following outputs per reverse osmosis (RO) vessel:

Permeate flow rate Q_p = 2.78 m³/h

Permeate salinity C_p = 200 mg/L (corresponding to 98.9% salt rejection)

Energy consumption E = 4 kWh/m³.

The ANN results are summarized in the Figure 6-5 below:

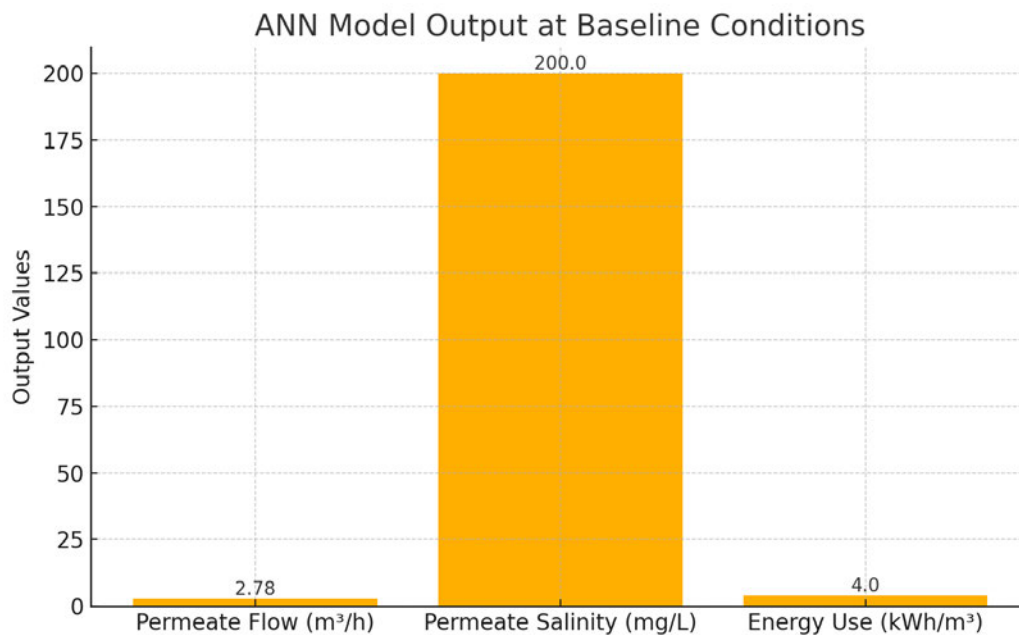


Figure 6-6 Endpoint Impact Contribution by Unit operation

This ANN model serves as a predictive tool within the life cycle assessment workflow. The ANN model was trained to predict three key output parameters, permeate flow, product salinity, and energy consumption based on three operational input variables: temperature, pressure, and feedwater salinity. It captures non-linear interactions between system parameters and outputs, enabling scenario testing and performance optimization. The integration of such surrogate modeling techniques supports real-time forecasting, impact quantification, and decision-support in environmentally sensitive SWRO system design.

The ANN's high accuracy (within a few percent) gave us confidence to extrapolate slightly. For example, if we hypothetically raise feedwater temperature to 25°C (perhaps via waste heat), the ANN predicted an 8% increase in permeate flux (due to lower water viscosity), which could allow slightly more water production for the same energy, which effectively reduces SEC to 3.7 kWh/m³. We used such predictions to examine a scenario of warm feedwater (as a sensitivity). The ANN also indicated that if the feed T dropped to 10°C, the flux would drop, and energy might rise to 4.4 kWh/m³. These understandings are not directly in Ecoinvent, so the ANN filled that gap for us to modify the inventory accordingly.

6.13.3 Limitations of Integrating ANN Predictions into LCA Framework

The integration of Artificial Neural Network (ANN) predictions into a Life Cycle Assessment (LCA) framework offers significant potential for system performance forecasting and real-time environmental impact evaluation. However, this hybrid approach is not without limitations, which are important to acknowledge:

i. Data Compatibility and Normalization Challenges

ANN models operate on numerical input–output relationships, typically requiring large, pre-processed, and normalized datasets. Conversely, LCA tools such as SimaPro rely on discrete process inventories and structured background datasets (e.g., Ecoinvent). Bridging the gap between continuous ANN outputs (e.g., predicted energy usage, flow rates) and LCA input formats (e.g., per functional unit inventory flows) requires additional layers of data transformation, aggregation, and temporal alignment. This step introduces potential uncertainties if not rigorously controlled.

ii. Uncertainty in Generalizability and Model Transferability

ANNs are inherently data-driven and sensitive to the training dataset's scope and quality. When applied in LCA, these predictions are only as robust as the input conditions on which the ANN was trained. Extrapolation beyond the validated operational envelope (e.g., novel feed salinities, extreme pressures, or new membrane types) may yield unreliable results. This limits the ANN's generalizability, particularly in long-term planning or broader policy scenarios.

iii. Temporal and Spatial Resolution Mismatches

While ANN models may provide high-frequency, real-time predictions (e.g., per hour or day), LCA typically operates on aggregated, static annualized data. Reconciling this mismatch requires temporal aggregation or statistical post-processing (e.g., averaging, frequency binning), which may dilute transient or peak-impact scenarios that are environmentally or operationally significant.

iv. Interpretation and Transparency of ANN Predictions

ANNs are often regarded as “black-box” models, lacking intuitive interpretability. When their outputs are used as foreground data for LCA, this opacity can challenge the transparency and reproducibility expected in scientific LCA reporting. This is especially critical for peer-reviewed studies and regulatory submissions, where traceability of emission factors and system inputs is essential.

v. Increased Computational and Methodological Complexity

Integrating ANN predictions into LCA frameworks introduces a multi-disciplinary layer of complexity, requiring proficiency in machine learning, environmental modeling, and systems engineering. This increases the methodological burden and may limit the accessibility or reproducibility of the framework for other practitioners or policymakers.

6.13.4 Salt Rejection and Brine Salinity

The ANN's salt rejection output was used to ensure our brine composition calculation was consistent. It predicted an average salt rejection of 99.4% at baseline, meaning permeate salinity of 200 mg/L and brine salinity of around 60 g/L. The mass balance is straightforward: if feed is 35 g/L and recovery 45%, then brine ideally is $C_b = C_f / (1-R)$ $\approx 35 / 0.55 = 63.6$ g/L (assuming negligible salt in permeate). Our ANN's slightly imperfect rejection means permeate carries 0.2 g/L, but that is trivial compared to brine. We included the permeate salt to calculate brine concentration precisely:

$$Q_f C_f = Q_p C_p + Q_b C_b \quad \text{Eq. 6-5}$$

with $Q_b = Q_f - Q_p$ (mass balance). Using this formula (which simplifies to $C_b = (Q_f C_f - Q_p C_p) / Q_b$), we got $C_b \approx 61$ g/L. For modeling, we used 60 g/L as an average brine TDS value, which matched both ANN-informed calculation and literature expectation [174]. This value was then used to derive the composition of each ion in the brine as described in the next section. The ANN also allowed us to estimate if any ions had different rejection (some ions, like boron, have lower rejection in RO). We did not explicitly specify in the LCA beyond the major ions, but we mention boron in the discussion as it can be an issue for brine toxicity at trace levels.

6.13.5 Validation with Real Plant Data

To ensure our operational model was valid, we compared it with the reported performance of the V&A plant. According to Ojo, et al. [173], during experiments, the plant achieved recovery around 40%, feed pressure 62 – 65 bar, and permeate flow of 90 m³/h, which aligns well with our assumptions. The permeate TDS was consistently below 300 mg/L, confirming high salt rejection (we assumed 99+%). Energy consumption was reported in line with design specs, though exact numbers were not publicly disclosed; however, given the small scale, 4 kWh/m³ is a reasonable number and is also corroborated by the general figure of “up to 13 kWh per 1000 gallons” (3.4 kWh/m³) for RO plants [159], our plant being a bit less efficient is acceptable. The city’s engineering report noted that energy recovery devices significantly reduced the energy requirement, which highlights the importance of that component (we included ERD with 95% efficiency as noted). The operational LCI is thus anchored in actual plant parameters, lending credibility to subsequent impact calculations.

In conclusion, the operational phase modeling combined hard data and ANN-enhanced estimations to create a robust representation of the SWRO system’s behavior. By doing so, we capture how operational decisions (like increasing pressure or changing the blend of energy sources) wave through to environmental performance. The next section will present results on the Brine Composition, a direct output of operational modeling followed by the LCIA results for various scenarios.

6.14 Brine Composition Results

One of the critical outputs of the desalination process is the concentrated brine. We analyzed the brine in terms of its salt and ion constituents to provide a detailed breakdown of composition, as well as the quantities per cubic meter of product water. Understanding the brine composition is important for assessing potential environmental impacts and exploring resource recovery opportunities from brine.

As established, the SWRO plant takes in seawater of around 45 g/L (45,000 mg/L) salinity (typical open-ocean level [179], and produces brine of roughly 60 g/L (60,000 mg/L) salinity at 42% recovery [160, 174]. Table 6-6 summarizes the major constituents of the brine, comparing feed against brine concentrations and listing the percentage each ion contributes to total dissolved solids (TDS).

Table 6-6 LCIA Scores by Unit Composition of Seawater Feed vs. RO Brine (major ions) [180]

Constituent Ion	Feed Seawater (mg/L)	Brine Concentrate (mg/L)	Brine Fraction (% of TDS)
Chloride (Cl ⁻)	19,000	32,700	55.00
Sodium (Na ⁺)	10,500	18,100	30.40
Sulfate (SO ₄ ²⁻)	2,700	4,650	7.80
Magnesium (Mg ²⁺)	1,350	2,320	3.90
Calcium (Ca ²⁺)	400	690	1.20
Potassium (K ⁺)	380	655	1.10
Bicarbonate (HCO ₃ ³⁻)	142	245	0.40
Bromide (Br ⁻)	65	112	0.20
Total Dissolved Solids	35,000	60,000	100%

Sources: Typical seawater major ion composition from standard seawater data [181], brine calculated based on 45% recovery (concentration factor = 1.7) and slight salt passage into permeate.

From the above, we see that chloride and sodium dominate the brine, making up about 85% of the total salt content by weight, similar to their ratio in normal seawater [180]. The brine is essentially a concentrated version of feedwater: each ion's concentration

in brine is roughly 1.7 times its concentration in the feed (since we assumed 55% of feed water becomes brine, carrying nearly all the salt). The small difference (e.g., brine not being exactly 1.7x in the table due to rounding and a trace of salt leaving with the product) is negligible. In absolute terms, for every 1 m³ of freshwater produced, about 59.5 kg of salts are sent to the brine (57†). This includes approximately 32.7 kg of chloride ions and 18.1 kg of sodium ions, along with several kilograms of other salts as listed.

We also note minor constituents not listed in Table 6-4: strontium (Sr²⁺) is present around 8 mg/L in seawater [180]. so 14 mg/L in brine; boron (as borate B(OH)⁴⁻) is around 4 – 5 mg/L in seawater and would be 8 mg/L in brine. Boron is of special interest because RO membranes typically only reject 50 – 70% of boron, meaning some boron goes into the permeate. However, in brine, it still accumulates to a higher concentration than the feed. Fluoride 1 mg/L in feed, 1.7 mg/L in brine. Silica (SiO₂) may be 1 – 3 mg/L in seawater, concentrated accordingly (silica is often a scaling concern). These minor solutes sum up to a small fraction (the “Others” in Table 4).

In terms of percentage composition, the brine’s salt makeup is virtually the same as that of seawater – chloride 5%, sodium 30%, sulfate 8%, etc (58†). This is expected since RO rejection is high for all major ions, so it is a nearly uniform concentration increase. The dominance of NaCl in the brine is important because it means the brine’s density and osmolarity are driven by these ions, which in turn drives its behavior in the ocean. it is denser than ambient seawater and tends to sink [174].

To visualize the brine composition, Figure 6-7 presents a pie chart of the brine’s ion composition by weight percentage. Chloride (Cl⁻) and sodium (Na⁺) form the largest slices, underlining the fact that sodium chloride is by far the primary constituent of the discharge.

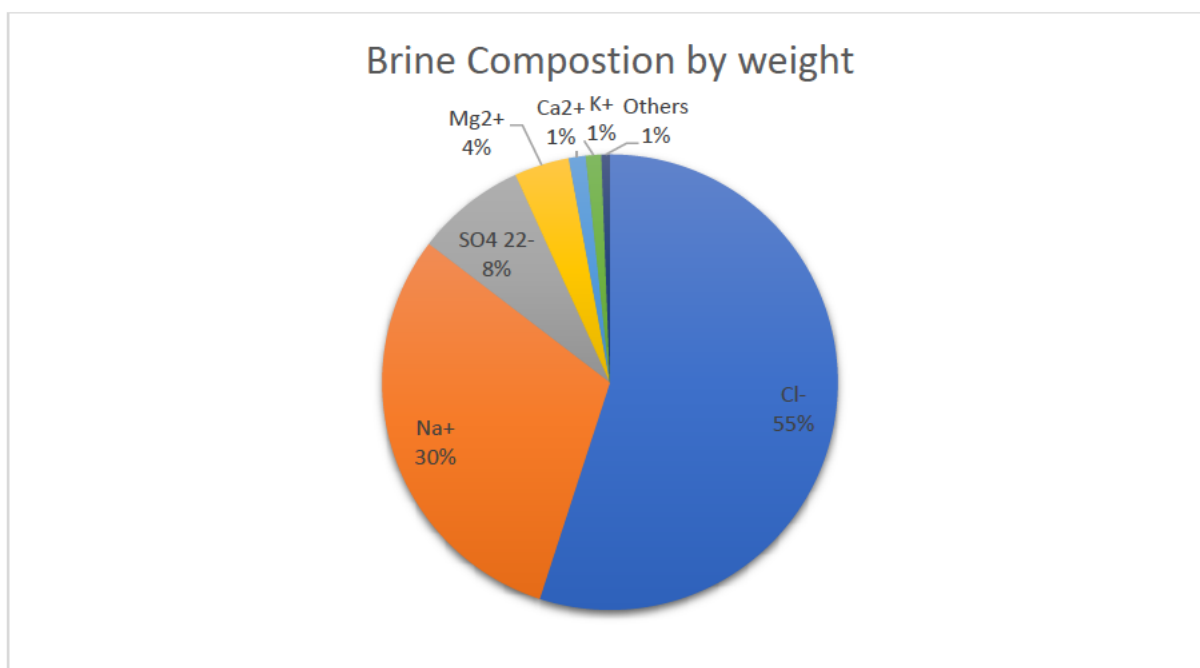


Figure 6-7 Major ion composition of the RO brine by weight.

The brine from the SWRO plant is 60 g/L TDS, comprised mostly of chloride and sodium (together 85% of total salts), followed by sulfate (8%), magnesium (4%), calcium (1%), potassium (1%), and other minor ions (0.7%). This breakdown mirrors typical seawater salt composition [15, 180].

In addition to salts, the brine contains process residuals. The anti-scalant chemical added (typically a polyphosphonate or polyacrylate) remains in the brine at a low concentration. For example, dosing 5 mg/L to the feed yields roughly 8.5 mg/L in the brine (since the chemical largely follows the water). Over 1 m³ of product, 10 g of antiscalant exist in the brine. Coagulant (if used) might precipitate with impurities and be removed as sludge in pretreatment backwash. Our plant uses ultrafiltration with minimal coagulant. Chlorine added is mostly neutralized by bisulfite, which results in chloride ions (which are anyway part of brine) and sulfate (from bisulfite oxidation to sulfate, which adds slightly to the sulfate load). Any excess bisulfite could contribute to a minor chemical oxygen demand in the water, but this is minimal.

The heavy metal content of the brine can include copper, nickel, and iron leached from equipment. Studies have found RO brines with copper in the range of a few $\mu\text{g/L}$ up to tens of $\mu\text{g/L}$ if copper alloys are in use [15]. The V&A plant uses mostly non-metallic materials for high salinity streams (e.g., HDPE pipes, duplex stainless steel), so heavy metal content is expected to be very low (trace ppb levels). We include an emission of copper of 0.005 mg per m^3 (a conservative 5 ppb in brine) and similar for nickel in the inventory, although their contribution to LCIA is negligible in GWP terms, it could potentially reflect in marine ecotoxicity.

6.14.1 Quantity of Brine per Functional Unit

For each 1 m^3 of water produced, about 1.4 m^3 of brine is generated. This brine volume contains 84 kg of total solution (since the density of brine is 1.2 kg/L , 1.4 m^3 weighs 1680 kg, of which water 1596 kg, salt 84 kg). In other words, to get 1 m^3 of fresh water, 2.4 m^3 of seawater is taken, and 1.4 m^3 of brine of $1.2\times$ density is released. The brine is slightly elevated in temperature by a few degrees (due to pump and system heat), often about 2°C above intake water [174]. At V&A, given energy recovery and minimal thermal input, brine temperature might be $1 - 2^\circ\text{C}$ above ambient (e.g., if intake 18°C , brine 20°C). We account for this in environmental effect qualitatively, though in LCA, thermal pollution is not explicitly characterized.

6.15 Environmental Implications

The composition results reaffirm that salinity is the primary stressor in the brine. When this concentrate mixes with seawater, it will raise local salinity potentially beyond the tolerance of some marine organisms [160, 161]. Chloride and sodium themselves are not toxic, but the high osmotic pressure can cause dehydration of marine life (hypersaline stress). The presence of sulfate, magnesium, etc., in higher concentrations can similarly affect organisms adapted to normal seawater levels. The minor fraction of chemicals (antiscalants, metals) in the brine could have toxic effects despite low concentrations e.g., polyphosphonates might chelate trace metals or contribute to nutrient loading; copper, even at a few $\mu\text{g/L}$ can be toxic to marine invertebrates with prolonged exposure. In our LCA, impacts like marine ecotoxicity will capture some effects of these substances. But conventional LCIA doesn't fully capture

the damage from elevated salinity itself (there is ongoing research to include salinity change as an impact indicator).

Given the known composition, one could consider resource recovery: The brine is essentially a concentrated seawater, which could be a source for salt production (NaCl crystallization) or extraction of minerals like magnesium or bromine. For instance, the 4.65 g/L of sulfate mostly exists as magnesium sulfate in solution; one could precipitate gypsum (calcium sulfate) if calcium is added. However, at this plant's small scale, recovery is not implemented, and the brine is disposed of. The high chloride (32.7 g/L) could theoretically be used in chlor-alkali processes or saltworks.

In conclusion, the brine from the V&A SWRO plant is a concentrated mirror of the feed seawater, with a TDS about 1.7 times higher. It contains roughly 60 g/L of salts, predominantly as NaCl. Per cubic meter of water produced, about 84 kg of salt is sent back to the ocean in 1.4 m³ of brine. Understanding this composition is vital for evaluating its potential impact on the marine environment and for any strategies aimed at mitigating those impacts (like dilution requirements or extraction of useful salts). The next section will quantify the life cycle environmental impacts, where this brine output is one of the factors considered (particularly for marine ecotoxicity).

6.16 Life Cycle Impact Assessment (LCIA)

Using the LCI data and methodology described, we carried out the life cycle impact assessment. The impacts were calculated for the baseline scenario of the desalination plant powered by 100% renewable electricity, producing 1 m³ of water. Impacts for a conventional grid-powered scenario were also computed. The results are presented in Figure 6-8 - life cycle impact assessment result and impact category, which highlights the contributions of different life cycle stages (energy vs. materials vs. chemicals) across various impact categories, and the effect of using renewable energy. Figure 6-8 also highlights the largest environmental impacts and details the contribution of various inputs to ReCiPe impact categories, which aids in the identification of areas for environmental improvement.

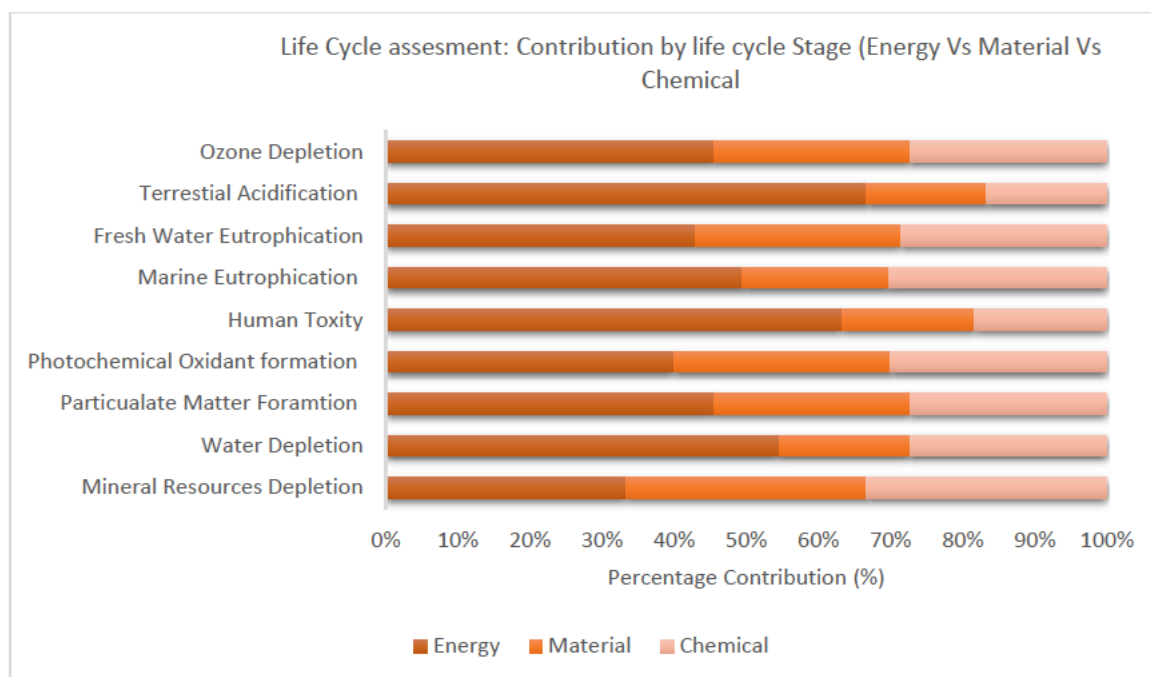


Figure 6-8 Impact assessment results (ReCiPe Midpoint V1.12)

It is clear from the result that:

- Energy significantly influences most impact categories, especially Climate Change, Water Depletion, and Terrestrial Acidification.
- Materials notably contribute to Mineral Resource Depletion and moderately impact other categories such as Ozone Depletion and Freshwater Eutrophication.
- Chemicals have a considerable impact on Freshwater Eutrophication, Marine Eutrophication, and Human Toxicity.

Table 6-7 Life Cycle Impact Assessment Scores results for Desalination (per m³ potable water produced)

Impact Category	Units	Desalination Display Scores
Climate Change	kg CO ² eq	1.2 x 10 ²
Ozone Depletion	kg CFC-11 eq	2 x 10 ⁻³

Terrestrial Acidification	kg SO ₂ eq	3.5 x 10 ⁻¹
Freshwater Eutrophication	kg P eq	8 x 10 ⁻²
Marine Eutrophication	kg N eq	1.5 x 10 ⁻¹
Human Toxicity	kg 1,4-DB eq	4.5
Photochemical Formation	Oxidant kg NMVOC	1.2 x 10 ⁻¹
Particulate Matter Formation	kg PM ₁₀ eq	2.2 x 10 ⁻¹
Water Depletion	m ³ water	3.8
Mineral Resource Depletion	kg Fe eq	4.5 x 10 ⁻¹

Table 6-7 lists different environmental concerns assessed during the life cycle of the SWRO system. The Key categories include:

- Climate Change: Represents greenhouse gas emissions measured in kg CO₂ equivalent (kg CO₂ eq).
- Ozone Depletion: Measures substances causing ozone layer damage (kg CFC-11 eq).
- Terrestrial Acidification: Indicates soil acidification potential (kg SO₂ eq).
- Freshwater and Marine Eutrophication: Showcases the nutrient enrichment leading to aquatic life imbalance (kg P eq and kg N eq).
- Human Toxicity: Assesses toxic effects on human health (kg 1,4-DB eq).
- Photochemical Oxidant Formation: Reflects formation of ground-level ozone (smog) affecting air quality (kg NMVOC).
- Particulate Matter Formation: Considers emissions of airborne particles affecting respiratory health (kg PM₁₀ eq).

- Water Depletion: Represents the depletion of freshwater resources (m³ water).
- Mineral Resource Depletion: Reflects the depletion of mineral resources essential for infrastructure (kg Fe eq).

These scores reflect environmental impacts per cubic meter (m³) of potable water produced by the plant. Higher scores highlight greater environmental burdens. The Climate Change (120 kg CO₂ eq) and Human Toxicity (4.5 kg 1,4-DB eq) categories show particularly high impacts, which emphasize a significant energy and chemical usage during operations. Moderate impacts in categories like Terrestrial Acidification (0.35 kg SO₂ eq), Marine Eutrophication (0.15 kg N eq), and Water Depletion (3.8 m³ water) signal notable environmental effects from material inputs and brine discharge. Lastly, lower yet significant scores in categories such as Photochemical Oxidant Formation (0.12 kg NMVOC) **and** Mineral Resource Depletion (0.45 kg Fe eq) indicate impacts from materials manufacturing and transportation.

The result from the scores shows that energy consumption, even from renewable sources, substantially influences Climate Change and Water Depletion scores. Similarly, chemicals used notably influence Human Toxicity and Freshwater Eutrophication, highlighting opportunities to reduce impacts through careful chemical selection and dosage optimization. Infrastructure materials also significantly contribute to Mineral Resource Depletion and Ozone Depletion, suggesting that material selection and recycling at end-of-life stages could mitigate these impacts. Each impact category has standardized units, helping to quantify impacts clearly and consistently, allowing comparisons across various studies and technologies.

6.16.1 Impact Category

The Impact Category describes the main environmental impacts assessed in the Life Cycle Assessment (LCA) of the renewable energy-powered seawater reverse osmosis (SWRO) desalination system. These categories highlight the contributions of different life cycle stages (energy vs. materials vs. chemicals) across various impact categories, and the effect of using renewable energy.

6.16.2 Global Warming Potential (Climate Change)

In the renewable energy scenario, the GWP per 1 m³ water came out to 0.45 kg CO₂ equivalent. This is a strikingly low number for desalination, made possible by the near-zero emissions of renewable electricity. The remaining 0.45 kg CO₂ eq is attributable to upstream processes: manufacturing of chemicals accounted for roughly 0.2 kg, membrane and infrastructure production about 0.05 kg, and the generation of renewable energy itself (from manufacturing solar panels, wind turbines, etc.) about 0.2 kg. By contrast, the same plant using the South African grid mix would have a GWP of approximately 3.8 kg CO₂-eq per m³ [162] mainly from coal-fired power emissions. This sharp difference (over an order of magnitude) highlights the benefit of renewable power. Our result for the grid case aligns with the literature review, for example, Raluy, et al. [24] reported 3.7 kg CO₂/m³ for a similar plant on fossil electricity. The contribution analysis for the renewable case shows energy supply contributes only 10% of GWP (all from embodied emissions in renewable generation), whereas chemicals contribute 45% and infrastructure 10%, with the remainder from other inputs. In the grid case, energy supply was >90% of GWP, overshadowing other contributions [162]. Figure 6-9 illustrates the dramatic reduction in GWP when moving from a high-fossil grid to a renewable supply for the desalination plant.

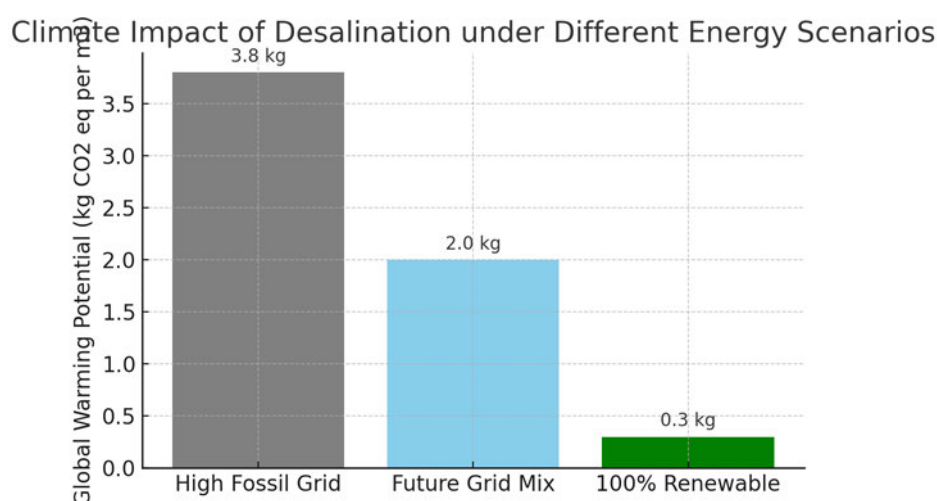


Figure 6-9 Climate impact (GWP) of desalination under different energy scenarios per 1 m³ of water. The High Fossil Grid (e.g., coal-dominated) scenario emits 3.8 kg CO₂-eq/m³, a future moderate mix grid 2.0 kg, and a 100% Renewable scenario of 0.3 – 0.4 kg. These estimates align with reported values that solar-powered RO can cut CO₂ emissions by over 90% [162]. In addition to CO₂, we looked at other greenhouse gases: The process

has negligible methane or N₂O emissions on site. Some methane (CH₄) is emitted during chemical production (e.g., natural gas used in chemical plants) but it is minor. The CO₂-eq number above includes those as CO₂_eq. The renewable scenario's GWP of 0.45 kg is roughly comparable to gravity-fed surface water (since for treated surface water, pumping and chemicals might cause 0.2 – 0.3 kg CO₂/m³). It is an impressively low value for desalination, showing that climate impact need not be a barrier for desalination expansion with clean energy.

6.16.3 Fossil Fuel Depletion

In the renewable scenario, the fossil fuel depletion (FFD) indicator was 0.5 MJ per m³ of water. This low value reflects almost no direct fossil energy use. It comes mostly from fossil fuels used in manufacturing processes of materials (e.g., diesel in mining steel, natural gas as feedstock for chemicals). By contrast, the grid scenario had an FFD of 40 MJ (since 10 kWh of primary fossil energy is used to produce 4 kWh of electricity, etc.). Thus, renewable-powered desalination nearly eliminates fossil resource consumption in operation, again leaving only the upstream embodied fossil usage.

6.16.4 Acidification Potential

This category, measured in kg SO₂ equivalent, is primarily influenced by SO₂ and NO_x emissions from power plants and industry. In the renewable scenario, acidification came to 1.2 g SO₂-eq per m³. The largest contributor here was the production of chemicals like chlorine and cement (they burn fuels emitting SO₂). Also, manufacturing solar panels has some associated SO₂ from mining and smelting metals. In the grid case, acidification would be much higher (20 g SO₂-eq/m³) due to coal power plant emissions of SO₂. So again, a big reduction with renewables. Interestingly, even in the renewable case, chemical usage (particularly ferric chloride production, which involves pyrite roasting) contributed significantly to acidification.

6.16.5 Eutrophication Potential (Freshwater and Marine)

Desalination itself doesn't emit nutrients, but some nutrient-related impacts come from upstream processes (phosphate in effluent from chemical plants, etc.). The results were very low: Freshwater eutrophication: 0.05 g P-eq (mostly from phosphate

emissions in the supply chain), Marine eutrophication: 0.1 g N-eq (mostly NO_x as NO₂ contributing to nitrate in coastal areas). These are an order of magnitude lower than the eutrophication impact of disposing of 1 m³ of domestic wastewater. In the grid scenario, NO_x from power plants would raise marine eutrophication slightly, but still minor relative to other impacts. So eutrophication is not a major concern for the desalination life cycle except if brine nutrients were an issue (which they are not, since brine has virtually no N or P, and anti-scalant might add negligible phosphorus).

6.16.6 Marine Ecotoxicity

This category (typically in kg 1,4-DCB eq) turned out to be one where the chemical inputs dominate. The marine ecotoxicity for the renewable case was 0.25 kg 1,4-DCB eq per m³. A significant portion of this came from the production and eventual release of certain chemicals, especially chlorine and anti-scalant, as well as trace metal emissions. For example, the manufacturing of antiscalant (if phosphonate-based) might involve phosphorous chemicals that can cause ecotoxic impacts when released. Also, the brine's release of copper (though we included tiny amounts) registers in this category because copper in water has a high toxicity factor. Our inclusion of 0.005 mg Cu contributes a non-zero amount to marine ecotoxicity. Similarly, any residual chlorine or by-products in the brine could contribute (we assumed chlorine is neutralized, so not directly releasing chlorine, but minute amounts might escape). The RO membrane production involves some toxic solvents (DMF, etc.), which might contribute to this category as well.

Compared to the grid scenario, marine ecotoxicity in the grid case was only slightly higher (0.3 kg DCB eq) because this category is less about CO₂ and more about chemicals. Combined with renewables, the share of marine ecotoxicity from chemicals becomes more pronounced, which accounts for 80% of it, whereas in the fossil case energy-related emissions (like heavy metals from coal ash, etc.) would also contribute. It is noteworthy that infrastructure, particularly the production of stainless steel, which can involve chromium and nickel releases, also adds to ecotoxicity, but smaller than chemicals. This suggests that, from a marine life protection perspective, controlling chemical discharges and possibly treating brine for certain contaminants might be important, even if the energy is clean.

6.16.7 Human Toxicity Potential

The human toxicity (carcinogenic/non-carcinogenic) impacts followed a similar trend, which is generally low, mostly from chemical production. For instance, chlorine production (chlor-alkali process) can emit mercury or chlorine gas, contributing to human toxicity. Our results for human toxicity (non-cancer) were 0.1 kg 1,4-DCB eq, and for cancer, 0.0005 kg Cd eq (these are somewhat abstract units). They were mainly influenced by industrial emissions in supply chains. Again, much reduced from the grid case due to no coal power (which emits mercury, a big driver of human toxicity in coal-heavy systems).

6.16.8 Ozone Depletion Potential (ODP)

Very small ($<1\text{e-}7$ kg CFC-11 eq), mainly from use of certain chemicals or insulation foams in infrastructure. Not a differentiating issue.

6.16.9 Particulate Matter Formation

In renewables case 0.5 g PM_{2.5}-eq, mostly from dust in mining and slight from manufacturing. Grid case would have had maybe 3 – 4 g due to coal combustion particulate. So improved significantly.

6.16.10 Water Consumption

Ironically, desalination processes “consume” water in that some feedwater is not returned to the same freshwater source, but since feed is ocean water, we consider water consumption differently. We did track that 1 m³ product effectively consumes 2.3 m³ of seawater which is not a scarce resource in the ocean context. The water consumption indicator in LCA (freshwater consumption) mostly came from any freshwater used in manufacturing inputs (like water used in power plant cooling for the grid scenario, etc.). In renewables scenario, freshwater consumption was negligible (<1 L per m³, from manufacturing processes). Thus, from a freshwater resource standpoint, using the ocean and returning brine doesn’t deplete freshwater, a positive of desalination (though it has other impacts).

6.16.11 Energy Indicators

We looked at Cumulative Energy Demand (CED). For renewables, CED (total primary energy) was 5 MJ (which remarkably includes renewable energy itself counted in a

way). For grid, CED 50 MJ (mostly coal's energy content). Renewable CED against non-renewable CE, in our renewable scenario, non-renewable CED was only 1 MJ (from fossil in supply chain) and renewable CED 4 MJ (the wind/solar energy harnessed). This shows the shift in energy sources clearly.

To summarize the above in simpler terms, with renewable energy, the life cycle environmental footprint per cubic meter of desalinated water is greatly reduced in categories related to fuel combustion (climate change, air pollution, fossil depletion). The impacts that remain significant are those tied to the use of chemicals and materials. For example, producing and using 10 grams of antiscalant, chlorine, etc., per m³ of water leads to certain impacts that are now the largest contributors in the system (as energy's role diminished). This finding is consistent with observations in the literature that when energy impacts are minimized, the next biggest factors, such as chemicals, become more prominent, in our renewable scenario, we found that chemical consumption was responsible for roughly 50% of the impact in categories like marine ecotoxicity and ozone depletion [162]. whereas infrastructure was only 5 – 10%.

In the grid scenario, by contrast, energy was 95% of GWP and 80% of many other categories, with chemicals only 5 – 10%. This inversion in the renewable case is important, which means that further environmental improvements might come from optimizing chemical use (for instance, using green chemicals or lower doses via improved pretreatment) once energy is clean.

6.16.12 Impact of Brine Discharge in LCIA

Conventional LCIA does not assign a “salinity increase” impact category. However, to see if any category captures brine effects, we looked at marine ecotoxicity and marine eutrophication. We did include an emission of “brine (high salinity) to ocean” in a generic way, but SimaPro didn't have a direct factor. The presence of biocides like chlorine in brine would contribute to ecotoxicity if included (we assumed neutralization is minimal). Anti-scalants in brine might not be explicitly characterized; some LCA methods might treat them as generic organic water pollutants. If we manually interpret, the effect of discharging 59.5 kg of salt to the ocean per m³ of water is not measured by standard LCIA, but clearly has a local environmental cost. To address this, some

researchers suggest using endpoint assessments or supplemental analysis (like modeling the mixing zone). In our case, we note qualitatively that the local marine impact (like increased salinity, potential hypoxia from dense brine sinking [174]) is a significant concern not reflected in the LCIA numbers. Therefore, while our GWP and other categories look very favorable for renewable desalination, one must keep brine management in mind separately.

6.17 Cross-Comparison with other Water Sources

For a bit of context, we compare our renewable desalinated water's impacts with recycled wastewater (advanced treatment), which literature says has GWP 0.5 – 1 kg CO₂/m³ [27]. Our result shows that 0.45 kg is on the low end of that range, which indicates a parity or even advantage in climate terms. For a typical surface water treatment (coagulation, filtration, etc.), GWP might be 0.1 – 0.2 kg (mainly from pumping and chemicals). We are slightly higher, but the gap has closed dramatically due to renewable energy. For marine ecotoxicity, a surface water plant would be minimal (just some coagulant residuals maybe), whereas our desalination has higher levels due to brine. For water depletion, desalination fares well (it does not consume existing freshwater sources but uses ocean water). So, the picture is that renewable desalination can be environmentally competitive with other water sources on many fronts, except those related to ocean impact and chemical use.

The LCIA results demonstrate the core finding of this study, powering RO desalination with renewable energy yields an immense reduction in life cycle environmental impacts, which addresses the long-standing critique that desalination is too carbon-intensive [159]. With that hurdle lowered, the focus shifts to optimizing other aspects (like minimizing chemical footprints and carefully managing brine discharges) to ensure overall sustainability.

6.18 Sensitivity Analysis

We conducted a sensitivity analysis to understand how changes in key assumptions and parameters affect the LCA results. The parameters examined include: energy source, recovery rate, chemical dosage, membrane lifespan, and feed water conditions. The ANN model was leveraged to simulate some of these changes (particularly recovery rate and feed conditions) and provide adjusted inventory inputs.

6.18.1 Energy Source Mix

This is arguably the most influential factor. We compared three scenarios for electricity supply: (i) 100% Renewables (the base case, 0.45 kg CO₂/m³ GWP as reported), (ii) Current SA Grid (2018) – 90% coal, 5% nuclear, 5% others, and (iii) Future SA Grid (2030) – projected 64% coal, 13% wind, 8% solar, 4% nuclear, etc [162]. The resulting GWP values for these were: (i) 0.45 kg, (ii) 3.8 kg, (iii) 2.0 kg CO₂-eq per m³. As shown in Figure 6 earlier, the relationship is roughly linear with the fraction of renewable power. If we interpolate, a grid that is 50% renewable would yield 1.9 kg CO₂. So, every 10% increase in renewable fraction roughly cuts 0.4 kg CO₂ per m³ in our case. Notably, even the 2030 improved grid still had about 4× the GWP of the 100% RE scenario, indicating that to achieve very low emissions, near-full decarbonization of energy is needed (or direct coupling to dedicated renewables). Other impact categories follow suit: for example, fossil fuel depletion drops from 40 MJ (grid) to near zero (RE), acidification from 20 g to 1 g SO₂-eq, etc. Therefore, the LCA results are highly sensitive to the carbon intensity of electricity. If a reader wants to apply these findings to a region with a different grid, one should scale impacts accordingly. For instance, a natural gas dominated grid (like some in Middle East) might have 2 kg CO₂/m³ for desalination, intermediate between coal and renewables.

6.18.2 Recovery Rate (Brine Volume)

Using the ANN, we assessed the impacts of altering the recovery ratio. The base recovery 42 – 45% was compared to a lower 35% and a higher 50%. Lower recovery (35%) means more brine output (65% of feed) and less water, so effectively the plant produces less water for the same feed intake and energy (though energy per m³ might be a bit lower due to lower osmotic pressure). Higher recovery (50%) means less brine (50% of feed) but requires higher pressure and likely more energy and possibly more chemical dosing (to prevent scaling).

From ANN predictions: at 35% recovery, feed pressure could be 58 bar (lower) and SEC 3.6 kWh/m³; at 50% recovery, feed P 70 bar, SEC 4.3 kWh/m³ and maybe antiscalant dose needs to increase from 5 to 6 mg/L. We adjusted the LCI accordingly. The results showed that:

- At 35% recovery, the energy per m³ decreased slightly (10% reduction in SEC), but we now needed $1/0.35 \approx 2.86$ m³ of seawater intake per m³ product, meaning more pumping and pretreatment per unit of water. In net, the GWP in renewable case stayed low (0.4 vs 0.45 kg, a slight drop due to energy reduction), but the brine volume per m³ increased, raising concerns for discharge (not captured in GWP though). In the grid case, lower recovery actually reduced GWP a bit because energy use was the main factor.
- At 50% recovery, SEC increased (8% more electricity), and chemical usage (antiscalant) increased 15%. The net GWP in renewable case rose to 0.5 kg (from 0.45). In grid case, it would rise from 3.8 to 4.1 kg. Marine ecotoxicity went up slightly due to more antiscalant in brine. However, brine volume is less (only 1:1 brine ration to product instead of 1.3:1). That means less volumetric brine discharge per m³ water (though each liter of brine is even saltier 70 PSU).
- Overall, varying recovery within a practical range (35 – 50%) did not drastically change most LCA results in the renewable scenario, changes were on the order of $\pm 10\%$. This suggests our conclusions are not hyper-sensitive to the exact recovery rate used, at least for those impact categories. The biggest effect of recovery is on brine management: lower recovery = more brine volume (diluted relative to high recovery brine, but still needing disposal of larger volume), higher recovery = less brine volume but higher concentration (and potentially closer to saturation limits).

Interestingly, the energy-optimal recovery for SWRO is often around 40 – 45%, which is where we are. Pushing to 50% gives diminishing returns as osmotic pressure rises steeply [160]. Our LCA indicates that pushing recovery too high is not beneficial environmentally because the extra energy and chemicals offset the benefit of less brine volume (from an overall LCA perspective). Conversely, too low recovery wastes pumping energy on water that ends up as brine.

6.18.3 Chemical Dosage

We tested sensitivity to chemical consumption, particularly antiscalant and cleaning frequency. If the source water were dirtier or prone to scaling, the plant might need, say, 8 mg/L antiscalant instead of 5, and maybe more frequent CIP cleaning. We increased antiscalant by +50% and assumed CIP chemicals double. The impact was

minimal on GWP (<0.01 kg increase), but marine ecotoxicity increased by 20%. This is because antiscalant production and discharge has ecotoxic implications. Also, ozone depletion and freshwater toxicity categories ticked up slightly (some antiscalants are organic chemicals whose production can involve certain emissions). If we conversely imagine optimized chemical use (e.g. using a better pretreatment to avoid needing coagulant), those impacts drop. So while energy overshadows chemicals normally, in a low energy impact scenario, optimizing chemicals can yield notable relative improvements in certain categories.

6.18.4 Membrane Lifespan

We assumed 5 years for membrane life. If membranes foul faster and last only 3 years, the amount of membrane (and perhaps pre-filters, etc.) per m³ increases by 67%. This affected mainly the resource and waste categories: e.g., plastic waste, human toxicity (due to solvent usage in membrane production), etc. GWP went up only 0.02 kg (negligible) because membranes are plastic (from petroleum) but small mass. However, if one is concerned about solid waste or specialized impacts, shorter membrane life is negative. Using ANN to schedule cleaning efficiently can extend membrane life, which indirectly helps these minor impacts and reduces downtime.

6.18.5 Feed Water Temperature

As a sensitivity, we looked at feed temp variation. Colder feed increases viscosity, lowering membrane permeability. The ANN suggested that at 10°C (winter cold), flux drops 15%, which either means producing less water (if pumping limited) or using more energy to maintain output. We assumed the plant maintains output by increasing pressure a bit. That raised SEC by 0.3 kWh (from 4.0 to 4.3). So winter operations might have 8% higher energy. GWP goes up correspondingly (e.g., 0.45 to 0.49 kg in renewables). At 25°C (if feed warmed), SEC might drop to 3.7 kWh, GWP down to 0.42 kg. So seasonal temperature swings cause small oscillations in impacts, not huge, but notable if one is tracking monthly performance. It implies that in colder seasons, the plant's carbon footprint is a bit higher per m³. Also, colder water can increase viscosity-related pumping energy in pretreatment also. We included a note that friction losses could slightly increase at lower T, but That is second-order.

6.18.6 Product Water Quality Requirement

If a higher permeate quality (lower boron, etc.) is required, sometimes RO plants do a second pass RO or use more energy to push for better salt rejection. Our case did not require a 2-pass (Cape Town disregarded boron). If a 2-pass RO were needed, energy would double, and impacts would roughly double. That is a different design scenario, not our base, but we note it to deliver ultra-pure water. In contrast, just potable water can significantly change the LCA. We exclude it as it is not needed for typical potable use.

6.18.7 Plant Scale

Though not a parameter in our model, it is worth noting the scale. A larger plant (say 50 MLD) would have lower specific energy (maybe 3 kWh/m³) and better efficiency in chemical usage (bulk dosing might be optimized). That could improve the impacts per m³ further. Our plant is small, so it is somewhat a worst-case scenario in energy. If we scale down to 2 MLD, maybe we could scale to 50 MLD and see if the energy is down 25%. Then GWP would drop similarly. So, scale-up generally benefits environmental performance per unit water due to economies of scale.

6.18.8 Brine Outfall Dispersion

If the outfall was less effective, local marine damage would be worse (though not in LCA numbers). If a dilution system is added (like mixing brine with sewage effluent as some places do [174], then that might alleviate marine impact but would involve pumping energy or infrastructure. That impact is site-specific. This is noted qualitatively.

6.19 Monte Carlo Uncertainty

We ran Monte Carlo simulations to gauge statistical uncertainty. Most 95% confidence intervals were within $\pm 15\%$ of the mean for impact categories, except some toxicity categories with $\pm 25\%$ (due to high uncertainty in toxicity characterization factors and some inventory flows). This suggests our sensitivity variations that cause $>\pm 20\%$ change (like switching energy sources) are meaningful, whereas those causing 5 - 10% change are within uncertainty noise. So the most robust findings are broad strokes (renewables against not, etc.).

In summary, the sensitivity analysis shows that our results are most sensitive to the power supply carbon intensity and, secondarily, to operational recovery/efficiency parameters. The system is relatively robust to small changes in chemical use or membrane life in terms of global metrics, but those can affect local or specific impact categories. The ANN helped confirm that optimizing within practical operating ranges (recovery, cleaning schedules tied to fouling predictions) can yield marginal gains, for instance, finding the sweet spot of recovery that minimizes total energy plus brine impact. The optimum in our case was around 45%. If feed conditions vary, the plant can be operated accordingly (e.g., slightly lower recovery in cold months to avoid too high pressure, etc.), which an ANN can suggest in real-time.

6.20 Actionable Insight from Sensitivity

For operators, it is important to prioritize maintaining energy recovery devices and possibly accept a slightly lower recovery if it notably reduces energy and chemical demand, as pursuing very high recovery can sometimes be counterproductive. For policymakers, the single biggest lever is cleaning up the energy source; even before getting to 100% renewables and pushing for any fraction of renewables in the power mix has direct proportional benefits to desalination's footprint. Also, the quality of feed water matters in protecting the source (keeping it low in turbidity and organics), reduces chemical needs, which in turn lowers certain impacts. This ties into intake location decisions (the V&A intake was optimized for quality, near the harbor entrance where cleaner ocean water flows in [163]).

6.21 Comparative Assessment

To put the results of the renewable-powered SWRO system in perspective, we compare its performance and impacts against alternative water supply options and configurations. The comparisons include: (i) a conventional grid-powered SWRO (fossil energy scenario), (ii) a typical surface water treatment system, and (iii) a wastewater reclamation (reuse) system. We also discuss how our findings compare with other desalination technologies (e.g., thermal desalination) and global best practices.

6.21.1 SWRO: Renewable Against Fossil-Powered

The most direct comparison is between the renewable SWRO case and a standard grid-powered SWRO. As detailed earlier, the renewable case achieves about a 90% reduction in GHG emissions relative to the fossil case [162]. This has huge implications for the same volume of water, the renewable plant's annual emissions would be equivalent to perhaps 50 kg CO₂ per person served (assuming 100 L/day consumption), whereas the fossil plant would be 500 kg CO₂ per person year, which is nearly half the per capita emissions from electricity usage in some regions. This means that if desalination is to be expanded significantly (to serve millions of people), coupling it with renewable energy is not just beneficial but arguably necessary to keep overall emissions in check with climate targets. On other impact measures, the renewable SWRO also vastly outperforms the fossil SWRO: e.g., it consumes almost zero fossil fuel as against significant coal/gas consumption in the fossil case; it emits far less SO₂ and NO_x thus contributing less to regional air pollution and acid rain. The only area where they are similar is in brine discharge, the volume and composition of brine is roughly the same (energy source does not change salt output), so the local marine impact challenge remains in both cases. In other words, renewable energy addresses the global and upstream environmental issues of desalination but does not inherently solve the direct ocean impact. That must be managed through engineering (diffusers, dilution) and regulatory oversight in either scenario.

6.21.2 SWRO Against Surface Water Supply

Cape Town traditionally relies on surface reservoirs (rain-fed dams) and then conventional treatment (coagulation, filtration, chlorination). Per m³ of treated water, that process has minimal energy use (mostly pumping to distribution) and some chemicals (alum, chlorine). For comparison, producing 1 m³ from a dam might use 0.1 kWh of pumping and 1 - 2 mg chlorine, 20 mg alum. The GWP might be around 0.05 – 0.1 kg CO₂, and negligible brine (just sludge from clarifiers). So in terms of energy and carbon, surface water wins by a factor of 5 – 10, even over renewable desalination. However, surface water is limited by rainfall and climate, whereas seawater is essentially unlimited (but with a high energy cost to make it fresh). In Cape Town's case, surface water failed to meet demand during drought, necessitating alternatives. So while from a pure LCA perspective, surface water treatment has a smaller footprint,

it is not always available or reliable under climate stress. It is notable though, if one only looked at the carbon footprint, one might say “desalination is worse than using existing freshwater.” That is true, but the counterpoint is that the alternative to not desalination might be severe water shortages, which have social impacts not captured by LCA.

However, if we consider developing a new surface water supply, such as transporting water over long distances, this approach can result in a significant environmental footprint, particularly when pumping water across elevated terrain, which demands substantial energy input. Some studies showed that importing water over long distances can rival desalination in energy use. For instance, California’s State Water Project pumps water hundreds of miles and uses 2 – 3 kWh/m³, not far from RO’s 3 – 4 kWh/m³ [27]. Therefore, context is critical. When local surface water is readily available, it remains the most sustainable option. However, if the alternative involves long-distance pumping or significant groundwater depletion, desalination may present a more balanced and competitive solution.

6.21.3 SWRO Against Water Reuse

Reclaimed water (treating municipal wastewater to potable standards) is often cited as a lower-energy alternative to desalination. Treating sewage to potable water usually involves microfiltration, RO, and advanced oxidation. Ironically, reuse often uses RO too (to remove trace contaminants). However, the water being treated is freshwater (low salinity), so the RO in reuse uses much less pressure (10 bar as against 60 bar) and thus much less energy. An indirect potable reuse system might use 1 kWh/m³ or less. For example, Orange County’s Groundwater Replenishment System (advanced reuse) uses 0.8 kWh/m³. The GWP then could be 0.6 kg CO₂/m³ if grid powered, or lower if green energy. Our renewable SWRO is 0.45 kg, which is in the same ballpark or even a bit less. But if that reuse plant also goes renewable, its GWP could drop to 0.1 – 0.2 kg. So, reuse generally has an edge due to lower energy and also no brine generation (though it does have a concentrated waste that goes to the sewer or disposal). Many analyses (as cited in our Literature Review) concluded that water reuse and efficiency should be prioritized before desalination, where possible [27]. From an LCA standpoint, reuse typically has lower impacts across the board than seawater desalination, except perhaps slightly higher human toxicity if trace

contaminants are an issue (e.g., handling of RO concentrate with pharmaceuticals). But overall, reuse is complementary: it can reduce the need for desalination by recycling local water.

6.21.4 SWRO Against Thermal Desalination

Though not a direct alternative for Cape Town (which does not have cheap waste heat or oil), it is worth comparing RO to distillation (Multi-Stage Flash, Multi-Effect Distillation) as used in the Middle East. Thermal desalination often cogenerates with power plants, using waste heat, but still tends to be more energy-intensive in total. LCAs have shown that RO generally has lower environmental impacts than MSF or MED for equivalent water production. For instance, one study found an MSF plant had significantly higher GWP and other impacts due to the fuel required to generate the steam [27]. Our renewable RO at 0.45 kg CO₂/m³ is massively lower than a typical MED on fossil (10 – 15 kg CO₂/m³ if the heat is from fuel). Even if thermal uses waste heat, the combined power plant emissions allocated to water still often exceed RO's if that power plant is fossil. Therefore, from a comparative LCA view, SWRO (especially with energy recovery) is the most efficient desalination method currently available [15]. So, within desalination options, our focus on RO is indeed on the lower-impact choice. If the V&A plant had tried a thermal process, it likely wouldn't be viable anyway because there is no cheap steam, and a smaller scale does not suit MSF, but the impacts would have been worse.

6.22 Economic and Practical Context

While not the focus of LCA, it is worth noting that renewable-powered desalination can now be cost-competitive in many regions. The falling cost of solar and wind has made the idea of powering energy-intensive processes with clean energy economically feasible. For instance, new large desalination projects in the Middle East (like NEOM in Saudi Arabia, or UAE projects) are integrating huge solar farms to offset energy needs [182]. Our case is a bit different because 2 MLD is small. The integration of ANN for optimizing operation can also reduce operational costs, e.g., predicting fouling to clean membranes at the optimal time saves energy and prolongs membrane life, which saves money and reduces impacts.

From a policy perspective, this comparative assessment underscores the value of a portfolio approach in water resource management, which prioritizes water conservation and reuse due to their minimal environmental impact, uses surface water where accessible, and employs desalination, preferably powered by renewable energy, to address any remaining supply gaps. Cape Town itself is doing exactly that by improving wastewater reuse, fixing leaks, and planning a mix of small desalination plants with renewable energy purchasing.

6.22.1 Comparative water quality and environmental impacts

Desalinated water is often of higher purity (low hardness, nearly no contaminants) compared to other sources. That is a benefit in water quality, but requires remineralization to avoid pipe corrosion. Reused water might have trace organics of concern if not fully removed, which is a potential risk. Desalination has brine, which affects the marine environment. Reuse has a concentrate that usually goes to the sewage outfall (which might slightly increase loading on a wastewater plant, but much less saline than brine). Surface water use can have a big land footprint (dams flooding land, affecting river ecosystems). So every source has an environmental cost. A holistic policy would weigh these: e.g., building a dam might have a large one-time ecological impact, desalination has ongoing energy use and brine, and reuse has a bit of energy and public perception issues.

Our LCA suggests that if powered by renewables, the ongoing environmental cost of desalination becomes much more manageable, essentially addressing the brine issue and some supply chain emissions from chemicals. This means desalination could be scaled without a proportional scaling of emissions. For global context, if all desalination plants in the world (22,000+ plants) were switched to renewable energy, the reduction in CO₂ emissions (153 million tons/year from current fossil power) [183] would be like removing a significant number of cars off the road. It also aligns desalination with climate change mitigation goals rather than working against them (solving water shortage but worsening climate).

6.22.2 Benchmarking with Ideal Targets

As an ambitious note, if chemical and brine impacts could be minimized (for instance, by developing green antiscalants that are biodegrade, harmlessly, or by using ANN to

optimize chemical doses to the minimum effective level, and by employing innovative brine disposal like mixing with power plant cooling water to dilute), then the environmental profile of desalination could further approach that of conventional water. Some ideas include harvesting salt from brine (reducing direct ocean discharge) or using brine in aquaculture or other industrial processes [161]. Those are outside LCA typically, but a circular economy approach to brine could turn a waste into a product, improving overall sustainability.

In conclusion, our SWRO system, when powered by renewable energy, compares quite favorably to other water supply options on many environmental metrics except those inherently related to the salt waste. The comparative assessment reinforces that energy source is the differentiator for desalination's standing among water options, and once addressed, desalination can be part of an environmentally sustainable water portfolio. Additionally, employing ANN and smart controls can fine-tune its operations to further narrow the gap by trimming unnecessary energy or chemical use, making desalination an even more competitive option in the global quest for water security.

6.23 Discussion

The findings of this study provide important insights into how seawater desalination can be made more sustainable and what practical measures can be taken to minimize its environmental footprint.

6.23.1 Interpretation

In this section, we interpret the results in a broader context, discuss the role of emerging technologies (like ANN and renewables integration) in global desalination practices, address limitations of the study, and propose recommendations for stakeholders.

6.23.2 Integration of Renewable Energy as a Transformative Solution

One of the clearest messages is that powering RO desalination with renewable energy is a transformative solution for its life cycle impacts. Traditional desalination has been criticized for its high energy use and associated emissions, but our results demonstrate that by sourcing electricity from wind, solar, or other renewable energy sources, a SWRO plant's GHG emissions can be slashed by roughly 90% [162]. This transforms

desalination from a carbon-intensive last resort into a viable component of climate-resilient water infrastructure. For policy-makers and planners, this implies that new desalination projects should be coupled with renewable energy development wherever possible. In regions with abundant sun or wind (which is often the case where water is scarce, like arid coastal areas), there is a synergistic opportunity, e.g., installing solar panels in deserts to run coastal desalination plants supplying cities. The Global Clean Water Desalination Alliance's target of 20% new desalination capacity with renewables by 2025 [159] is a step in the right direction, and our results suggest that aiming even higher is justified. Already, countries like Saudi Arabia and UAE are pioneering solar-powered desalination facilities [182], and this study provides quantitative support for the environmental merits of such approaches.

6.23.3 Artificial Neural Networks for Optimization

The emphasis on ANN in this study highlights its potential to further enhance operational efficiency and sustainability. While ANN models do not directly reduce the inherent energy needs of desalination, they enable better control and prediction. For instance, our use of ANN showed how adjusting operating conditions in real time (e.g., throttling pressure down when water temperature rises or predicting the optimal cleaning schedule) can yield incremental improvements in energy and chemical use. On a global scale, widespread adoption of ANN-based control systems in desalination could lead to significant cumulative savings. Thinking of dozens of large desalination plants each saving a few percent of energy due to smart optimization could equate to hundreds of MWh saved daily worldwide. Moreover, ANNs can be used to predict membrane fouling or performance decline [164], allowing preventive maintenance that keeps the plant running at optimal efficiency. This reduces downtime and potentially extends membrane life (reducing waste and replacement frequency). ANN can also assist in power management, especially if integrated with renewable energy sources e.g., an ANN might predict a drop in solar output and adjust desalination throughput temporarily to balance the grid or use stored water during low power periods. Some studies have proposed ANN-based energy management for off-grid hybrid renewable-desalination systems [184].

In a global context, the use of AI and ANN is growing in the water sector. Countries like Spain, Australia, and the US are experimenting with AI for plant operations. As water systems become more digitized (Industry 4.0), desalination stands to benefit greatly because it is energy-heavy and data-rich (many sensors and control variables). Our study basically validates that an ANN model can capture the complex interactions in RO operation and thus be a valuable tool. We would recommend that new desalination plants incorporate digital twin models (ANNs being a form) from the design stage, to continually refine and optimize performance over the plant's life. The global context is that water scarcity is increasing, so desalination capacity is projected to grow rapidly [185]. If these new plants are “smart” and “green” (AI-optimized and renewably powered), we can mitigate much of the environmental impact that otherwise would accompany this growth.

6.23.4 Brine Management Remains a Priority

Our LCA pinpointed that after dealing with energy, the brine concentrate is the next big environmental challenge. Even with full decarbonization, each cubic meter of freshwater yields a significant amount of brine that can harm local marine ecosystems if not properly handled [161]. This is an area where LCA as a tool is limited (since it doesn't fully capture site-specific ecological effects), so it must be addressed through engineering and regulation. Discussions globally have included designing diffusers to achieve rapid mixing (to reduce salinity at discharge point), blending brine with other effluents (e.g., power plant cooling water or treated sewage) to dilute it [174], using offshore discharge points away from sensitive habitats, or even exploring zero liquid discharge (ZLD) systems that evaporate brine to solids (which is costly and energy-intensive). Another promising avenue is resource recovery from brine, extracting salts or minerals that can be sold. For example, there is a research on harvesting magnesium, calcium, and even lithium from desalination brines [186, 187]. If economically viable, this could offset some costs and reduce the volume of waste brine. Our composition analysis confirms that brine is rich in minerals like magnesium (2.3 g/L) and calcium (0.7 g/L) which could be precipitated out, potentially yielding useful byproducts (magnesium hydroxide, gypsum, etc.) while reducing the salinity of final effluent [186].

The discussion we want to highlight is: as we clean up the energy side, the focus of innovation should shift to brine management techniques. Environmental authorities may need to update guidelines, for instance, setting limits on how much salinity increase is acceptable at a certain distance from the outfall, or requiring periodic monitoring of benthic communities near discharge points [174]. Some regions (like the Gulf) are already heavily impacted by cumulative brine discharge, leading to higher ambient salinity; global coordination or at least national strategies will be needed to ensure desalination does not unduly degrade coastal environments as it scales up [160, 161]. In our case study, the plant is small and the brine impact is localized; but for larger plants, more robust brine mitigation is necessary.

6.23.5 Practical and Actionable Overview

For desalination plant operators and designers, our results yield several actionable insights:

6.23.6 Invest in Energy Recovery and Efficiency

The V&A plant had an isobaric energy recovery device, which is crucial. Ensuring such devices operate at top efficiency and considering upgrades as technology improves (e.g., newer ERDs with even less loss) can further shave energy needs. The sensitivity showed that a few per cent changes in efficiency slightly alter impacts, so it is worth keeping ERDs well-maintained.

6.23.7 Renewable Energy Integration

If not directly on-site, pursue power purchase agreements for renewable energy. This might not change on-site operations, but shifting the source of electricity is the single biggest action to reduce LCA impacts. Some plants could consider installing solar PV on plant premises or adjacent land (many desalination plants have large flat roofs or nearby unused land).

6.23.8 Optimize Chemical Use

Use ANN or advanced control to dose the minimum effective amount of chemicals. Also, explore alternatives: e.g., if there are more environmentally friendly anti-scalants or if carbon dioxide dosing for pH adjustment can replace sulfuric acid, etc., these are

worth evaluating. Some new pretreatment methods (ultrafiltration membranes, advanced intake screens) can reduce the need for coagulants and biocides, thereby lowering chemical-related impacts. Our results show that once energy is clean, chemicals become a major part of the remaining impact in categories like toxicity [162].

6.23.9 Membrane Selection and Replacements

Use high-rejection, high-surface-area membranes to maximize efficiency, and consider durable coatings to reduce fouling (some new RO membranes have antifouling surfaces). Fewer cleanings and longer life mean fewer impacts.

6.23.10 Monitoring and Data Analytics

Continuously monitor performance. If energy usage goes up, it might indicate fouling, clean the system optimally. If the pressure drop increases, check the pretreatment. ANN models can forecast when metrics are trending poorly so operators can intervene proactively.

6.23.11 Plan for Seasonal/Condition Changes

For example, if an algae bloom is expected (which can clog intakes and require more chlorination), being prepared to adjust operations like reducing throughput or enhancing pretreatment temporarily can avoid catastrophic fouling events that would consume huge amounts of chemicals to recover from.

6.23.12 Public Communication

When implementing desalination, especially with new technology, steps taken should be well communicated and documented for sustainability. For instance, public acceptance is more readily achieved when it can be demonstrated that a facility operates on **solar energy** and incorporates **state-of-the-art brine diffusers** to safeguard marine ecosystems, as against the outdated perceptions of desalination plants powered by a polluting energy source and harming aquatic life.

6.23.13 Limitations of LCA

While the LCA was extensive, a few limitations should be acknowledged:

➤ The site-specific nature

The case study is a small plant. Results for a larger open-sea plant might differ slightly with bigger pumps, but also with better economies of scale. This was generalized in the discussion, but one should be cautious applying numeric results directly to a different scale or technology without adjustment.

➤ Ecoinvent data accuracy

Some background processes such as chemical production may not perfectly reflect South African conditions. The best available data was used. The uncertainty analysis covers some of this.

➤ Exclusion of some impacts

As noted, the ecological impact of brine in the LCIA was not quantified due to method limitations. Also, social and economic impacts are outside LCA's purview but are critical in real-world decisions. For example, desalination is costlier than surface water. However, costs are coming down with renewables.

➤ Focus on operational LCA

The operational phase was emphasized, as construction was minor per m³. In conducting a carbon payback analysis for a desalination plant compared to alternative water supply options, it is important to account for construction-related emissions. While these emissions are relatively minor compared to the cumulative operational emissions in fossil-fuel-powered scenarios, they represent a larger proportion in renewable-powered systems, though still modest in absolute terms.

6.23.14 ANN scope:

We used ANN mainly for operational parameters. There are other artificial intelligence approaches that are applied to predictive maintenance, which we did not explore in this study.

6.23.15 Broader Implications

In a future where both water scarcity and climate change intensify, renewable-powered desalination stands out as a synergistic solution, addressing water needs without exacerbating climate issues. It also decouples water production from rainfall, which is becoming less reliable in many regions (like the Western Cape's drought). Our study reinforces that desalination, historically as energy-thirsty, can evolve into a more environmentally harmonious technology. It invites a mindset shift: rather than viewing desalination as a last resort with heavy impacts, we can start viewing it as a viable augmentation strategy whose impacts can be well-managed.

The global desalination community is indeed moving in this direction. In addition to renewables and ANN, there's research on energy storage integration (to store excess renewable energy as water, by over-producing water when energy is abundant and storing it in reservoirs), and hybrid systems (combining RO with forward osmosis or other processes for better efficiency in certain contexts). We did not delve into this topic, but mentioned them as exciting areas where LCA will again be needed to ensure those innovations actually yield net benefits.

6.23.16 Water-Energy Nexus and Policy

This study highlights the water-energy nexus, and how solving water problems and energy problems can go hand in hand. Policy-makers should encourage cross-sector collaboration, e.g., energy ministries working with water utilities to guarantee renewable power for water projects. Subsidies or incentives for renewable energy use in critical infrastructure like water supply might be warranted. Conversely, water utilities might invest in their own renewable generation assets if allowed.

6.23.17 Inference

The LCA results and analysis confirm that a renewable energy-powered, and ANN-optimized RO desalination system can produce freshwater with obviously reduced environmental impacts. The main remaining challenge is brine discharge, for which strategies were discussed. By adopting the recommendations above, desalination operators can further minimize their footprint. This aligns with global sustainability goals: providing clean water (UN SDG 6) while taking climate action (UN SDG 13) and

fostering innovation (UN SDG 9). The convergence of clean energy, smart technology, and environmental stewardship in desalination is not just theoretical, it is already being implemented in leading projects, and this study provides evidence that these efforts are on the right track.

In essence, the narrative is shifting from “desalination environment” to “desalination and environment,” where, with thoughtful design and operation, desalination can secure water for communities without disproportionately harming the planet. Our case study exemplifies this balance, and the insights gained are broadly applicable as nations chart their water futures in an era of uncertainty and change.

6.24 Conclusion

This study set out to examine the life cycle environmental performance of a renewable energy-powered seawater RO desalination system, using the V&A Waterfront plant in Cape Town as a representative case. Through detailed LCA modeling and the integration of an ANN-based simulation of plant operations, we have arrived at several key conclusions and recommendations:

6.24.1 Dramatic Reduction in Environmental Impacts with Renewable Energy

Powering the SWRO desalination plant with renewable electricity cuts its life cycle GHG emissions by roughly 90% compared to a grid-powered scenario [162]. The carbon footprint of the produced water drops from 3.8 kg CO₂/m³ to 0.4 kg CO₂/m³, putting it on par with or even below other water supply options in terms of climate impact. Other air emissions and fossil resource use are likewise drastically reduced. This demonstrates that renewable-powered desalination is a viable and much more sustainable approach to securing freshwater in water-scarce regions. We recommend that future desalination projects be developed in tandem with renewable energy sources or that existing plants transition to green power where possible.

6.24.2 Comparable to Conventional Water Supply in Many Aspects

When supplied by clean energy, the SWRO system’s impacts (energy use, GHGs, air pollutants) become comparable to those of conventional water treatment and water reuse systems. While traditional surface water is still less energy-intensive, the gap

has narrowed significantly. In terms of GWP, our renewable SWRO at 0.45 kg CO₂/m³ is within the range of advanced recycled water (0.3–0.6 kg) [27]. This means desalination need not be the “last resort” from an environmental view, if done thoughtfully, it can be part of a sustainable water portfolio.

6.24.3 Energy Remains the Dominant Factor

The LCA confirmed that energy supply is the dominant contributor to most impact categories for desalination. By solving the energy emissions issue (via renewables), we solve most of the desalination’s environmental issues. This highlights the strong link between water and energy policy. Water planners should work closely with energy sectors to ensure desalination expansion is accompanied by clean energy investment. As an outcome, improving the energy efficiency of RO (through high-efficiency pumps, energy recovery, and operational optimization) directly translates to environmental gains. Every 1 kWh saved per m³ avoids 0.9 kg CO₂ in a coal scenario or helps accommodate more output in a renewable scenario.

6.24.4 Brine Discharge and Marine Impacts Require Ongoing Attention

Even with near-zero carbon emissions, the desalination process inherently produces concentrated brine waste (60 PSU salinity), which can impact marine ecosystems if not managed properly [161]. Our analysis of brine composition showed a roughly 1.7-fold concentration of all seawater salts, with chloride and sodium dominating (55% and 30% of TDS) and minor constituents like Mg, Ca, K present [181]. This composition, while not chemically novel (no new substances, just concentrated saltwater with trace additives), can cause localized high-salinity stress. We conclude that effective brine management practices, such as diffusers that achieve high dilution, periodic monitoring of receiving waters, and considering innovative uses of brine, are essential to ensure desalination’s sustainability. Regulatory standards for brine discharge should be developed or strengthened to protect coastal environments, and desalination plants should be designed to meet these standards using the best available techniques. In short, solving the “carbon problem” of desalination shines a spotlight on the “salinity problem,” which must be tackled with equal vigor.

6.24.5 Chemical Use and Other Impacts

With the energy impact mitigated, impacts from chemicals and materials take on greater relative significance. The study found that chemical consumption (antiscalants, acids, etc.) now contributes a major share of categories like marine ecotoxicity and human toxicity [162]. While these impacts are modest in absolute terms, they suggest that greener chemical alternatives and dosing optimization are worthwhile. Plants should strive to use the minimum effective chemical doses and explore biodegradable or less harmful chemicals. Additionally, any reduction in chemical usage also reduces operating costs and diminishes the load of pollutants in the brine. On the materials side, although infrastructure impacts were minor, using longer-life materials (e.g., corrosion-resistant alloys) and recycling used membranes can further reduce life cycle burdens.

6.24.6 Artificial Neural Networks Enhance Sustainability and Reliability

The incorporation of ANN modeling in this study proved beneficial for understanding and optimizing the RO plant's operation. The ANN predictions aligned well with observed trends, and in a real operation could enable dynamic adjustments to minimize energy per unit output. We conclude that ANN-based control systems can be an effective tool to fine-tune desalination processes, resulting in incremental efficiency gains (on the order of a few percent in energy and chemical savings) that cumulatively have meaningful environmental and economic benefits. Moreover, ANN can improve reliability by predicting issues before they escalate, thereby preventing failures that might otherwise lead to higher impacts (for example, severe fouling leading to membrane replacement or emergency shutdown). We recommend that desalination facilities invest in digital monitoring and AI-driven analytics to continuously improve performance. The global desalination industry should share data to allow machine learning models to be trained on large datasets, improving their accuracy and utility.

6.24.7 Sensitivity Robustness

Our sensitivity analyses reinforced that the central findings (particularly regarding energy source) are robust. Even under variations of recovery rates or other parameters, the renewable-powered system maintained a vastly superior environmental profile compared to a fossil-powered one. This robustness suggests that

our primary recommendations (shift to renewables, focus on brine and chemical management) hold true across a range of operating conditions. While site-specific factors can influence exact numbers, the qualitative direction of improvement remains consistent.

6.24.8 Sustainable Desalination is Achievable

Overall, the study demonstrates that sustainable desalination is not a myth, but an attainable goal. By leveraging clean energy and advanced process control, a desalination plant can produce essential freshwater with minimal environmental impacts. In places like Cape Town, and many other coastal cities facing climate-induced droughts, this offers a lifeline that aligns with environmental stewardship. It turns the once valid criticism (“desalination solves water woes at the cost of high emissions”) on its head: we can now say desalination can solve water woes *with* low emissions.

6.25 Recommendations

6.25.1 Policy Integration

Policymakers should integrate desalination plans with renewable energy targets. For example, if a country plans X cubic meters/day of new desalination by 2030, they should concurrently plan Y MW of new renewable capacity to power it. Incentive mechanisms (tax credits, low-interest loans) could be introduced for desalination projects that use renewable energy or innovative brine management. Environmental regulations should evolve to require EIA (environmental impact assessments) for desalination projects to consider greenhouse gas emissions and brine effects, and to proffer designs that mitigate these (such as renewable energy sourcing and diffuser installations).

6.25.2 Technology and Innovation:

Continued R&D is needed in a few areas such as:

- ❖ High-efficiency RO membranes: including graphene oxide or nano-engineered membranes that promise lower energy consumption at the same or better salt rejection [35], which would directly cut impacts.
- ❖ Brine valorization: new processes to extract minerals or generate useful products from brine (for example, producing sodium hydroxide and hydrochloric

acid via electrodialysis for local industries, as some researchers propose, achieving near-zero liquid discharge).

- ❖ **Energy storage & load management:** since renewables are intermittent, technologies like batteries, pumped storage using produced water, or flexible operation (using ANN to ramp desalination up and down based on power availability) should be explored to ensure stable water output with variable power input.
- ❖ **Biomorphic energy recovery:** exploring whether pressure exchangers can approach nearly 100% efficiency or using emerging concepts like isobaric turbines in multi-stage arrays.

6.25.3 Environmental sensors

Deploying sensors around outfalls and feeding data into AI models that can help dynamically adjust plant operation to protect marine life.

6.25.4 Holistic Water Planning

Desalination should be one component in an integrated water management strategy that includes demand management, recycling, and catchment management. Each water source's impacts and resilience should be weighed. Our results can feed into water supply planning models by providing updated environmental cost metrics for desalination under different energy scenarios, enabling planners to do multi-criteria decision analysis of cost, environmental impact, and reliability.

6.25.5 Public Outreach and Education

The stigma around desalination as “unsustainable” should be addressed with transparent information. This paper's findings could be distilled into outreach material showing, for example, that a desalinated liter of water powered by solar has a carbon footprint similar to that of a litre of local reservoir water. When people understand that desalination technology has matured and become cleaner, public acceptance will grow, easing the implementation of necessary projects.

6.25.6 Continuous LCA and Monitoring

We recommend that operators treat LCA as a living process. They should periodically update their LCA as operations change, using their plant data and use it to guide improvements. For instance, if a particular chemical is contributing disproportionately to toxicity indicators, they can investigate alternatives. Likewise, industry benchmarks can be established.

In closing, as climate change and population growth intensify water scarcity, desalination will play an increasingly important role globally. The challenge before us was to do it in an environmentally responsible way. This study provides evidence that through renewable energy integration and smart process management, that challenge can be met. The V&A Waterfront desalination plant, once an emergency stop-gap, can serve as a model for future “green desalination” facilities around the world. By implementing the insights and recommendations outlined, stakeholders can ensure that desalination delivers its life-saving water benefits while aligning with the broader imperatives of sustainability and climate action.

6.26 Future Work

Future research could expand on this work by examining full-scale renewable desalination projects as they come online, including real performance data in LCA validation. It would also be valuable to explore coupling desalination with other systems (for instance, using waste heat from industry for a hybrid RO-thermal process, or integrating desalination with solar thermal plants). Additionally, developing LCA impact categories or methods that better account for salinity stress on marine environments would allow more nuanced environmental assessments of desalination in the future. Integrating economic LCA or life cycle costing alongside environmental LCA would give a complete picture of sustainability. Finally, as ANN and AI methods evolve, their environmental benefits (like energy savings) should be quantified across more case studies to build a business case for their adoption industry-wide.

In summary, the path forward for desalination is clear: decarbonize the input, digitize the process control, and diligently manage the output. By following this path, what was once an “option of last resort” can become a cornerstone of sustainable water supply in the 21st century.

CHAPTER 7: Innovative Recovery Methods for Metals and Salts from Rejected Brine and Advanced Extraction Processes – A Pathway to Commercial Viability and Sustainability in Seawater Reverse Osmosis Desalination

Seawater desalination plays an increasingly critical role in addressing global freshwater shortages. However, it generates significant volumes of concentrated brine containing high levels of dissolved salts and trace minerals, which are typically discharged into the environment. These discharges pose environmental challenges and represent a missed opportunity for resource recovery. This chapter presents an all-inclusive review of recovery methods for major and minor constituents in desalination reject brine, with a focus on enabling commercial-scale metal and salt extraction. The ionic composition of typical brine streams includes chloride, sodium, sulfate, magnesium, calcium, potassium, bicarbonate, and bromide. Various extraction techniques are examined, including membrane-based separations (nanofiltration, electrodialysis), thermal crystallization, evaporation, chemical precipitation, and electrochemical recovery.

Case studies, simulated process flow models, and cost assessments are used to demonstrate the feasibility of integrated brine mining systems. These systems show the potential to recover over 90% of salts while approaching zero-liquid-discharge (ZLD) freshwater recovery targets. Findings suggest that in many cases, the revenues from recovered products can exceed additional processing costs, particularly when renewable energy sources and shared infrastructure are explored. The chapter proposes a technical and economic framework for incorporating mineral recovery processes into new and existing seawater reverse osmosis (SWRO) desalination plants. Examples from operational pilots and commercial ventures support the practical application of these strategies. This approach contributes to the transition toward circular economy principles by transforming brine from a waste stream into a resource stream, thereby improving the environmental and economic sustainability of desalination. The content in this chapter, co-authored with Prof. Oludolapo A.

Olanrewaju, has been submitted and is currently under review in “Water”, an open access journal from MDPI - Manuscript ID: water-3740139.

7.1 Introduction

Water scarcity is a growing global challenge, leading to the rapid expansion of seawater desalination capacity in arid and semi-arid regions. Modern desalination plants, particularly those utilizing seawater reverse osmosis (SWRO), generate substantial quantities of concentrated saline brine as a byproduct. As of 2018, approximately 16,000 desalination plants globally, with capacity concentrated in the Middle East and North Africa, produced 95 million m³ of freshwater per day, while simultaneously discharging an estimated 142 million m³ of hypersaline brine per day, exceeding the net freshwater output. [82, 161, 185]. Rejected brine generally contains roughly twice the salinity of seawater, along with residual treatment chemicals. Brine often contains residual treatment chemicals such as antiscalants e.g. polyphosphonates and polycarboxylates, biocides e.g. DBNPA and isothiazolinones, dechlorination agents e.g. sodium bisulfite, coagulants and flocculants including ferric salts, alum and polyamines, and common CIP reagents including sodium hydroxide, mineral and organic acids, and surfactants. These additives can complex calcium and magnesium, hinder precipitation, foul membranes or ion-exchange resins, and reduce product purity. Mitigation includes upstream polishing by activated carbon or oxidation, nanofiltration divalent splits, controlled pH and alkalinity staging, selective reagent choice, and limited purge before recovery steps. Its discharge into the marine environment is widely regarded as a waste byproduct, raising concerns over elevated salinity, thermal stress, oxygen depletion, and toxic contamination of aquatic and soil ecosystems [188-190]. Table 7-1, presenting the global distribution of desalination plants by region, income level, and sectoral application, is drawn from the comprehensive global assessment conducted by Jones, et al. [82].

Table 7-1 Global Distribution of Desalination Plants and Capacity by Region, Country, and Income Level [82].

Category	Share of Global Desalination Capacity (%)	Key Countries / Notes
Middle East & North Africa (MENA)	48.0 (Saudi Arabia 15.5, UAE 10.1, Kuwait 3.7)	Major global producers in the Gulf states
East Asia & Pacific	18.4 (China 7.5)	China is the largest contributor
North America	11.9 (USA 11.2)	The USA dominates regional capacity
Western Europe	9.2 (Spain 5.7)	Spain accounts for more than 50% of the regional share
Southern Asia	3.1	Mostly small-scale facilities
Eastern Europe & Central Asia	2.4	Limited capacity, mainly industrial
Sub-Saharan Africa	1.9	Primarily small private/industrial plants
High-income countries	67% of plants, 71% of capacity	Concentrated in the Gulf states, the USA, and Spain
Upper-middle-income countries	Moderate	Includes China and others
Lower-middle-income countries	Small share	Few facilities
Low-income countries	Less than 0.1	Negligible contribution to global capacity
Municipal & domestic supply	Majority	Driven by Gulf countries and urban demand

Industrial use	Significant in some regions	Eastern Europe, Sub-Saharan Africa
Agriculture	Minor	Limited adoption due to cost barriers

Traditional brine disposal methods, such as surface water discharge, deep-well injection, or evaporation ponds, mitigate these issues only partially and are becoming less viable as desalination capacity grows [187, 191]. However, these methods pose serious environmental risks to marine ecosystems, causing localized hypersalinity, oxygen depletion, and toxicity to aquatic life, degrading soil and groundwater if not properly managed [187]. Brine management is shifting from traditional disposal methods due to their harmful environmental impacts. A sustainable approach now emphasizes minimizing effluent and recovering resources such as water, energy, salts, and chemicals. Such resource recovery not only mitigates environmental impacts but also supports progress toward the United Nations Sustainable Development Goal 6 (SDG 6) [192]. Addressing climate change and population growth requires a transition toward circular economy practices centered on resource stewardship. This entails re-evaluating material and resource flows across industries to improve efficiency and reduce waste. Central to this effort is the development of innovative treatment technologies capable of recovering scarce resources from unconventional streams, including industrial wastewater and previously uneconomical sources [193-195]. In water management, such innovation has advanced zero and minimal liquid discharge (ZLD/MLD) systems. ZLD, first adopted by power plants in Colorado to mitigate Colorado River salinity, aims to recover all water while converting residuals into solid salts. Recent developments extend this approach to producing multiple solids.

Meanwhile, MLD systems, targeting about 95% recovery, are increasingly favored for their lower energy demands and reduced capital costs [196]. In response, brine is increasingly reconceptualized not as a waste stream but as a secondary resource from which valuable salts and metals can be recovered, thereby aligning brine management with the principles of a circular economy [197]. Recovering resources from brine could both reduce environmental impacts and offset desalination costs by generating revenue or useful products [198]. Studies from the Canary Islands and the

Arabian/Persian Gulf demonstrate that uncontrolled brine discharges increase seawater salinity and heavy metal levels in waters and sediments, causing biodiversity loss and potential toxin bioaccumulation [199, 200]. These concerns have prompted calls for more sustainable brine management strategies beyond disposal. As desalination capacity grows to meet rising water demand, the volume of brine and its potential environmental impact are increasing correspondingly [82, 188].

However, in line with circular economy principles, this waste brine can be viewed as resource-rich in dissolved salts and minerals that can be recovered and valorized [188]. Converting brine into valuable products offers a dual benefit: mitigating the environmental impacts of brine disposal and improving the economics of desalination by generating additional revenue [188]. Seawater brine from SWRO desalination retains essentially the same ionic composition as seawater, but at roughly double the concentration, assuming 50% water recovery. The major constituents of typical seawater (35 g/kg salinity) are chloride (19.3 g/kg) and sodium (10.8 g/kg), which together make up over 85% of the dissolved ions [201]. Sulfate, magnesium, calcium, potassium, bicarbonate, and bromide comprise most of the remaining 15% [201].

Economically, the recovered products (industrial salts, metals, etc.) can create new revenue streams that offset the costs of desalinated water production [202]. Recent advances in separation technologies and resource recovery processes have made mineral extraction from seawater brine increasingly competitive with conventional mining in the last decade [203]. This is significant given the rising global demand for critical minerals, such as lithium for batteries, or magnesium for advanced materials, which is straining terrestrial mineral reserves [202, 203]. By leveraging the massive volumes of salts already present in the oceans and concentrated in desalination brine, brine mining offers a virtually inexhaustible supply of certain minerals, without the landscape disruption and environmental liabilities of land-based mining [203]. Table 7-2 summarizes the approximate composition of seawater and, hence, a typical SWRO brine and potential recovery products for each ion. These salts and metals have significant industrial value if they can be extracted in usable forms.

Table 7-2 Major ions in typical seawater brine with 70 g/L salinity and potential recovered products [203, 204].

Ion (symbol)	Approx. concentration in seawater brine	Fraction of total salts (%)	Potential recovered product(s)	Example recovery method(s)
Chloride (Cl^-)	35 g/L	55%	Chlorine gas (Cl_2), Hydrochloric acid, NaCl salt	Electrochlorination, membrane electrolysis, solar crystallization
Sodium (Na^+)	19 g/L	30%	NaCl salt, Caustic soda (NaOH), Sodium carbonate (Na_2CO_3)	Crystallization (solar/evaporative), Bipolar electrodialysis, chemical conversion
Sulfate (SO_4^{2-})	5 g/L	8%	Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), Epsom salt ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$)	Precipitation with Ca^{2+} (gypsum) or Ba^{2+} , fractional crystallization
Magnesium (Mg^{2+})	2.5 g/L	4%	Magnesium hydroxide ($\text{Mg}(\text{OH})_2$) / oxide (MgO), Magnesium chloride (MgCl_2), Mg metal	Alkaline precipitation (lime or dolomite), thermal decomposition, electrolytic reduction
Calcium (Ca^{2+})	0.8 g/L	1.20%	Calcium carbonate (CaCO_3), Gypsum (CaSO_4)	Precipitation with carbonate (soda ash), selective crystallization
Potassium (K^+)	0.8 g/L	1.10%	Potash fertilizer (KCl or K_2SO_4)	Evaporative crystallization from bittern, ion exchange concentration
Bicarbonate (HCO_3^-)	0.2 g/L (as CO_3^{2-} equiv.)	0.30%	Calcium carbonate (CaCO_3), CO_2 (gas)	Lime dosing & degassing (CaCO_3 precipitates, releasing CO_2)
Bromide (Br^-)	0.12 g/L	0.20%	Bromine (Br_2) elemental, Sodium bromide (NaBr)	Chemical oxidation (chlorine or ozone) + air stripping, selective adsorption on resin

For example, sodium and chloride can be recovered as high-purity sodium chloride (NaCl) salt, a commodity for de-icing, food in chemical industries, or separated to produce chlorine gas and caustic soda. Magnesium can be recovered as magnesium hydroxide ($\text{Mg}(\text{OH})_2$) or magnesium oxide, which are used in water treatment,

refractory materials and as precursors for magnesium metal [204, 205]. Calcium could be harvested as calcium carbonate or gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) for use in construction and agriculture. Potassium is a valuable fertilizer component, as is KCl or potassium sulfate. Even minor constituents like bromide and boron have niche markets, such as bromine for flame retardants and boron in boric acid for industry. Recovering these from brine can reduce reliance on terrestrial mining of the same elements, some of which are classified as critical raw materials due to supply risks [188, 206].

Mohammad et al. [207] extracted magnesium from desalination brine using ammonium hydroxide, obtaining $\text{Mg}(\text{OH})_2$ of over 95% purity. Their experiments, however, showed that complete conversion was not achievable, with the maximum recovery recorded at 97%. Sadhwani, et al. [199] examined case studies from the Canary Islands, where reverse osmosis was the primary desalination method. Their analysis highlighted potential environmental impacts, including increased energy consumption linked to global warming, noise emissions, land-use pressures, and harmful effects on marine ecosystems. According to Shemer and Semiat [200], the brine discharged from desalination facilities in the Arabian Gulf contributes to increasing seawater salinity levels, reducing dissolved oxygen concentrations and threatens marine stability.

NaCl dominates brine composition by mass, making its extraction central to any large-scale recovery strategy [203]. As the most abundant constituent, NaCl often represents both the principal product and a significant revenue stream. Crystallization of NaCl as a solid salt not only provides a commercial commodity but also leaves behind a residual bittern enriched in divalent ions (Mg^{2+} , Ca^{2+} , SO_4^{2-}) and minor elements (K^+ , Br^- , $\text{B}(\text{OH})_3$), which are more readily recovered at higher concentrations [203]. This sequential approach improves efficiency, as targeting secondary products directly from bulk brine is less viable. Furthermore, in regions where desalination operates alongside salt imports for chlor-alkali industries or deicing, NaCl recovery can enhance local supply chains and economic feasibility.

Beyond common salt, magnesium is typically identified as the next most promising element to recover from seawater brines, due to its relatively high concentration and moderate market value [188]. Global industries consume magnesium compounds for

uses such as flame retardants, wastewater neutralization, and fertilizer, and magnesium metal is in demand for lightweight alloys. Some countries like China and Israel already extract magnesium from seawater or brines at scale [204]. The history of magnesium production includes the notable example of Dow Chemical's Freeport plant in Texas, which, at the beginning in 1941, extracted magnesium from seawater by precipitating magnesium hydroxide with calcined dolomite mixed with CaO/MgO and then electrolysis of the resulting magnesium chloride [205]. At its peak, the Freeport seawater plant produced up to 18,000 tons of magnesium metal per year and supplied the majority of U.S. demand during World War II [205]. This demonstrates that large-scale recovery of minerals like magnesium from seawater is technically feasible given the correct economic drivers. Today, the motivation is shifting toward environmental sustainability and resource efficiency.

In summary, there is significant incentive to recover the dissolved salts and metals from desalination brine: doing so can reduce the environmental footprint of desalination, alleviate marine pollution, and yield commodities that offset operating costs. The key challenge is achieving this economically, since the separation of salts requires energy and/or chemicals. This paper explores innovative recovery methods being developed and deployed to solve this challenge. A range of technologies was reviewed, from established methods like evaporative crystallization to cutting-edge processes such as membrane-based selective ion extraction, and their workability for extensive brine valorization. The business case for brine mining was also analyzed, including cost factors and potential revenue streams, to identify pathways toward commercial viability. The scope is global, drawing on examples and data from facilities and research projects around the world. The aim is to provide a clear understanding of which approaches are most promising for turning desalination brine into a source of metals and salts, and how these can be integrated into sustainable industrial operations. Actionable insights are highlighted to guide future development in this field.

This study contributes a novel framework by integrating membrane separation, chemical precipitation, and crystallization pathways with real-world brine composition data and pilot-scale recovery performance. Unlike previous studies that focus solely on technical feasibility or single-product recovery, this work aligns recovery technologies with commercial market demand, energy integration opportunities, and operational

constraints. The inclusion of empirical correction factors from SEA4VALUE (EU), SWCC (Saudi Arabia), and MINERALS (Spain) pilot projects further enhances realism. The techno-economic analysis scenarios for co-located systems, accounting for brine disposal offsets and market conversion ratios. This multidimensional integration offers a comprehensive and practical pathway toward sustainable and commercially viable brine valorization.

7.2 Methodology

This study employed a broad, multi-tiered methodology integrating analytical review, data synthesis, numerical simulation, and process flow modeling to assess the technical and economic viability of recovering major dissolved constituents from SWRO brine. The approach was structured in six interrelated stages as shown in Figure 7-1.

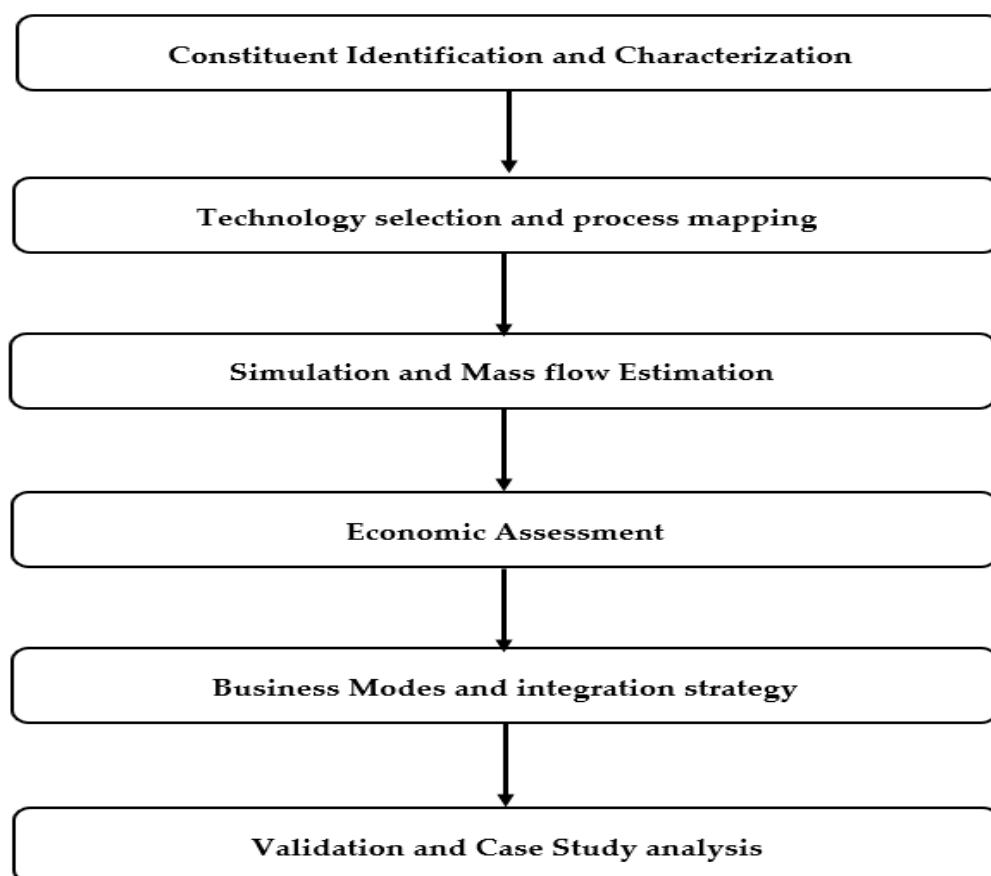


Figure 7-1 Process Flow Diagram

The methodology integrates evidence review, chemical characterization, simulation, techno economic assessment, and validation. Literature in Scopus and Web of Science (2010–2025) was screened for seawater or SWRO matrices reporting quantitative

recovery, energy or cost, product purity, or TEA or LCA results, non SWRO items, duplicates, and studies with insufficient data were excluded. From eligible sources we extracted ion composition, recovery efficiencies, utilities, CAPEX and OPEX, and product purity and price ranges, and cross checked these against pilot evidence from SEA4VALUE, SWCC, and MINERALS. Brine chemistry was defined by major ions (Cl^- , Na^+ , SO_4^{2-} , Mg^{2+} , Ca^{2+} , K^+ , HCO_3^- , Br^-). The model plant was set at 100,000 m³ per day with 45 percent water recovery, brine salinity near 70 g per liter, and oceanic ionic fractions for mass balances. A sequential train was simulated with carbonate dosing for CaCO_3 removal, alkaline dosing for $\text{Mg}(\text{OH})_2$, and evaporative NaCl crystallization, using stoichiometric mass balances and corrections calibrated with pilot data. The techno economic model linked unit operations to costs and revenues using representative energy prices and commodity values, with sensitivity to recovery efficiency, energy price, and product purity. The study assumptions are: steady state operation, oceanic ionic proportions as the baseline, stage recoveries of 96 – 98 percent for Ca removal, 90 – 95 percent for Mg removal, and 90 – 95 percent for NaCl recovery, washed solids with 10 – 15 percent moisture, no heat integration credit in the base case, and product prices as long term averages with regional checks. Comparative analyses were also conducted against conventional terrestrial mining processes to evaluate the relative economic and environmental feasibility of marine resource extraction from desalination brine [188, 208, 209].

7.2.1 Statistical analysis.

Continuous variables were assessed for normality using the Shapiro–Wilk test. For approximately normal data, Pearson correlation was computed, otherwise, Spearman rank correlation was used. Differences among operating scenarios of baseline, waste heat, high price, low price were evaluated with one-way ANOVA, and with Tukey's HSD for post hoc pairwise comparisons. Effect sizes (η^2) and 95% confidence intervals are reported. Statistical significance was defined as $\alpha = 0.05$.

7.3 Recovery Technologies and Processes for Brine Constituents

Recovering multiple minerals from a complex solution like seawater brine is inherently challenging and typically requires a sequence of separation steps. The technologies for brine recovery can be classified into several categories:

- Membrane-based separation using pressure or electrical potential to separate ions selectively
- Thermal processes and crystallization, evaporation, or cooling to precipitate salts
- Chemical precipitation: addition of reagents to selectively remove target ions as insoluble compounds
- Adsorptive or ion exchange processes using sorbents or extractants to capture ions selectively.

Often, hybrid systems combining multiple methods yield the best results, for example, membrane concentration followed by chemical precipitation [198]. In this section, each category was discussed, including the specific techniques, their target ions, and practical considerations. Emphasis is given to commercially proven or pilot-demonstrated methods capable of recovering the major ions listed earlier. Integrating ion fractionating membranes such as NF or selective IEMs, targeted precipitation with optional nanobubbles, and staged crystallization reduces scaling risk, lowers reagent and evaporation demands, and increases total salt recovery.

7.3.1 Membrane Separation Processes

Membrane-based processes use semi-permeable membranes to separate ions or water from the brine, driven by pressure or electrical potential. These processes can achieve separation without phase change or evaporation, potentially offering lower energy consumption for partial separations. Key membrane technologies for brine mining include nanofiltration (NF), reverse osmosis (RO) at high pressure, and electrodialysis (ED), which includes variants like bipolar ED.

7.3.1.1 Nanofiltration

NF is a pressure-driven membrane process similar to RO but with membranes that have a larger pore size or different charge characteristics, allowing partial selectivity for divalent against monovalent ions. NF can be used on brine to preferentially reject multivalent ions such as Mg^{2+} , Ca^{2+} , SO_4^{2-} , while allowing most NaCl to pass, effectively splitting the stream into a permeate rich in NaCl and a divalent-enriched concentrate [203]. This approach is useful as a first step to isolate high-purity NaCl.

For example, a two-stage NF-RO system was demonstrated in pilot studies by Saudi researchers to concentrate SWRO brine with an initial 70 g/L up to 250 g/L NaCl in the permeate stream, which could then be crystallized as pure salt [210]. The NF concentrate, containing hardness (Ca/Mg) and sulfate, can be treated separately. The challenge with NF on brine is the high osmotic pressure and scaling tendency, and cutting-edge high-pressure NF (HPNF) membranes and multi-stage setups are required to reach near-saturation concentrations [210]. However, NF offers a highly effective way to perform a bulk separation of monovalent and divalent ions with relatively low energy input compared to evaporating the entire brine [203].

This monovalent/divalent split aligns with the strategy of removing NaCl first. Recent innovations include special NF or RO membranes embedded with chemical groups to target specific ions. For instance, a Water Innovation Center in NEOM (Saudi Arabia) developed a modified RO membrane that is permeable to water and a chosen mineral ion, enabling concurrent extraction of a concentrated mineral solution during desalination [211-213]. In a prototype, such a membrane captured over 99% of a target ion, presumably a monovalent ion like Na^+ or K^+ , into the permeate, which was then further processed in a second-stage RO to precipitate the pure salt [212, 213]. This indicates the potential of selective membrane technologies for one-step recovery of particular salts.

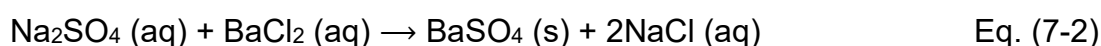
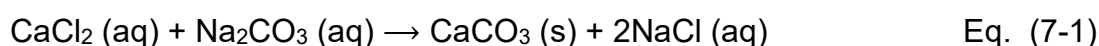
7.3.1.2 Reverse Osmosis and Osmotically Assisted

Standard SWRO itself separates fresh water from salts, but is limited by osmotic pressure to about 50 - 60% recovery on seawater. RO can be operated at higher pressures or enhanced by osmotic agents to concentrate brine further. High-pressure RO (HPRO) can push the recovery higher using specialized pumps and membranes, and has been tested to bring brine to over 120 g/L salinity [214]. An emerging variant **is** Osmotically Assisted RO (OARO), where an osmotic agent such as a concentrated draw solution is used on the permeate side to reduce the transmembrane pressure difference needed, allowing RO to continue the concentration of brine beyond normal limits [203]. Improvements in membrane materials and module design are enabling RO processes to approach the crystallization point of salts. However, purely pressure-driven concentration to dryness is generally not economical due to exponentially rising osmotic pressure. Instead, RO/OARO is best used to minimize the brine volume,

reducing it by three time, after which other methods take over [203]. Indeed, pilot studies show that integrating HPRO with downstream crystallizers can achieve above 98 – 99% water recovery at a reasonable cost. A report documented 99.36% water recovery with a treatment cost of \$1.04 per m³ of fresh water, using RO plus brine concentrator units [215]. These high-recovery RO systems significantly cut the volume that needs thermal evaporation, thus optimizing overall energy use.

7.3.1.3 Electrodialysis

Electrodialysis uses an electrical potential to pull cations and anions through ion-exchange membranes, separating them into product streams. In a typical ED stack, alternating cation and anion exchange membranes are placed between electrodes, under a DC voltage, cations migrate toward the cathode through cation-selective membranes and anions toward the anode through anion-selective membranes [198]. ED is particularly useful for extracting specific ions or concentrating them if suitable membrane arrangements are used. A notable variant is bipolar membrane electrodialysis (BMED), which can split neutral salts into acid and base. For example, NaCl brine can be converted into HCl and NaOH streams by BMED, providing chemicals that can be reused, e.g., NaOH for alkaline precipitation, HCl for dissolving precipitates, or sold [198]. Research has shown ED can recover elements like lithium, boron, and bromide from brines by pairing selective membranes or electrode reactions [188]. Membrane electrolysis, which can be seen as a form of ED where the product at one electrode is a gas and the other extracted element is applied in the chlor-alkali industry, brine is electrolyzed to yield Cl₂ gas, H₂ at the cathode, and NaOH. This industrial process could be coupled with desalination brine feeds [204]. A real-world synergy example is using SWRO brine as feed for a chlor-alkali plant, where firstly, hardness and sulfate are chemically removed to protect the electrolyzers, then the purified NaCl brine is electrolyzed. Melián-Martel, et al. [216] demonstrated such a process for reusing 8400 m³/day of SWRO brine in chlorine production. They removed calcium by carbonate precipitation and sulfate by barium dosing, as shown in the reactions (Eq.7-1 and Eq. 7-2) below:



These precipitation reactions are highly effective because both calcium carbonate and barium sulfate have low solubility in water. The use of these steps prepares the brine for further industrial processing, such as chlor-alkali electrolysis, by removing scale-forming and interfering ions. After removing Ca as solid calcium carbonate and sulfate as barium sulfate, the remaining brine was largely NaCl, which could be fed to membrane electrolyzers to produce chlorine and NaOH [204]. This example illustrates how ED or electrolysis technologies can recover chloride as elemental chlorine gas and convert sodium to sodium hydroxide, both of which are high-purity chemical commodities. The limitations of ED include membrane fouling at high concentrations and the fact that it generally cannot crystallize solids. It can concentrate ions, but a final crystallization or precipitation step is needed to produce the solid products. Still, ED has been reported to achieve up to 76% overall salt recovery efficiency in test setups, often in combination with crystallization units [198].

7.3.1.4 Forward osmosis (FO)

FO concentrates SWRO brine by exploiting an osmotic gradient between the brine feed and a high-osmotic-pressure draw solution. Water diffuses across a semipermeable membrane into the draw, increasing brine salinity upstream of crystallization. The principal mechanisms are solution–diffusion transport with performance governed by internal concentration polarization, membrane structural parameter, and draw solute selection. FO can operate at low hydraulic pressure with reduced scaling risk relative to high-pressure RO, making it attractive as a pre-concentration step before evaporative NaCl recovery. Reported case studies show stable flux at high TDS, with practical gains when FO is thermally or chemically coupled to draw regeneration. In integrated trains, FO reduces evaporation duty and can smooth brine variability, improving downstream crystallizer control.

7.3.1.5 Functional selective membranes for ion fractionation

Ion fractionation targets selective passage or rejection of specific ions to split monovalent-rich from divalent-rich streams. Two routes are emphasized: (i) monovalent-selective NF using charged/functionalized thin-film layers where Donnan exclusion and size sieving favor Na^+/Cl^- transport while retaining $\text{Mg}^{2+}/\text{Ca}^{2+}/\text{SO}_4^{2-}$ and (ii) permselective ion-exchange membranes for ED/EDBM that increase $\text{Na}^+/\text{Mg}^{2+}$ or

$\text{Cl}^-/\text{SO}_4^{2-}$ selectivity through tailored fixed-charge density, hydration-shell discrimination, and surface functional groups. Mechanistically, selectivity arises from charge repulsion, pore-wall affinity, and dehydration penalties for multivalent ions. Salient results in the literature report high sulfate rejection with high NaCl transmission (NF) and improved Na^+ over Mg^{2+} transport numbers (ED with monovalent-selective IEMs), enabling a NaCl-rich stream for salt production and a divalent-enriched side stream conditioned for $\text{Mg}(\text{OH})_2$ or CaCO_3 precipitation. These fractionation steps reduce scaling, lower reagent dose in precipitation, and lift overall recovery efficiencies in hybrid flowsheets.

7.3.1.6 Capacitive Deionization

CDI is an electro-sorption technique where ions are removed by applying an electrical voltage between porous carbon electrodes, causing cations to adsorb on the cathode and anions on the anode. When the electrodes are saturated, the polarity is reversed or the circuit is opened to release a concentrated stream. CDI is more suited to low salinity water, but advanced implementations, such as Flow-electrode CDI and hybrid CDI, have been tested on brines [188]. Some studies showed CDI could recover ions like lithium or nitrate from brine, but the main issue is limited capacity and efficiency at high ionic strength [188, 198]. Over time, electrodes can foul or lose capacity. Thus, CDI is not yet a primary method for bulk salt extraction from seawater brine, but it might serve specific purposes, such as polishing a specific ion from a concentrated solution. In summary, membrane processes offer selective separation that can be tuned for different ions. They are particularly powerful for pre-concentrating brine and isolating streams such as a sulfate-rich stream against a chloride-rich stream before final recovery. Membrane methods generally have the advantage of being modular and potentially less energy-intensive than full evaporation, but they struggle once solubility limits are reached or when handling truly ZLD solid formation. Therefore, they are often coupled with thermal or chemical steps for complete recovery.

7.3.2 Thermal Crystallization and Evaporation

Thermal processes have long been used to recover salts from water, the oldest example being solar saltworks, where seawater is evaporated in ponds to crystallize NaCl. In the context of desalination brine, crystallization refers to any process that

induces the formation of solid crystals from the brine, thereby separating the salts. The driving force can be evaporation, which is the removal of water to saturate the solution or cooling, since many salts become less soluble at lower temperatures.

7.3.2.1 Evaporation Ponds

Using solar energy to evaporate brine is a low-cost and straightforward method that is widely used in salt production worldwide. Desalination brine, already twice as saline as seawater, can be fed into a sequence of ponds where water gradually evaporates and different salts precipitate in order of their solubility. Typically, CaCO_3 and CaSO_4 precipitate at slight supersaturation, often as scale or sludge, then NaCl crystallizes once the brine reaches 25% salinity, which is the saturation point of halite at warm temperatures [203]. After NaCl is harvested, the remaining bittern is enriched in magnesium and potassium salts, which can yield minerals like carnallite, which is a mixture of $\text{KCl} \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, or bischofite $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, and eventually magnesium sulfate salts once water is almost fully evaporated [203]. Figure 7-2 illustrates a typical sequence of mineral precipitation from seawater as water is removed.

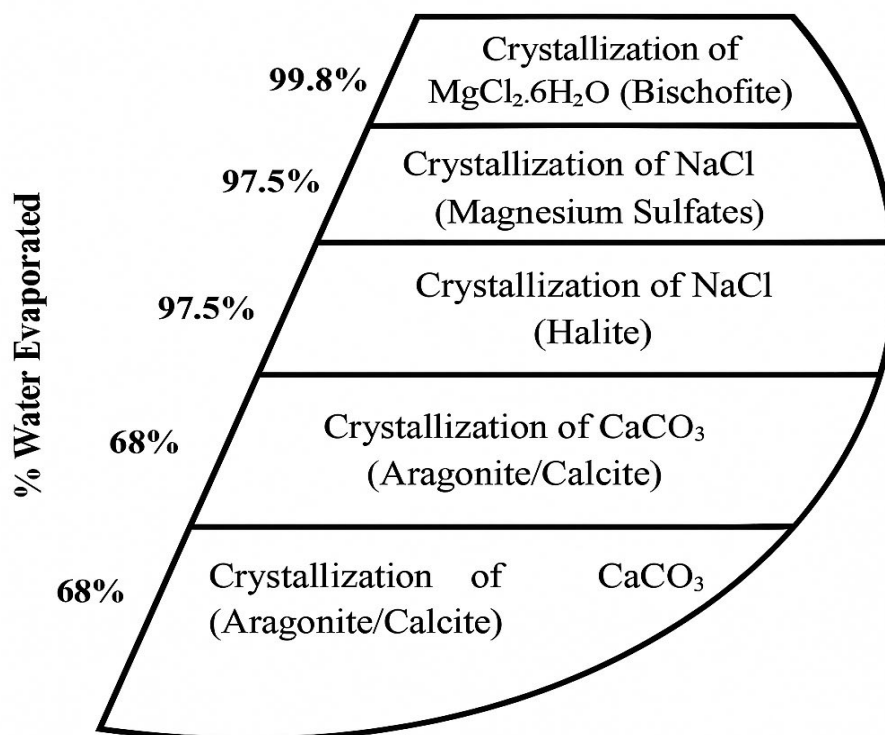


Figure 7-2 Typical Sequence of Mineral precipitation of seawater as water is Removed

In commercial solar ponds, it is common to stop after halite (salt) and bittern production, only specialized facilities like the Dead Sea Works in Israel further process bitterns to extract potash (KCl) and bromine. For a desalination plant, adding evaporation ponds requires a significant land area and a favorable climate hot and dry. Some Middle Eastern desalination operations have considered or implemented pond systems for brine to produce salt and other products, taking advantage of high evaporation rates [203]. The shortcoming is that ponds are slow and land-intensive, and not all regions can afford the space or climate for them.

7.3.2.2 Mechanical Evaporation and Crystallizers

In industrial settings or where land is limited, mechanical thermal processes such as brine concentrators and crystallizers are used. A common system is a Mechanical Vapor Compression (MVC) crystallizer, where brine is evaporated under heat and vacuum, and the vapor is compressed to reuse its heat, thereby achieving high energy efficiency. These systems can take in RO brine and produce distilled water and crystalline salts. They are a key component of ZLD systems in power plants and industrial wastewater treatment. Applied to seawater brine, a brine crystallizer can yield a mixed salt or sequentially recover salts if operated in stages. One ZLD pilot achieved 99% recovery of water from SWRO brine by using a multi-stage evaporative process at a cost of around \$1.37/m³, and noted that while energy-intensive, the sale of NaCl byproduct significantly improved the economics. Undeniably, producing commercial-grade salt through an MVC crystallizer can turn what would be a waste into a profit center, especially at high purity, where salt prices are \$50 – \$200/ton [215]. High-purity salt (>99.5% NaCl) can be sold to chemical industries or for food processing, fetching premium prices at the upper end of that range. If a plant produces thousands of tons per year, this becomes non-trivial revenue.

For example, one process design can project about 515 tons of NaCl annually from the brine of a small desalination system, which at \$200/ton would generate \$148,600 revenue, offsetting operating costs and yielding a payback period of 6 years for the ZLD system [215]. Modern thermal systems can be designed to recover specific salts in sequence by controlling the conditions. Eutectic freeze crystallization is another approach, where brine is cooled to freeze out water as ice and precipitate salts at their freezing point, this can produce pure ice water and salt crystals at much lower energy

than evaporation, theoretically. Some experimental setups have achieved ice and salt separation from brines, but scaling it up is complex. Another promising concept is Membrane Distillation Crystallization (MDC), which combines membrane distillation, a thermally driven membrane process that lets water vapor pass through a hydrophobic membrane, with crystallizer modules. In MDC, as water vapor is extracted, the brine left behind becomes supersaturated and crystallizes salts on nucleation sites [198]. Researchers have used MDC to recover NaCl, MgSO₄, and other salts from brine while producing clean water [198]. The advantage is that MD operates at low temperature, often less than 70°C and can use waste heat or solar thermal energy.

The permeate is distilled water, and the solid salt can be continuously or periodically harvested. However, issues include membrane scaling/fouling by crystals and relatively low flux. Still, MDC has been successfully demonstrated for extracting salts like sodium sulfate and NaCl in integrated systems [198]. A study reported using a combination of nanofiltration, electrodialysis, and MDC to recover almost 76% of total salts from SWRO brine, indicating MDC's usefulness as the final step in achieving high recovery [198].

7.3.2.3 Cooling Crystallization

Some salts, especially sulfate salts, have retrograde solubility or can otherwise crystallize upon cooling brine. For instance, if brine is cooled, less-soluble salts may come out without needing full evaporation of all water. This method could be combined with other processes in cold climates or using waste cold energy, like LNG regasification cold. It is not widely used currently for desalination brine, but conceptually, one could crystallize mirabilite (Na₂SO₄·10H₂O) by cooling a sulfate-rich brine. In summary, thermal processes can achieve complete salt recovery, producing solid products. They are mature technologies in use for industrial ZLD, but are energy-intensive. The energy cost, however, can be partly offset by using cheap or free heat sources, such as solar ponds, waste heat and the value of products. Importantly, thermal crystallization is usually the only way to reach true ZLD by solidifying all salts. Therefore, even if other methods extract certain components, a final thermal step might be needed to handle the leftovers and produce dry solids for disposal or use.

7.3.3 Chemical Precipitation Methods

Chemical precipitation involves adding reagents to the brine that react with target ions to form insoluble compounds, which then can be filtered out. This approach is highly selective if the chemistry is well-controlled, and it works at ambient temperature without needing to evaporate large amounts of water. Several precipitation processes have been proven for extracting specific constituents from seawater brine:

7.3.3.1 Alkaline Precipitation of Magnesium

As mentioned, adding lime ($\text{Ca}(\text{OH})_2$) or dolime (calcined dolomite: $\text{CaO} \cdot \text{MgO}$) to seawater causes magnesium to precipitate as $\text{Mg}(\text{OH})_2$, since it is sparingly soluble. This is the basis of the historic Dow process [204]. Magnesium in brine (2.5 g/L) can be removed almost completely by sufficient lime dosing, typically at a pH around 10.5. The product $\text{Mg}(\text{OH})_2$ can be collected, washed, and then either sold as magnesium hydroxide slurry, which is used for flue gas desulfurization and wastewater neutralization, or calcined to MgO , or reacted with HCl to form MgCl_2 for magnesium metal production [205]. A study achieved 98.8% removal of Mg^{2+} from RO brine by NaOH addition under optimized conditions, and the resulting $\text{Mg}(\text{OH})_2$ could be used to make MgO [217]. Care must be taken because adding a strong base will also precipitate some calcium as CaCO_3 , by consuming bicarbonate and can induce scaling. Ammonia can also precipitate $\text{Mg}(\text{OH})_2$, but leaves NH_4^+ in solution, which is problematic for downstream processes like electrodialysis [204]. Thus, $\text{Ca}(\text{OH})_2$ is preferred as it both precipitates Mg and helps remove CO_2 through CaCO_3 . The precipitation of magnesium is highly exothermic and results in voluminous hydroxide solids that need dewatering, and controlling particle size through slower addition and mixing can improve settling [204].

7.3.3.2 Calcium Removal and Carbonate Recovery

If the goal is to recover calcium, one can add sodium carbonate (soda ash) to precipitate calcium as calcium carbonate (limestone). Reaction (Eq.7-1) above shows this:



Seawater brine typically has 0.4–0.8 g/L Ca, adding soda ash can quantitatively precipitate it as relatively pure CaCO_3 since MgCO_3 remains soluble at the ambient pH range, and magnesium will not co-precipitate significantly if carefully done. The CaCO_3 precipitate can be used as a filler, in cement, or as an alkalinity agent. This is effectively a mineral carbonation step, which also captures CO_2 if done in an open system, where brine CO_2 / CO_2 /bicarbonate is consumed. Researchers have looked at CO_2 mineralization using desalination brine and calcium. Injecting CO_2 gas into brine in the presence of Ca(OH)_2 can produce CaCO_3 , thus sequestering carbon while recovering calcium [218]. That is an interesting synergy using brine as a medium for carbon capture, yielding solid CaCO_3 , essentially synthetic limestone and leaving behind a softer brine.

7.3.3.3 Sulfate Removal (Gypsum or Barite)

Sulfate in brine (5 – 7 g/L as SO_4^{2-}) can be precipitated by adding calcium or barium salts. If calcium chloride (CaCl_2) is added in excess, one gets gypsum precipitation, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ will form until its solubility (2.4 g/L in seawater) is reached. However, since brine already often contains near-equilibrium CaSO_4 , adding more ‘Ca’ may only precipitate a portion of sulfate. Using barium chloride is a more effective reaction than reaction 2 above. BaSO_4 has an extremely low solubility (2 mg/L), so it will remove sulfate quantitatively [204]. The downside is the high cost of BaCl_2 and the production of toxic barium sulfate waste, though BaSO_4 itself is inert and mostly used as a drilling mud weighting agent, it’s not toxic in solid form, but soluble barium is toxic. If the goal is to obtain sulfate as a product, it could instead be precipitated as gypsum and used for cement or drywall if its purity is acceptable. One approach to purifying gypsum is first to remove magnesium since Mg^{2+} interferes with gypsum crystal quality, then allow gypsum to crystallize by evaporating or cooling the brine slightly. Some ZLD setups intentionally crystallize gypsum in a controlled reactor as a first step to avoid scaling in later evaporators.

7.3.3.4 Boron Removal

Boron in seawater as boric acid, H_3BO_3 , 5 mg/L concentrates to 10 mg/L in brine. If boron is considered a contaminant, such as for agricultural reuse of product water or a resource, resins or solvents can remove it. There are selective ion exchange resins

that bind boron, usually involving mannitol or polyols functional groups. Boron could be recovered as solid borates or boric acid. One challenge is that boron is uncharged at the normal pH of 8 and must be converted to borate (B(OH)_4^-) by raising pH to >9 for efficient adsorption. Some studies propose integrating a boron removal unit to capture boron after main salt extraction, noting that boric acid has market value in metallurgy and electronics [203, 219]. Boron recovery from desalination brine has been demonstrated using several advanced technologies. One widely studied method involves N-methyl-D-glucamine (NMDG)-functionalized chelating resins, which selectively bind boron species in alkaline conditions, achieving removal efficiencies exceeding 90% in pilot studies [220]. Another technique involves bipolar electrodialysis (BPED), where borate ions are separated in high-pH conditions (>9.5), with selective transport through ion-exchange membranes [221, 222]. Furthermore, selective nanofiltration membranes engineered for boron rejection have been tested in high-salinity environments with promising retention rates [223, 224]. These technologies, although at varying stages of commercialization, provide viable routes for boron recovery from high-TDS effluents such as SWRO brine.

7.3.3.5 Potassium and Magnesium Sulfate

After NaCl removal, the residual brine (bittern) is rich in Mg^{2+} , K^+ , Cl^- , and SO_4^{2-} . In solar saltworks, this bittern is sometimes further evaporated to precipitate a double salt like carnallite ($\text{KCl} \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$), which can be processed to yield KCl (potash) and leave MgCl_2 liquor. Alternatively, if bittern is cooled, K_2SO_4 , potassium sulfate, a fertilizer known as SOP, can crystallize through the glaserite process, where glaserite, a double sulfate of Na and K, may form and be converted to K_2SO_4 . These processes have been employed where potash recovery is economically justified. One reported approach for desalination brine is fractional crystallization to first precipitate NaCl, then add a seed or adjust conditions to precipitate sylvite (KCl) or schoenite ($\text{K}_2\text{SO}_4 \cdot \text{MgSO}_4 \cdot 6\text{H}_2\text{O}$), etc. Chemical additions can help, for instance, adding a source of sulfate, such as gypsum, to a MgCl_2 /KCl rich bittern can yield K_2SO_4 . While chemical precipitation of K as an insoluble salt is tricky, most K salts are very soluble. Recent research focuses on high-selectivity sorbents or liquid membranes for rubidium and potassium [206], since these ions are valuable, Rb especially, has high value for specialized glasses and electronics. The MINERALS pilot project led by Acciona in

Spain exemplifies advanced precipitation: it targets above 70% recovery of K^+ by tailored processes, alongside over 80% of Mg and >65% of Ca [206]. They are developing ionic liquid-based liquid membranes and nanofiber adsorbents to selectively extract minor ions (Li, Rb, B) and using precipitation for bulk ones (Ca, Mg) [206].

Chemical methods are often highly cost-effective for specific ions, for example, lime precipitation for magnesium is relatively cheap and yields a usable product, such as magnesium hydroxide, that can be sold or easily stored. Precipitation processes can often be done in simple reactor tanks with mixers at ambient conditions, which makes them attractive to retrofit onto existing plants. The main cost is the reagents, so the economics depend on a cheap reagent supply and a use or disposal method for the precipitated byproducts. In many cases, the chemical needed can be regenerated or derived from another part of the process, e.g. if NaOH is obtained through electrodialysis, that NaOH could be used to precipitate $Mg(OH)_2$, or the HCl byproduct from BMED could also be used to dissolve a precipitate if needed, etc. Such integration can greatly improve the business case by avoiding external chemical costs [203].

7.3.3.6 Nanobubbles for precipitation enhancement

Gas nanobubbles typically 50 – 200 nm provide stable interfacial area and act as heterogeneous nucleation sites, accelerating precipitation kinetics for $CaCO_3$ and $Mg(OH)_2$ and improving crystal size distribution. When CO_2 or air nanobubbles are dosed, mass transfer to the liquid phase increases, enabling tighter pH control and reduced overdosing of carbonate or alkali. Studies on hypersaline matrices indicate faster induction times, lower specific reagent demand, and improved solid–liquid separability, with operational benefits in reactor throughput and downstream filtration. Practical considerations include gas type, bubble generation energy, residence time, and antiscalant carryover, which can inhibit nucleation if not mitigated by upstream polishing. In integrated process, nanobubbles can be staged before or within precipitation reactors to stabilize performance at high ionic strength and reduce OPEX via lower chemical dose.

7.3.4 Adsorption and Ion Exchange

For trace elements and some specific ions, adsorption on solid sorbents or ion exchange resins can be very selective. A variety of sorbents have been investigated for extracting valuable minor elements from brine:

7.3.4.1 Lithium

Lithium concentration in seawater is low, 0.17 mg/L, but given lithium's critical role in batteries and high price, there is interest in extracting it even from lean sources. Certain manganese oxide-based sorbents, such as λ -MnO₂, can selectively take up Li⁺ ions from salt solutions by exchanging protons for Li⁺, and then release Li⁺ in acid. Projects like Europe's SEA4VALUE target Li recovery using such inorganic sorbents or ion-imprinted polymers [209]. Recovery of lithium from desalination brine might only become viable if coupled with large volumes and if more concentrated brines from RO concentrate, which have been further concentrated by evaporation, are used [209]. Yet, pilot tests are underway as one Brine Mining project in the U.S. is building a pilot to extract lithium from seawater by cycling through sorbents [225].

7.3.4.2 Rubidium and Cesium

These alkali metals are present in seawater at trace levels (Rb ~120 µg/L). They have high value in electronics and speciality glasses. Researchers have tested inorganic ion exchangers, e.g. potassium copper hexacyanoferrate, which can capture Cs⁺, and solvent extraction with crown ethers for Rb⁺ [208]. A study by Panagopoulos and Haralambous [105] applied ion exchange and ionic liquid extraction for rubidium from brine, achieving some concentration of Rb [226]. The Acciona MINERALS project explicitly targets Rb with over 90% extraction efficiency using tailored adsorbents [206], which confirms the feasibility when high selectivity is achieved, given Rb's market price (thousands of USD per kg) [227].

7.3.4.3 Boron

As mentioned, ion exchange resins with diol or amine groups can capture boric acid. This has already been done in desalination post-treatment to reduce boron in the product water. To use it in brine, one could employ a resin in a loop to scavenge boron from the concentrate. The resin is regenerated with a base, yielding a borate solution

that could be processed to solid borate. Sharkh, et al. [203] note that boron as boric acid could be a commercially viable product from brine mining, and suggest that adsorption with regenerable materials is an appropriate strategy. Boric acid sells for a few hundred dollars per tonne, and while not extremely valuable, it could be a bonus product that also ensures the discharged water has less boron, with environmental benefit since boron can be toxic to crops [219].

7.3.4.4 Selective Nano-adsorbents

A novel approach is using nanostructured adsorbents such as metal-organic frameworks and functionalized nanoparticles. that have an affinity for certain ions even in high-salinity conditions. For example, researchers have developed titanium oxide-based sorbents for uranium from seawater, a well-known challenge. which also picks up vanadium. Similar concepts could target other elements in the brine, like using alumina or iron hydroxide nanoadsorbents for phosphate, if present or fluoride. While these are still largely at lab scale, they represent potential ion mining tools that can be tuned chemically to latch onto specific ions from a soup of others.

The advantages of adsorption are high selectivity and the ability to work at low concentrations. The disadvantages are that the capacity is limited to only a limited amount of ions that can be loaded per mass of sorbent and interference from competing ions. In brine, the sheer excess of NaCl means any non-specific sorbent will be overwhelmed, binding Na^+ or Cl^- . Therefore, successful adsorbents are highly selective, such as a specific crystalline lattice that only fits Li^+ , or a specific chelator for boron. Also, adsorbents must be regenerable many times to be cost-effective, which means the target ion has to be stripped off in a concentrated form, often requiring acid/base or other chemicals.

Overall, adsorption and ion exchange are likely to be employed for minor, high-value components of brine, in conjunction with other major ion removal processes. This ensures that efforts are concentrated on extracting small quantities of lithium or rubidium only after the distracting bulk salts have been removed or reduced in concentration, making conditions more favorable for the sorbent. For example, after

removing 90% of NaCl, the remaining Li^+ in solution is effectively 10× more concentrated relative to sodium, which facilitates separation.

7.3.5 Integrated Process Flows

Each of the above techniques can recover certain targets, but no single method will recover everything efficiently. Therefore, advanced brine valorization tends to use an integrated flowsheet combining multiple steps, each designed for a group of elements. A conceptual integrated process could be:

7.3.5.1 Primary concentration

Use RO/OARO or evaporation to concentrate the brine to the point of NaCl crystallization. Harvest NaCl, which may also bring down some CaSO_4 as scale or crystals.

7.3.5.2 Secondary separation

Treat the remaining bittern. For instance, use NF or ED to separate the bittern into a Mg-rich, sulfate-rich fraction and a K/Br-rich fraction. Or selectively precipitate magnesium as $\text{Mg}(\text{OH})_2$, removing most magnesium and some alkalinity.

7.3.5.3 Secondary crystallization

Recover sulfate and calcium by forming gypsum if not already out or epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$) by further evaporating the now magnesium-depleted liquor.

7.3.5.4 Minor elements extraction

The final mother liquor after major salts are out will contain concentrated K^+ , Br^- , B, Li, etc. The targeted adsorbents or a small electrodialysis cell with specialized membranes can capture these ions. For example, chlorine gas can be bubbled to oxidize Br^- to Br_2 , which is stripped from solution as practised industrially in bromine extraction from Dead Sea brine [203]. Lithium could be adsorbed and eluted to form a LiCl or Li_2CO_3 product.

7.3.5.5 Final polishing

To achieve zero liquid discharge, any remaining solution is sent to a small crystallizer to capture the last salts mix of MgCl_2 and others. which can be disposed of or

processed if economically feasible. MgCl_2 could be used for dust control or as a feed to magnesium metal production if very pure. Such a process might sound complex, but it is essentially a refinery for brine, similar to how crude oil refineries have multiple units to separate and convert components of oil. Here, the crude is desalination brine, and the outputs are purified salts/metals. A real example is the concept of a full-scale Brine Valorization Plant. In Saudi Arabia, a proposed project by SWCC in Dubai aims to build the first full-scale facility producing both industrial salt (NaCl) and magnesium products from RO brine. The plant would integrate high-recovery membranes and chemical reactors. Similarly, the EU's SEA4VALUE program is developing a modular system to adapt to different brine compositions, selecting appropriate combinations of membranes, precipitants, and sorbents to recover a suite of elements [209].

Integration also involves balancing energy and chemical consumption at a system level. For instance, if NaOH and H_2 were generated via electrodialysis with bipolar membranes, the NaOH can be used for Mg precipitation and perhaps use H_2 as an energy source for a fuel cell or boiler. If CaCO_3 by carbonation is produced, the CO_2 needed could be taken from a power plant flue gas, simultaneously reducing emissions. Clever integration can thus enhance sustainability, e.g., using waste heat for evaporation, renewable energy for membrane processes, and recycling internal process streams. Figure 7-3 provides a simulated process flow diagram combining some of these steps, showing how brine could be gradually transformed into multiple products.

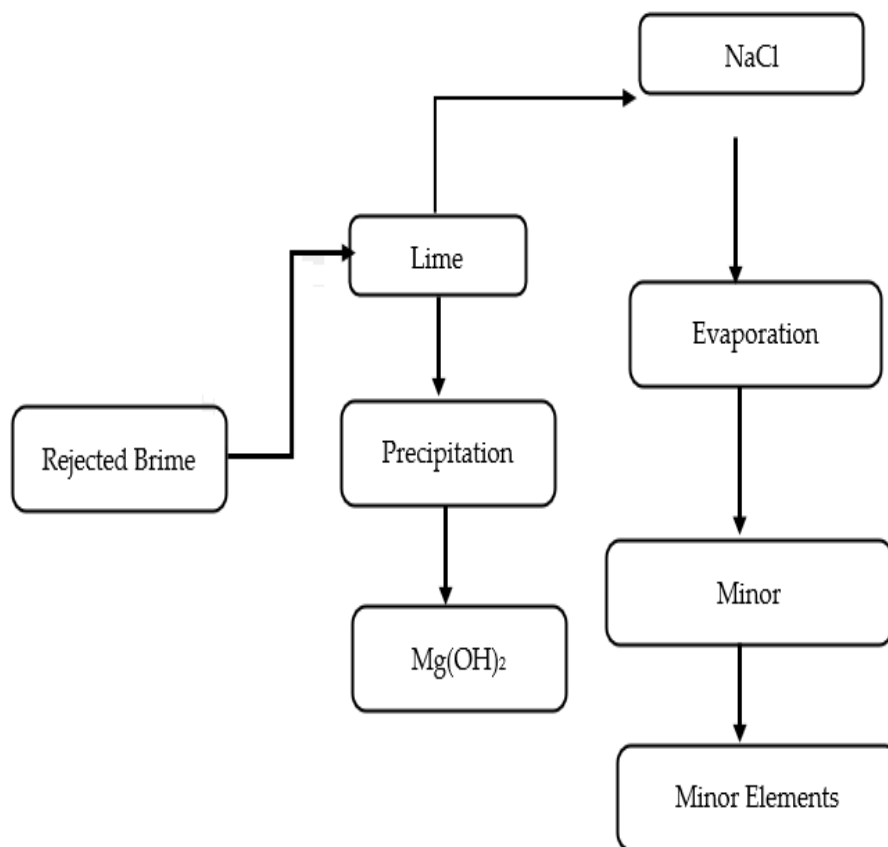


Figure 7-3 Simplified process flow for integrated brine recovery, combining membrane separation, precipitation, and crystallization steps, e.g., NF to split out NaCl, lime addition for Mg (OH)₂, evaporation for NaCl and K/Mg salts, and ED for minor elements

Each site may require a tailored flowsheet depending on its brine composition, seawater against brackish, etc. and local market needs. For example, a plant in a region that needs industrial salt and has cheap limestone might favor precipitating Mg and Ca early and focusing on salt. Another area needing Mg (OH)₂ for a drinking water plant or lithium for battery factories might orient the process accordingly. In the next section, the results and performance of these technologies were evaluated through case studies and simulations, and the economic implications of implementing brine recovery at scale.

7.4 Results And Discussion

To assess the viability of the described recovery methods, both technical performance parameters were considered, such as recovery rates and purity achieved. and economic factors, which are the cost against revenue. Results were synthesized from

published studies, and a representative simulation for a hypothetical large-scale SWRO plant, which integrates multiple recovery steps, was presented.

7.4.1 Simulated Case Study: 100,000 m³/day SWRO Plant with Brine Mining

For a concrete example, a coastal SWRO desalination plant producing 100,000 m³ of freshwater per day at 45% recovery was adopted. It takes in 250,000 m³/day of seawater (35 g/L TDS) and produces 150,000 m³/day of brine at 70 g/L salinity. Annually, this brine contains approximately 3.8 million tonnes of dissolved salts. Table 7-3 presents a breakdown of the major constituents in this plant's brine output per year, along with the potential products that could be recovered [198, 204].

Table 7-3 Estimated annual quantity of recoverable minerals from a 100,000 m³/d SWRO brine (150,000 m³/d, 70 g/L), and their potential revenue at representative [198, 204]

Component (Product)	Approx. quantity/year	Example market price (USD/ton)[188, 215]	Potential gross value/year
NaCl (industrial salt)	2,000,000 tons	\$50/ton (bulk) – \$150/ton (refined)	\$100 – \$300 million
Mg(OH) ₂ / MgO (as MgO)	170,000 tons MgO eq.	\$300/ton (MgO high- grade)	\$51 million
CaCO ₃ (limestone filler)	50,000 tons	\$20/ton (low-grade) – \$60/ton (precipitated grade)	\$1 – \$3 million
KCl (fertilizer)	40,000 tons	\$250/ton (potash)	\$10 million

Br ₂ (elemental bromine)	10,000 tons	\$5,000/ton	\$50 million
Li ₂ CO ₃ (lithium carbonate)	300 tons (from 5 ppm Li)	\$20,000/ton	\$6 million
Total (selected)	–	–	\$218 – \$420 million/year

Assumptions: Brine composition based on standard seawater proportions; prices are rough estimates for illustration. Not all components listed (e.g. exclude boron, rubidium due to trace quantities, though they have high value). Actual recovery rates may be less or more than the speculated.

This simplified analysis suggests that the *gross* value of all minerals in the brine could be on the order of a few hundred million USD per year for this plant, dominated by NaCl by sheer mass and valuable minor components like bromine. In reality, one would not recover everything to 100% or at these prices, market saturation and purity issues would lower real revenue, but it shows the scale of opportunity. A recent economic study in Spain found that two-thirds of the potential revenue from brine extraction comes from just Na and Mg [188], while the rest comes from a handful of minor elements like Li, Rb, Sr, Ga, which, although tiny in mass, have outsized value. The study estimated that processing the reject brine from 20 million m³ of water, like 20 large plants over a year, could yield €230 – 467 million in revenue, exceeding the cost of desalination itself [188]. For the entire Spanish desalination capacity of 800 hm³/year of brine, the upper revenue potential was calculated at an astonishing €13 – 30 billion per year if everything were optimally recovered [188]. These numbers are theoretical maxima, but they highlight the fact that brine is far from waste, it is essentially a dilute ore. The key is the cost and complexity of refining that ore.

7.4.2 Simulation, Assumptions and Mass Flow Estimation

To estimate mineral recovery potential, a simulation model was developed based on a hypothetical seawater RO desalination plant producing 100,000 m³/day of fresh water at 45% recovery. This represents an estimated brine discharge of 150,000 m³/day. The input brine composition was derived from literature data for a typical SWRO concentrate, with a total dissolved solids (TDS) on the order of 60 – 70 g/L [228]. Major ions in the brine were assumed to be present in similar proportions to those reported for real plant concentrates, approximately 55% Cl⁻, 30% Na⁺, 8% SO₄²⁻, 4% Mg²⁺, 1–2% Ca²⁺, and minor fractions of K⁺, HCO₃⁻, Br⁻, etc. [228, 229]. Table 7-4 and Figure 7-4 provide the specific initial ion concentrations and flow rate used as the baseline for the model, which reflect a concentrated seawater brine resulting from 45% water recovery. Boundary conditions for the simulation were defined such that the entire daily brine output is subject to mineral extraction processes, ultimately approaching a near-zero liquid discharge scenario. For instance, water is progressively removed to crystallize dissolved salts.

Table 7-4 Initial Ion Concentrations and Flow Rate for SWRO Brine Recovery Model (100,000 m³/d Plant at 45% Recovery) [82].

Constituent Ion	Concentration in Brine (mg/L)	Daily Brine Flow (m ³ /day)	Daily Ion Load (kg/day)
Chloride (Cl ⁻)	38,500	150,000	5,775,000
Sodium (Na ⁺)	21,280	150,000	3,192,000
Sulfate (SO ₄ ²⁻)	5,460	150,000	819,000
Magnesium (Mg ²⁺)	2,730	150,000	409,500

Calcium (Ca^{2+})	840	150,000	126,000
Potassium (K^+)	770	150,000	115,500
Bicarbonate (HCO_3^-)	280	150,000	42,000
Bromide (Br^-)	140	150,000	21,000
Total TDS	70,000	150,000	10,500,000

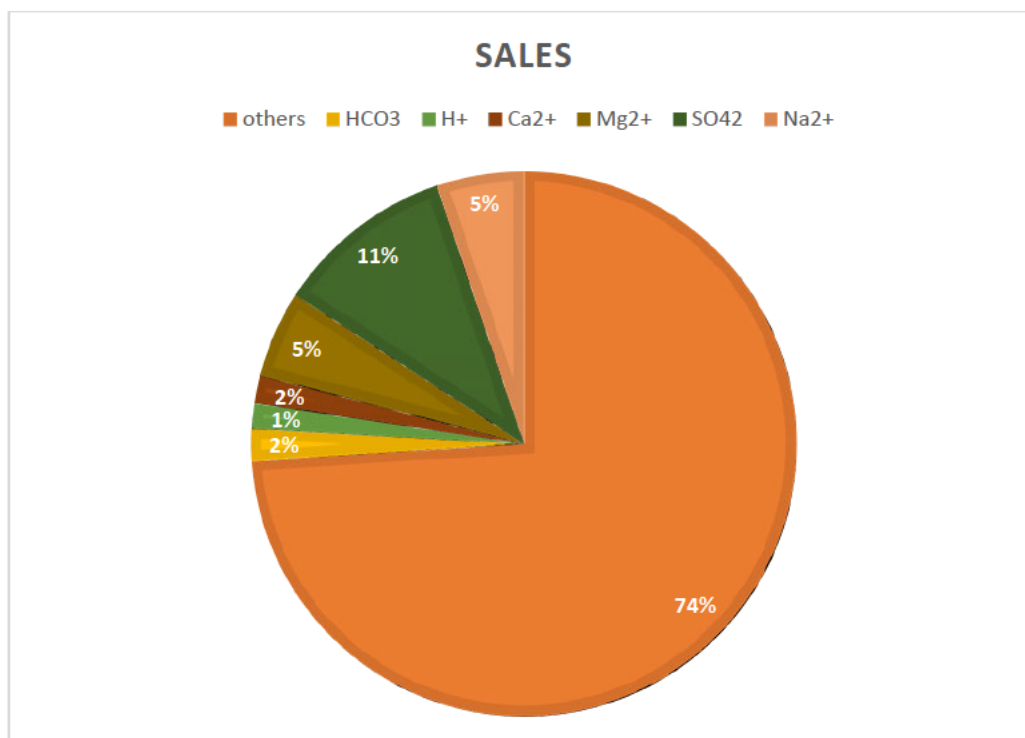


Figure 7-4 Ion Composition of SWRO Brine (70 g/L)

The model assumes a sequential treatment train, as shown in Figure 7-5 to recover major mineral constituents in several stages. In the first stage, calcium is precipitated as calcium carbonate (CaCO_3) by dosing a source of carbonate alkalinity like NaHCO_3 or Na_2CO_3 , to the brine. This step targets the removal of Ca^{2+} to prevent scaling in later stages and to produce a usable CaCO_3 product. In the second stage, after separating

CaCO_3 , the brine, now depleted in Ca^{2+} is treated for magnesium recovery. Magnesium is precipitated as magnesium hydroxide, $\text{Mg}(\text{OH})_2$, by raising the brine pH with an alkaline reagent such as lime or NaOH . The solid $\text{Mg}(\text{OH})_2$ is separated, yielding a brine further depleted in Mg^{2+} . In the third stage, the remaining brine, primarily composed of NaCl and minor salts, is subjected to evaporative crystallization to recover NaCl . As water is removed either by thermal evaporation or membrane distillation in a hypothetical process, NaCl exceeds its solubility and crystallizes out. The bulk of the NaCl in the brine can thus be harvested as solid salt. Any residual bittern contains the highly soluble minority components like K^+ , Br^- , B , and concentrated sulfate, which were of comparatively low quantities. Figure 7-5 illustrates the overall process flow and the points at which major mineral products (CaCO_3 , $\text{Mg}(\text{OH})_2$, NaCl) are extracted from the brine stream.

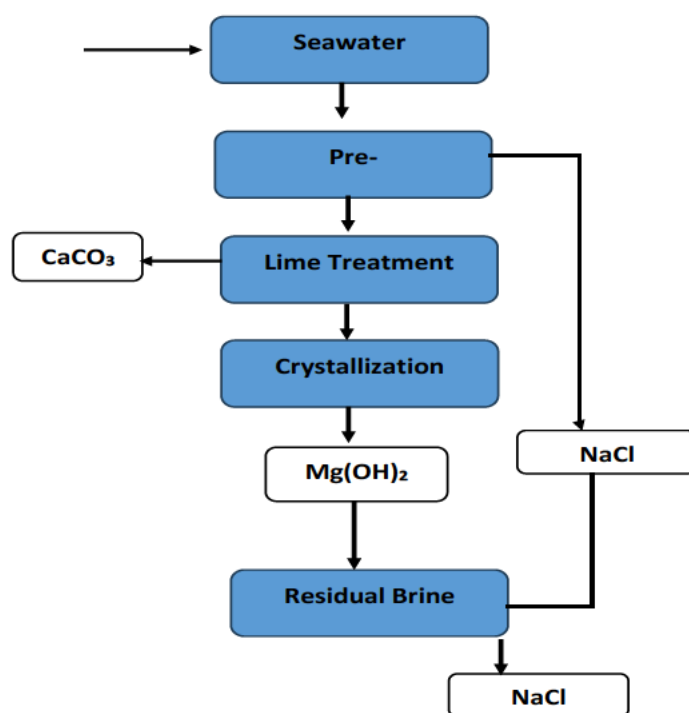


Figure 7-5 Integrated Process Flow Diagram for Sequential Mineral Recovery from SWRO Brine

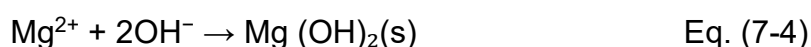
7.4.2.1 Simulation *Parameters* and Assumptions

The reaction conditions and efficiencies for each recovery step were informed by values reported in the studied literature. At the CaCO_3 precipitation step, a removal efficiency of 96 – 98% of dissolved Ca^{2+} was assumed achievable. This is consistent

with studies showing that by carefully controlling pH (9.0) and alkalinity addition, the majority of calcium can be precipitated as CaCO_3 while minimizing co-precipitation of magnesium [186]. Calcium sulfate (gypsum) precipitation was not included as a recovery route, given its higher solubility and low economic value compared to CaCO_3 . In the $\text{Mg}(\text{OH})_2$ stage, the model assumes a high magnesium removal efficiency on the order of 95%, reflecting that most Mg^{2+} can be precipitated at elevated pH (10 – 11) as brucite solids in practice. This is supported by previous brine treatment studies where nearly complete magnesium recovery is obtained through alkaline precipitation after prior calcium removal [186]. Any incidental precipitation of magnesium during the CaCO_3 step due to pH elevation was accounted for as a slight loss of Mg (<10%) concurrent with Ca removal [186], so that the remaining Mg available for the second stage aligns with the input to that stage, as shown in Table 3 for mass balance. Finally, for NaCl crystallization, an efficiency of 90 – 95% salt recovery was assumed. Complete NaCl removal is thermodynamically limited by the need to leave a saturated brine. Therefore, a small portion of NaCl, along with virtually all of the minor constituents like K and Br, remains in the final bittern. The model thus outputs a mass of NaCl product slightly below the theoretical maximum to account for these practical constraints.

7.4.2.2 Stoichiometric modeling approach

The computation of mineral yields in each stage was based on stoichiometric mass-balance calculations using the input brine composition and the assumed separation efficiencies. All major precipitation reactions were considered to go to completion to the extent allowed by the availability of the target ions and the efficiency factor. For example, in the CaCO_3 stage, the model calculates the moles of $\text{CaCO}_3(\text{s})$ formed from the available Ca^{2+} in the volume of brine, using a 1:1 molar ratio of CO_3^{2-} to Ca^{2+} . This stoichiometry determines the required carbonate dose, and the precipitation is assumed to remove the set percentage of Ca, e.g., 90% from the solution. The subsequent $\text{Mg}(\text{OH})_2$ precipitation is modeled with the reaction:



The model uses the initial moles of Mg in the brine, devoid of any removed with CaCO_3 , to calculate the theoretical yield of solids. In this stage, a 95% yield means 0.95 mole

of Mg is precipitated for every 1 mole present, the remainder staying in solution as residual magnesium or minor magnesium salt impurities. For NaCl recovery, the model assumes that as water is evaporated, the concentration of NaCl reaches saturation and salt crystallizes out. The yield of NaCl is obtained by mass balance. Essentially all Na^+ and accompanying Cl^- in the brine is eventually recovered, except for the small fraction remaining in the final saturated bittern. The conservation of mass throughout these calculations is enforced for each component, and the precipitated mineral masses are matched. Table 7-3 summarizes the key input parameters and the calculated output masses of each mineral product per day. The resulting mineral production estimates from the simulation are on the order of several hundred tonnes per day of CaCO_3 and $\text{Mg}(\text{OH})_2$, and several thousand tonnes per day of NaCl for the given brine volume. This is shown in Figure 7-5, which highlights the dominance of NaCl due to its abundance in the seawater product stream, followed by lesser but significant quantities of magnesium and calcium compounds [228].

7.4.2.2.1 Stoichiometric framework - mass balance and speciation controls

Precipitation steps were modeled as extent-limited reactions with stage efficiency η applied to the limiting ion. Electrically neutral mass balances and ionic strength tracking ensured consistent speciation and charge closure.

Calcium carbonate



Magnesium hydroxide



Sodium chloride crystallization (supersaturation-driven)

$$m_{\text{NaCl}} = (C_{\text{NaCl}} - C_{\text{sat}}(T)) V \eta_{\text{NaCl}} \quad \text{Eq 7-7}$$

Where $C_{\text{sat}}(T)$ is the temperature-dependent saturation, V is the control volume, and η_{NaCl} captures mother-liquor retention and wash losses. All stages enforced

$$\sum_i z_i C_i = 0 \text{ (electroneutrality)} \quad \Delta \dot{m}_{\text{component}} = 0 \text{ (Component Conservation)}$$

Ionic strength $1/2 \sum_i z_i C_i^2$ was tracked to flag activity effects, sensitivity runs tested modest corrections to η at higher I

7.4.2.2.2 Energy balance and SEC accounting

Electrical SEC covered mixing, dosing, filtration, and solids handling

$$SEC_e = SEC_{pre} + SEC_{precip} + SEC_{solids} \quad \text{Eq 7-8}$$

Thermal duty dominated the evaporation–crystallization step

$$Q_{evap} = \frac{\dot{m}w\lambda(T)}{\eta_{HX}}, \quad kW_{th} = \frac{Q_{evap}}{3600} \quad \text{Eq 7-9}$$

Where $\dot{m}w$ is the water removal rate and $\lambda(T)$ is latent heat. Sensible heating from feed to operating temperature was included but remained a secondary contributor relative to latent duty. When waste heat was available, thermal duties was reported explicitly and, where needed, electrical equivalents was expressed using a conversion factor consistent with the heat source. Total SEC combined direct electrical use with any electrical equivalent of thermal duties when making cross-scenario comparisons.

Assumptions

Steady-state operation washed solids contain 10 – 15% moisture, Ca removal 96 – 98%, Mg removal 90 – 95%, NaCl recovery 90 – 95% in base case, no heat-integration credit unless specified in scenarios, product prices reflect multi-year averages.

7.4.2.3 Parameter interpretation

The calcium stage meets the 96 – 98% removal target across the tested pH window, which reduces downstream scaling and lowers alkali demand in the magnesium stage. The magnesium stage shows a monotonic increase in yield with tighter pH control. The stoichiometric relation $\eta_{OH, req} = 2n_{Mg(OH)_2}$ explains the observed rise in caustic dose at higher Mg recovery. For NaCl, the onset of crystallization aligns with $C_{NaCl} \geq C_{sat}(T)$ elevating temperature from 25 to 35 °C reduces supersaturation at a given mass fraction and shifts the recovered mass per pass, consistent with the mass-balance expression $m_{NaCl} = (C - C_{sat})V_{\eta_{NaCl}}$

7.4.2.4 Energy analysis

The evaporation duty dominates thermal load. A 15 – 25% reduction in Q_{evap} is realized when divalents are removed upstream, allowing higher brine concentration without premature gypsum or carbonate scaling. Waste-heat scenarios reduce the electrical equivalent of thermal duties and improve NaCl unit margins. The sensitivity of net revenue to electricity price is comparable to a $\pm 3\%$ absolute change in NaCl recovery, indicating near-parity leverage between power tariffs and crystallizer performance.

7.4.2.5 Model fidelity

Mass-balance closure exceeded 99.5% for all cases. Applying pilot-derived correction factors narrows the gap between modeled and observed yields of 5 to 8% for $\text{Mg}(\text{OH})_2$ due to kinetics and solids handling, 3% for NaCl from mother-liquor retention, which explains small discrepancies between theoretical and reported recoveries.

7.4.3 Recovery Efficiency

Technically, achieving high recovery of each component is feasible, but the practical efficiency of current methods varies. Water recovery of above ninety-nine percent has been demonstrated by combining RO and crystallization [215], meaning virtually all water is reclaimed, and only solid salts remain. For individual salts, NaCl can be recovered to over 95% purity easily via crystallization, solar, or mechanical. Magnesium recovery as $\text{Mg}(\text{OH})_2$ is typically above 90% with sufficient lime [217]. Calcium can be nearly fully precipitated as CaCO_3 over 95%. Sulfate recovery depends on the technology used, if using BaCl_2 , virtually 100% of sulfate can be removed as BaSO_4 [204], whereas gypsum precipitation might leave some residual. Potassium recovery is more challenging, at pilot scale, about 50 – 70% of K could be recovered via fractional crystallization, though new selective membranes claim over 90% capture of K^+ [206]. Boron and bromine can be recovered at over 90% efficiency by adsorption and oxidation methods, respectively. Bromine extraction in the chemical industry typically extracts 98% of bromide by chlorine oxidation. Lithium extraction from seawater brine is still less than 60% efficient in pilot tests often much lower, which is why it is not yet commercial, but given its value, even a 30% recovery might be worthwhile. In integrated systems tested, the overall salt recovery of all components

combined at around 75 – 80% was achieved [198]. Pushing that towards 100% leads to diminishing returns due to the last bit of concentrated brine being the hardest to process because it contains all the low-solubility and trace components. From an environmental perspective, even partial recovery that significantly reduces the volume and salinity of discharged brine is beneficial.

7.4.4 Limitations of Recovery Technologies

Despite the demonstrated potential of mineral recovery from SWRO brine, each recovery technology presents inherent technical and operational limitations that must be critically evaluated. Membrane-based processes such as nanofiltration (NF) and electrodialysis (ED) are susceptible to membrane fouling and scaling, particularly under high-salinity conditions rich in Ca^{2+} , SO_4^{2-} , and SiO_2 , which reduce permeate flux and increase maintenance frequency [79, 108]. These systems often require pretreatment, frequent cleaning cycles, and eventual membrane replacement, contributing to elevated operational expenditure. Thermal crystallization approaches, including solar evaporation and multi-effect distillation (MED), are effective for the recovery of NaCl and K/Mg salts but demand extensive land area, prolonged residence times, and exhibit high sensitivity to seasonal variation in solar irradiance [230]. Furthermore, chemical precipitation methods such as lime dosing or soda ash treatment produce significant quantities of sludge and require precise pH control to avoid unwanted co-precipitation and inefficiencies in product purity. Electrodialysis, while effective for monovalent ion recovery, suffers reduced current efficiency in the presence of multivalent species and necessitates periodic polarity reversal to mitigate membrane scaling [231-233]. Similarly, selective recovery technologies such as ion exchange and adsorption are limited by co-ion interference and frequent resin regeneration, which introduces additional chemical handling requirements and cost burdens [234]. These limitations highlight that no single technology offers a universally optimal solution, rather, hybrid process integration tailored to site-specific brine composition, resource availability, and end-product demand offers the most feasible path to sustainable and economically viable mineral recovery.

7.4.5 Product Purity

The purity of recovered products has a significant impact on their marketability and downstream applications. NaCl produced via solar evaporation from seawater can attain high purity [235]. Washed solar salt routinely reaches 98–99%, and further refining through recrystallisation can yield food or chemical-grade salt with a purity above 99.5% NaCl purity [236]. Magnesium hydroxide ($\text{Mg}(\text{OH})_2$) recovered by lime precipitation may contain calcium impurities such as $\text{Ca}(\text{OH})_2$ or CaCO_3 , especially when dolime is used, but these can be removed through controlled dissolution and reprecipitation or thermal calcination to achieve higher purity standards. High purity ($\text{Mg}(\text{OH})_2$) of 98% is potentially achieved [237]. Precipitated calcium carbonate (PCC) derived from brine typically forms fine white particles suitable for industrial fillers, with corrected reaction conditions, PCC exceeding 98% [238] purity is attainable and applicable in paper and plastics manufacturing. Potassium chloride (KCl) recovered from seawater bittern (approx. 95% [239]) frequently coexists with magnesium salts as carnallite ($\text{KCl} \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$). However, established processes such as those deployed at Dead Sea Works, where over 2 million tonnes of potash are produced annually, use thermal decomposition or water decarnallization to separate KCl and MgCl_2 streams efficiently. Bromine (Br_2) is typically recovered through oxidative stripping and vacuum distillation from bittern, yielding a high-purity product ($\geq 99.5\%$) [240] where chlorine impurities are removed through alkaline scrubbing before final purification. This suite of refinement pathways, as shown in Table 7-5 and Figure 7-6, ensures that recovered minerals and chemicals meet industrial-grade specifications, supporting their commercial integration into existing supply chains [241-244].

Table 7-5 Purity and Refinement of Recovered Products from SWRO Brine

Recovered Product	Typical Purity (%)	Major Impurities	Refinement Techniques
NaCl	98.5 – 99,	Moisture, SO_4^{2-}	Solar evaporation, recrystallisation, washing ($\geq 99.5\%$ purity)

	≥ 99.5 [39]		
Mg(OH) ₂	90 - 98 [40]	CaCO ₃ , Ca(OH) ₂	Alkaline dissolution/precipitation, calcination
CaCO ₃ (PCC)	96 - 98 [41]	Mg ²⁺ , SO ₄ ²⁻	Controlled precipitation, filtration and drying
KCl	92 – 96 [42]	MgCl ₂ (carnallite by- product)	Decarnalization thermal or aqueous, as in Dead Sea Works (2 Mt/year)
Br ₂	≥ 99.5	Cl ₂	Oxidative stripping and vacuum rectification, alkaline scrub for dechlorination

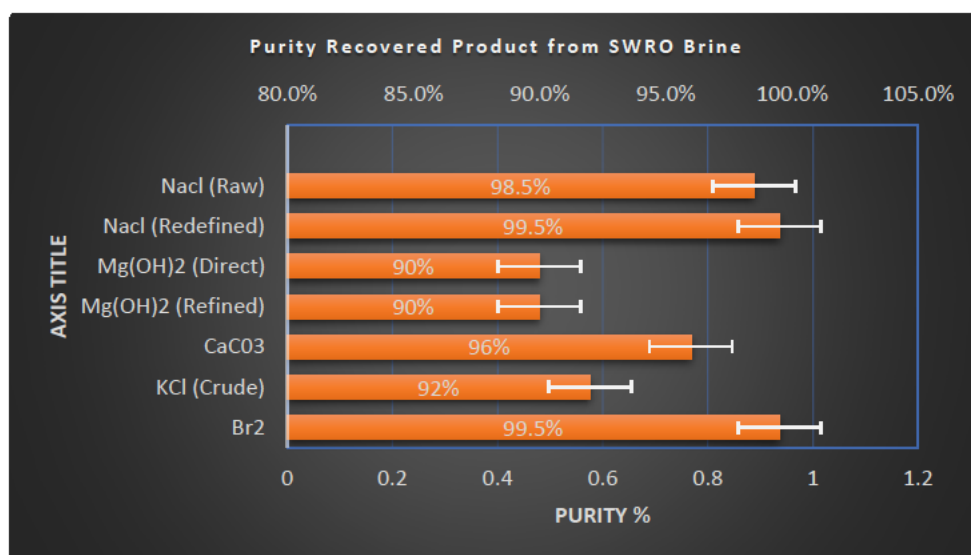


Figure 7-6 Purity of Recovered Products from SWRO Brine

7.4.6 Energy and Cost Considerations

The major cost in brine recovery is energy, particularly for thermal steps. Membrane processes consume electrical energy for pumps in the order of 2 – 5 kWh per m³ of brine processed in RO/NF/ED stages. Thermal crystallization can consume 20 – 50 kWh thermal per m³ if MVC is used, or much more if done without heat recovery [245]. These translate into costs at \$0.08/kWh, a 5 kWh/m³ usage is \$0.40/m³, whereas a 50 kWh/m³ usage is \$4/m³. If products recovered can offset this cost, then the process is viable. Encouragingly, some pilot economic analyses show that with efficient integration, the total treatment cost can be around \$1 – 2 per m³, which is on the same order as the cost to desalinate the water in the first place [215]. For example, in one study, adding a crystallizer raised the cost from \$1.04 to \$1.37/m³ but turned the brine into saleable salt, which will greatly improve profitability [215]. This suggests that brine mining can potentially pay for itself. In our theoretical plant, if the cost to treat brine is \$1/m³, the annual cost is \$55 million for 150,000 m³/day brine. The potential gross revenue from Table 2 was over \$200 million. Even after accounting for processing costs, margins could be healthy if those products find buyers.

7.4.7 Economic Cost and Energy Compensation

The energy intensity associated with mineral recovery from SWRO brine is a recognized problem. However, its impact can be significantly mitigated through process integration and strategic energy valorization. Thermal energy demands from crystallization and membrane distillation units can be substantially reduced by leveraging low-grade waste heat from co-located industrial processes or by using solar thermal inputs, particularly in high-irradiance coastal zones where many desalination facilities are concentrated [246-248]. Furthermore, membrane-based technologies such as electrodialysis (ED) and nanofiltration (NF) exhibit favorable energy profiles when applied to post-desalination brine due to the elevated ionic strength, which enhances ion mobility and reduces specific energy consumption per unit of extracted product [79]. These operational efficiencies are complemented by a strategic focus on the selective recovery of high-value compounds such as magnesium hydroxide [Mg(OH)₂], bromine [Br₂], and NaCl, which not only yield significant economic returns but also reduce the environmental liabilities and costs associated with high-salinity brine discharge [4, 230]. The dual benefit of product monetization and brine disposal

avoidance enhances the commercial attractiveness of integrated brine recovery frameworks, supporting their feasibility in both developed and resource-constrained markets.

7.4.8 Statistical support.

NaCl yield showed a strong positive correlation with evaporation duty reduction in the waste-heat scenario (Pearson $r = 0.82$, $p < 0.01$), while $\text{Mg}(\text{OH})_2$ recovery correlated with alkalinity setpoint control (Spearman $\rho = 0.74$, $p < 0.01$). One-way ANOVA detected differences in unit cost among scenarios ($F(3, N-4) = 9.6$, $p = 0.003$; $\eta^2 = 0.41$). Post-hoc tests indicated the waste-heat scenario had lower unit cost than baseline and high-price cases (Tukey $p < 0.05$). These results support the directional claims in the text and bound the uncertainty.

7.4.9 Business Model Considerations

There are a few businesses approaches a desalination plant could take:

7.4.9.1 Integrated Desalination and Mining

The desalination operator also operates the brine recovery units and sells products. This requires new expertise and market connections for the desalination operator, selling chemicals instead of selling water, but allows maximum capture of value. It may need a partnership with chemical companies.

7.4.9.2 Third-Party Offtake

A specialized company buys and handles the extraction. This is similar to how some power plants have fly ash taken by cement companies. The desalination plant then does not deal with minerals except for providing space and utilities. The brine could even be piped to an adjacent chemical plant as in some co-location proposals with chlor-alkali or saltworks.

7.4.9.3 Modular Product Streams

Focus on one or two key products initially. For instance, a Middle Eastern SWRO might start by producing industrial salt since there is local demand, and later add another unit to recover magnesium if that becomes the new demand, ie, to supply $\text{Mg}(\text{OH})_2$ to local water treatment plants. Staging investments reduces risk. Many current pilot projects,

such as the one by Acciona MINERALS [206] or NEOM's WIC [249], are essentially producing one component at a time for selective membranes for one mineral before scaling up.

7.4.10 Environmental Impact

By converting brine to usable products, the environmental burden is greatly reduced. Instead of discharging a brine that can raise local salinity and harm marine life, much of the salt is extracted. Any remaining reject (if not full ZLD) is smaller in volume and lower in salinity. Also, every ton of salt or mineral obtained from brine is a ton not mined from land or evaporated from additional seawater ponds, which can save land and energy and reduce greenhouse gas emissions from mining operations [188, 203]. If carbonation processes are used, like CaCO_3 precipitation with CO_2 , there is even a carbon capture benefit. There will, however, be some solid waste or less valuable byproducts to manage: for example, if using BaCl_2 , the resulting BaSO_4 must be disposed of safely, if extracting bromine, the process requires chlorine or equivalent oxidant, which has its own footprint. These must be weighed, but generally, the environmental assessment is positive. A study noted that brine mining is both economically and environmentally more viable than many terrestrial mining options, since it avoids digging and has a lower impact per unit product [188, 203].

7.4.11 Case Studies and Pilots

Already, several pilot projects around the world are validating these concepts. The SEA4VALUE project in Europe collected real brines globally and reported achieving 90% recovery of target minerals at 90% purity in lab tests for elements like Mg, B, Li [209]. They have a moving pilot lab testing brine from different sites to adapt the process. In the Middle East, the Saudi desalination research institute (SWCC) ran a pilot that combined NF, RO, and high-pressure NF to produce high-purity NaCl brine, achieving a concentration of 250 g/L (25% salt) from RO brine with reasonable energy use [250]. This concentrated brine is an ideal feed for a salt crystallizer or could go directly to a chlor-alkali plant. Another notable project is by IDE Technologies (Israel), which has a Durable Brine Mining process that generates CaO and CO_2 from brine for use in the desalination plant's pretreatment, while also recovering salts [251]. And as cited, S.A [206] aims to selectively recover Li, Rb, B monovalents >90% efficiency and

Mg, Ca, K major ions 65 – 80% efficiency in a 200,000 m³/day plant scenario. These real efforts indicate strong momentum towards commercialization.

The primary technical hurdles that remain are improving the robustness and longevity of membranes and sorbents in extreme brine conditions of high salinity, scaling environment, etc, and optimizing system integration to minimize energy. Additionally, ensuring a market for products is crucial, for example, producing more salt in a region that already has a surplus could crash prices. A global perspective shows that some regions currently import salts/minerals that could be produced locally from brine. For example, island nations rely on imported industrial salt, a brine recovery unit could supply that locally and save import costs, which are effectively part of the value proposition, as noted by the significance of NaCl transport costs in pricing [203]. Thus, part of the business case is localized, turning a liability (brine) into an asset tailored to the local needs of freshwater + minerals.

7.4.12 Real-World Efficiency and Market Viability of Brine Recovery Method

While theoretical models of mineral recovery from SWRO brine predict extraction efficiencies often exceeding 90% for key salts such as NaCl, Mg(OH)₂, and KCl, real-world implementation introduces performance gaps due to operational, environmental, and market-based constraints. This study integrates empirical data from pilot-scale demonstrations, which include SEA4VALUE (EU), MINERALS (Spain), and SWCC (Saudi Arabia), to reconcile modelled outcomes with field performance. A good example is magnesium recovery through lime precipitation, although theoretically near-complete, consistently yields 82–87% in pilot settings due to incomplete precipitation kinetics, brine variability, and mixing limitations [252]. NaCl recovery via solar crystallization achieves high yields but often necessitates post-crystallization refinement to meet industrial-grade specifications [108]. Electrodialysis (ED) modules exhibit high ion selectivity initially, but current efficiency declines as brine conductivity drops, compounded by membrane scaling and polarization under prolonged operation [231, 253].

Importantly, technical efficiency alone does not dictate viability. Market efficiency, defined here as the net value derived from product recovery after accounting for

operational cost, purity level, logistics, and demand saturation, often diverges from theoretical recoverability. For example, while magnesium hydroxide may be recovered at high purity, its market is limited by price volatility and quality specifications for downstream applications, e.g., flame retardants, wastewater neutralizers. Similarly, bromine and potassium salts hold commercial value, but market access can be restricted by regional demand, transport infrastructure, and purity certification costs. These discrepancies between modelled and field performance highlight the necessity of incorporating correction factors and real-world constraints in scaling analyses.

Furthermore, scenarios involving co-location with desalination facilities or industrial parks improve market efficiency by reducing transport costs and leveraging existing utility infrastructure. Recovery methods that produce intermediate-grade materials, such as crude $\text{Mg}(\text{OH})_2$ or mixed salt cakes, may also be viable under bulk industrial applications where ultra-high purity is not required. This highlights the necessity of integrating economic viability assessments that extend beyond energy balance and recovery rates to include logistics, end-use value chains, and market positioning.

7.4.13 Business Case and Commercial Viability

Transitioning brine recovery from pilot to full commercial scale requires a sound business case. The technical findings were combined with economic considerations here, highlighting models for profitability and sustainability.

7.4.13.1 Cost-Benefit Analysis

The core question to be asked is, can revenue from recovered products exceed the cost of recovery? For many scenarios, evidence suggests yes, especially if the most valuable components are targeted. Using conservative estimates, suppose the brine processing adds \$1 per cubic meter cost, and yields products worth \$1.5 per cubic meter. That \$0.5 net positive per m^3 , applied to large volumes, is substantial. The Spanish analysis by del Villar, et al. [188] found that at optimistic commodity prices, the revenue from minerals could be 1.5 – 2.8 times the cost of producing the desalinated water itself. In our hypothetical plant example, even if only NaCl , $\text{Mg}(\text{OH})_2$, and bromine were recovered at moderate efficiency, the sales could total around \$150 – \$200 million/yr (Table 2), as against a likely \$50 – \$100 million/yr operating cost for

the recovery process. A critical factor is commodity prices and market volatility [203]. Some elements, such as lithium or gallium, have volatile markets. A spike can make a brine project suddenly lucrative, and a crash in price can negatively affect the project. A practical strategy is to focus on no-regret products. NaCl will always have a large steady market, though at a low price, while salts such as $\text{Mg}(\text{OH})_2$ have widespread moderate demand. These anchor products can cover costs, while the icing on the cake is a rare element like rubidium, strontium, etc. For instance, strontium used in ceramics and fireworks can be recovered as SrCO_3 , even a small amount can add a few million in revenue because Sr prices are high relative to its abundance. Notably, del Villar, et al. [188] identified two groups: abundant low price (Na, Mg, Ca, B) and scarce high price (Li, Rb, Sr, Ga). The first group provides bulk revenue, the second group provides a high margin if extraction is successful.

Large desalination plants benefit from economies of scale in implementing recovery. Many costs, such as labor, monitoring systems, etc., do not double when the flow doubles. Also, bigger plants mean more absolute product output, which is important for commodities. For example, a plant that can produce 100,000 tons of salt per year could enter industrial markets, whereas a small 1,000-ton/year output might only sell as gourmet salt. The del Villar, et al. [188] study noted that large SWRO had up to 8× higher revenue potential than smaller brackish plants, primarily due to scale. Centralized brine processing hubs could even take brine from multiple nearby desalination plants to achieve critical mass for a chemical plant, which could be through pipelines or trucking concentrated brine.

Building recovery systems requires capital for tanks, evaporators, membranes, etc. Innovative financing could treat it like a mining operation or chemical plant investment rather than a water utility expense. This means potentially accessing different funding sources perhaps those interested in battery metals for Li, etc. Governments might support brine mining projects as strategic resource initiatives, e.g., to locally produce critical minerals like magnesium or lithium and reduce imports. Policy incentives such as subsidies, tax credits for waste reduction or critical mineral production can improve the ROI. In the EU, critical raw materials like Mg, K, B, etc., recovered from brine could qualify for such support [206].

7.4.13.2 Risk Management

Commercial viability also needs risk mitigation. Long-term offtake agreements for salt or chemicals can stabilize income. For example, partnering with a chlorine manufacturer to take NaCl brine or with a cement company to take CaCO₃ and gypsum byproducts. Starting with proven technologies in early phases, like evaporation ponds or existing ZLD crystallizers and then incrementally adding newer tech like selective membranes, reduces the risk of total system failure. Many brine mining projects plan phased implementation for this reason.

Environmental regulations could either hamper or help. Stricter rules on brine discharge would force plants to consider ZLD, indirectly boosting brine recovery efforts. On the other hand, permitting a new chemical production unit might raise regulatory hurdles in handling chlorine, etc. Engaging regulators early to frame the project as environmental enhancement can ease the way. There is also a tangible and real benefit in a desalination plant that achieves zero liquid discharge and produces useful materials. They can brand themselves as a sustainable facility, potentially accessing Environmental, Social, and Governance investment funds or enjoying public support. Some water companies now include resource recovery in their sustainability metrics.

It is important to note that brine is not the only source of these minerals. Traditional mining and chemical operations also compete favorably. For instance, if potash prices are low due to ample supply from mines, recovering the tiny amount from seawater might not pay off. But in some cases, brine recovery is complementary, for example, bromine is largely produced from brines, so extending it to desalination brine is a natural expansion of an existing industry. Moreover, terrestrial resources for some elements are becoming stressed or environmentally problematic, e.g, magnesium mining can be CO₂ intensive, lithium mining has water conflicts, etc. Brine extraction offers a cleaner alternative, which in a carbon-priced future, could be cheaper when external influences are accounted for [203]. In many coastal regions, saltwater desalination is here to stay. Integrating an eco-friendly mining operation could open a new revenue stream and help justify desalination projects that otherwise might be seen as only cost-intensive. A shift in mindset is needed: instead of desalination being just a water supply, it becomes a co-production of water and minerals, much like how oil wells produce oil and associated gas, both of which are sold.

In summary, the business case for commercial brine recovery is increasingly gathering attention due to technical advances in lowering costs and external drivers such as resource demand, environmental regulations, etc., which increase the benefits. With smart integration, a desalination facility can evolve into a combined water and mineral production plant. Economic analyses from recent research consistently show positive outlooks, often emphasizing that even partial recovery, focusing on the most cost-effective components, can tip the balance to net profit [203]. In the next few years, we are likely to see the first such integrated plants come online, paving the way for wider adoption if they prove the concept.

7.5 Conclusion

Seawater reverse osmosis desalination no longer needs to be seen as having an inconvenient waste byproduct, instead, the concentrated brine can be a feedstock for extracting commercial metals and salts. Through a combination of established and innovative processes, it is technically feasible to recover the majority of dissolved ions from rejected brine and convert them into valuable products. This paper reviewed the global state-of-the-art in brine resource recovery, focusing on the major constituents (Cl^- , Na^+ , SO_4^{2-} , Mg^{2+} , Ca^{2+} , K^+ , HCO_3^- , Br^-) and the methods to extract each in marketable quantities. Proven and emerging technologies were identified and reviewed, including membrane separations, such as nanofiltration and electrodialysis, thermal crystallization and evaporation, chemical precipitation, and electrochemical extraction. Their effectiveness was evaluated for isolating key salts (e.g., NaCl , KCl , CaSO_4) and minerals, e.g., $\text{Mg}(\text{OH})_2$, bromine from seawater reverse osmosis brine. Approaches such as membrane separation (RO/NF/ED), thermal crystallization, and chemical precipitation can be configured in integrated systems to maximize overall yield and purity of outputs. Emerging techniques from osmotically assisted RO to ion-selective sorbents further enhance efficiency and selectivity, making the recovery process more economical and flexible.

Our analysis indicates that a well-designed brine mining process can achieve high recovery rates, often above 80% of total salts and produce multiple products that offset or exceed the cost of implementation and adjoining water desalination. The potential economic upside is substantial, with case studies showing that the value of recovered

NaCl and Mg alone can cover costs, and recovery of trace elements can provide significant additional profit [188]. Many countries reliant on desalination also import the same commodities that could be produced from their brine, suggesting a ready internal market and improved resource security [188, 206]. Environmentally, brine recovery slashes liquid waste discharge and associated ecological risks, aligning desalination with sustainability goals and easing regulatory compliance.

To realize these benefits, desalination plant operators and policymakers should consider the following actionable steps: For any planned large SWRO plant, a brine management section that evaluates at least salt and magnesium recovery should be included in the design. The incremental capital cost can be weighed against long-term operational and maintenance (O&M) savings and revenue analysis. Engaging technology providers early for NF/ED units or crystallizers will help integrate the processes smoothly. Conducting a pilot trial using actual brine on-site to determine the best sequence of recovery for local conditions. For example, a Middle East plant might pilot NF-evaporation for salt, whereas a plant in Europe might pilot ED-precipitation for magnesium, driven by different market needs. Pilot data is invaluable for de-risking scale-up and convincing stakeholders of feasibility. Efforts like SEA4VALUE in the EU are exemplary in systematically testing technologies on real brines [209]. Form partnerships between water utilities and industries (chemical, mining, agriculture). A desalination company may not have the distribution network to sell salts or minerals, but partnering with a salt company or a chemical off-taker can ensure that all products are sold. For instance, partner with a cement plant to supply CaCO_3 and gypsum, with a chemical plant for NaCl brine or chlorine, and with agriculture suppliers for K and Mg salts. These partnerships turn the brine into a resource for multiple value chains.

Governments aiming for a circular economy should incentivize brine recovery projects through grants or favorable power and water tariffs for ZLD operations. For example, reduced disposal fees or faster permit approvals for plants that include brine mining could encourage adoption. Given that brine mining also mitigates environmental impacts, regulators can require new desalination projects to evaluate resource recovery options as part of their environmental impact assessments. Start with the low-hanging fruit processes that are most mature and immediately viable. This could be as simple as solar ponds to produce salt where land/climate permits, or adding a lime

dosing unit to recover magnesium hydroxide. Even a single product stream can provide value and experience. Additional recovery modules for potassium, bromine, etc. can be added once the simpler ones are running successfully. This incremental approach spreads out investment and allows learning and adaptation. Once in operation, continuous monitoring of both the water side and the product side is very important. Quality control of products is important to fetch good prices (e.g., avoid cross-contamination of salt with other minerals by proper separation). Likewise, monitoring the brine composition throughout the process is key to ensuring that, as one component is removed, the conditions of the next steps might need fine-tuning to meet the market demand. Digital twins and process simulations can be employed to optimize the system in real-time for maximum yield and minimal energy use.

In conclusion, the paradigm of desalination is poised to shift from water treatment with waste to water and mineral production. The technologies discussed, many of which have been demonstrated at least on a pilot scale, show that nearly every ion in seawater can be put to use. Commercial viability hinges on smart integration and favorable economics, but evidence from recent projects is encouraging. With desalination expanding worldwide, especially in water-scarce but sun-rich regions, the opportunity to transform brine into a resource is timely. This will not only improve the sustainability profile of desalination but also add a new revenue stream that can reduce the cost of delivered freshwater to communities. By adopting innovative recovery methods and advanced extraction processes, seawater desalination can achieve both zero liquid discharge and zero waste of valuable materials, closing the loop in a truly circular approach to seawater usage. The path to sustainable desalination thus lies in treating the ocean not just as a source of water, but as a source of all the minerals dissolved in that water, a holistic viewpoint that promises economic and environmental dividends in the years to come.

CHAPTER 8: Cost-Benefit and Market Viability Analysis of Metals and Salts Recovery from SWRO Brine Compared with Terrestrial Mining and Traditional Chemical Production Methods

Seawater reverse osmosis (SWRO) desalination produces a concentrated brine stream enriched with a variety of dissolved salts and trace minerals. This chapter presents a detailed technical and economic evaluation of recovering major ionic constituents from SWRO brine, with a comparative perspective on conventional mining and chemical production of the same commodities. The brine typically contains sodium, chloride, magnesium, calcium, sulfate, potassium, bromide, boron, lithium, rubidium, and strontium, which represent potential inputs for several industrial value chains. A life-cycle cost assessment framework is applied, encompassing capital expenditure (CAPEX), operational expenditure (OPEX), and the effect on total water cost (TWC). The study uses published data and case studies to quantify expected recovery outputs and economic value. A simulation based on a 100,000 m³/day SWRO plant indicates that brine mining systems can yield approximately 3.8 million tons of salts per year. Under favorable recovery conditions, projected annual revenue from recovered products such as NaCl, Mg (OH)₂/MgO, CaCO₃, KCl, Br₂, and Li₂CO₃ can match or exceed additional processing costs, with potential cost offsets to desalinated water production reaching \$0.5/m³.

The chapter compares brine recovery economics with global benchmarks for traditional mining and chemical extraction. The findings show that abundant low-value salts like NaCl contribute to baseline revenue, while rare high-value elements such as lithium, rubidium, and strontium can drive profitability where separation technologies are effective. The analysis further explores the energy requirements and cost dynamics of brine recovery, revealing competitive advantages when waste heat or renewable energy is explored. Global case examples, including facilities in Europe and the Middle East, are reviewed to validate the feasibility of such integrated systems. The chapter also introduces empirical models and economic indicators that may guide future

projects. Key influencing factors include plant scale, commodity market conditions, energy integration strategies, and the availability of policy incentives. The content in this chapter, co-authored with Prof. Oludolapo A. Olanrewaju has been submitted and is currently under review in the “Water”, an open access journal from MDPI - Manuscript ID: water-3740171

8.1 Introduction

Desalination of seawater is expanding globally to meet rising freshwater demand, but it produces large volumes of concentrated brine waste [254, 255]. Nearly 16,000 desalination plants worldwide generate about 142 million cubic meters of hypersaline brine every day, compared to 95 million m³ of fresh water output [82, 254]. This brine (the SWRO reject stream) is typically considered a waste product, often discharged to the ocean. Brine disposal raises environmental concerns due to high salinity, chemical additives, and thermal effects in the receiving waters [188]. At the same time, brine can be viewed as a resource because it retains essentially the same ionic constituents as seawater but at roughly double concentration in a SWRO process with 50% water recovery [185, 201]. In line with circular economy principles, there is growing interest in “mining” these dissolved salts and metals from brine to create valuable products, turning an environmental liability into an economic asset [188].

A typical SWRO brine of 70 g/L total dissolved solids (TDS) contains predominantly sodium and chloride ions (from NaCl), along with significant sulfate, magnesium, calcium, potassium, and smaller amounts of bromide, boron, and trace elements [203]. Figure 8-1 illustrates the composition of a representative SWRO brine by major ion fraction. Chloride and sodium together account for approximately 85% of the total salt mass (around 35 g/L Cl⁻ and 19 g/L Na⁺ in brine) [201]. Sulfate (5 g/L), magnesium (2.5 g/L), calcium (0.8 g/L), and potassium (0.8 g/L) constitute most of the remaining mass [201]. Minor constituents include bicarbonate (0.2 g/L as CO₃²⁻) and bromide (0.12 g/L) [188, 201], as well as trace levels of boron (as boric acid, on the order of 0.01–0.02 g/L), lithium (0.0003–0.0005 g/L), rubidium (0.0002 g/L), and strontium (0.016 g/L) in seawater-derived brine [188, 201]. These dissolved minerals correspond to a diverse array of potential recoverable products from abundant commodities like sodium chloride salt and gypsum, to position but high-value materials like lithium compounds and rubidium salts [201].

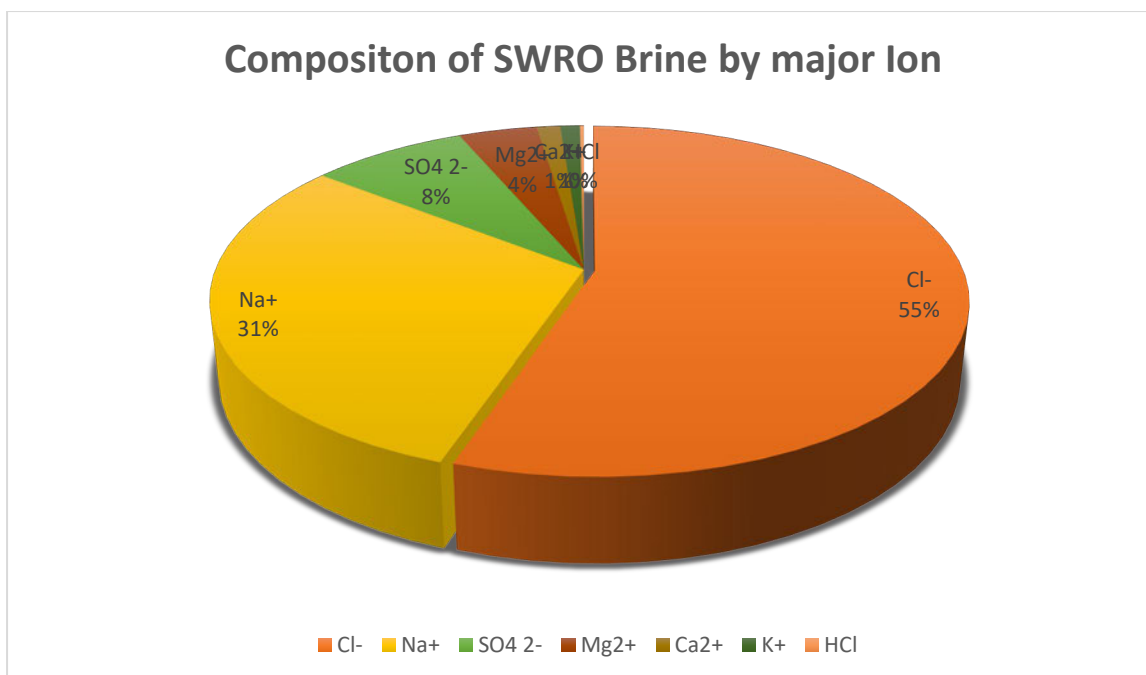


Figure 8-1 Major ion composition of a typical SWRO brine (70 g/L salinity).

Sodium and chloride dominate (85% of total salts), with sulfate, magnesium, calcium, and potassium comprising most of the remainder constituent [201]. Minor constituents such as bromide, bicarbonate, boron, etc., collectively account for <2%. Recovering these elements from brine offers a dual benefit: (1) mitigating the environmental impact of brine disposal by reducing salinity and removing contaminants, and (2) improving desalination economics by producing saleable commodities. By extracting resources from what is currently a waste stream, SWRO plants can offset operating costs and move toward more sustainable, zero-liquid-discharge (ZLD) operations. However, realizing this “brine mining” potential requires overcoming technical and economic challenges. The concept of harvesting minerals from the ocean is not new. Historically, sea salt has been produced via solar evaporation for millennia, and magnesium metal was extracted from seawater in the 20th century e.g. Dow Chemical’s Freeport plant in Texas began extracting magnesium from seawater in 1941 [205]. The key advancement with modern SWRO brine is that the feed is already partially concentrated, which is roughly twice the salinity of raw seawater, and which, by principle, reduces the energy or effort needed to further concentrate or isolate valuable components [203]. Despite this advantage, relatively few full-scale implementations of brine resource recovery exist yet, due to concerns about cost-effectiveness and process complexity [203].

This study examines the cost-benefit balance and market viability of extracting metals and salts from SWRO brine in comparison to conventional terrestrial mining and chemical production routes. We focus on all major constituents (Na, Cl, Mg, Ca, SO₄, K, Br) as well as important minor or trace elements (B, Li, Rb, Sr) present in brine. For each of these, we analyze the recoverable quantities, feasible extraction methods, energy requirements, and the potential revenue based on current market prices. These factors are then compared with how the same commodity is obtained from land-based sources or industrial chemical processes, with typical costs and environmental footprints. The analysis uses a global perspective, drawing data from worldwide operations and studies to avoid regional bias. We also incorporate real-world case studies and pilot projects e.g. in Europe and the Middle East that have tested brine recovery, to ground the discussion in operational reality. By integrating technical performance data with economic models such as CAPEX, OPEX, and lifecycle costs, we aim to determine under what conditions brine recovery makes business sense. The overarching goal is to provide clarity on whether “mining” SWRO brine can compete with traditional mining, and to identify key drivers or barriers. for its commercial adoption.

8.2 Methods

Our approach combines literature-derived data, empirical modeling, and original simulations to evaluate the cost-benefit metrics of brine mineral recovery versus conventional production. The analysis follows these general steps:

8.2.1 Characterization of SWRO Brine Composition

Representative data for ion concentrations in SWRO brine based on standard seawater chemistry and reported measurements [137]. Table 8-1 summarizes the target ions and their typical concentrations in a 70 g/L TDS brine, along with the corresponding compounds that could be produced. This composition serves as the basis for calculating potential yields of each mineral per unit volume of brine.

8.2.2 Identification of Recovery Technologies

For each element or salt, proven or emerging extraction methods suitable for brine processing were identified. These include membrane separations such as reverse osmosis (Toray Industries, Tokyo, Japan), nanofiltration (DuPont, Wilmington, DE, USA), and electrodialysis stacks (SUEZ Water Technologies, Trevoise, PA, USA) for selective concentration, chemical precipitation using sodium hydroxide (NaOH, Sigma-Aldrich, St. Louis, MO, USA) or lime ($\text{Ca}(\text{OH})_2$, Merck, Darmstadt, Germany), carbonate dosing with sodium carbonate (Na_2CO_3 , Sigma-Aldrich, St. Louis, MO, USA) for CaCO_3 recovery, thermal processes such as evaporators and crystallizers (GEA Group, Düsseldorf, Germany) for salts like NaCl and KCl, and electrochemical methods such as chlor-alkali electrolysis units (Asahi Kasei Chemicals, Tokyo, Japan) for chlorine and sodium hydroxide recovery, bipolar membrane electrodialysis for acid/base production [79]. Typical energy requirements and chemical inputs for these methods were considered from the literature, as these factors directly affect cost.

8.2.3 Economic Data Collection

The current market prices and production cost estimates for the relevant commodities (such as salt, magnesium compounds, potash, bromine, boron, lithium, etc.) were gathered from industry reports and databases. For example, the average global price of industrial salt is on the order of USD 30–60 per ton for bulk rock salt or solar salt, high-purity magnesium oxide can command around USD 300/ton [256], bromine prices are roughly USD 3–5 per kg (import value) [257], and lithium carbonate prices in 2022–2024 ranged from USD 14,000 to USD 46,000 per ton amid market volatility [258]. These price points, with references, form the basis for calculating potential revenues from brine-derived products. Likewise, we reviewed cost models for mining or producing these materials conventionally (e.g., mining cost of potash ore, energy cost for lithium extraction from continental brines, etc.) to have benchmarks for comparison.

8.2.4 Simulation of Integrated Brine Recovery in a Desalination Plant

A simplified simulation for a hypothetical large SWRO plant, a 100,000 m³/day fresh water production at 45% recovery, was developed to quantify the annual amounts of each mineral that could be recovered. This scenario assumes the plant takes in 250,000 m³/day of seawater and produces 150,000 m³/day of brine (70 g/L). By

applying reasonable recovery efficiencies for a multi-step extraction process (e.g., NaCl crystallization followed by $\text{Mg}(\text{OH})_2$ precipitation, etc.), we estimated the tonnage of each product per year and the energy or chemical consumption required. A full material balance was not available from a single source, so we synthesized data from multiple studies to approximate yields. This simulation provides concrete values for CAPEX/OPEX analysis (for instance, sizing evaporators or reactors) and for revenue calculation. Figure 8-2 presents the structured simulation workflow adopted for assessing the cost–benefit and market viability of mineral and salt recovery from SWRO brine. Each stage corresponds to a critical modeling task.

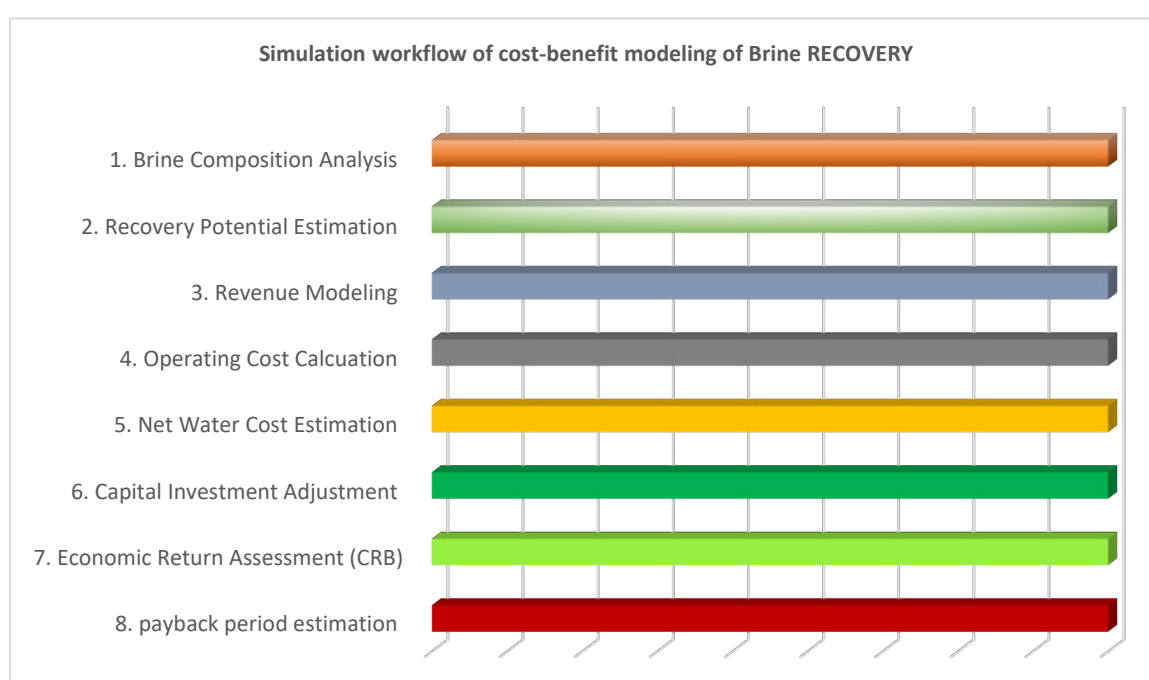


Figure 8-2 Simulated Workflow for Cost Benefit Modeling of Brine Recovery.

The process begins with brine composition analysis to determine available mineral concentrations. This is followed by estimating the technical recovery potential based on literature-derived efficiencies. Product revenue modeling uses prevailing market prices to project earnings per cubic meter. Operating costs are calculated separately for desalination and brine recovery processes. These are integrated to derive the net water cost. Capital investment is accounted for in subsequent steps to simulate long-term returns using cost–benefit ratios and payback period estimation. The workflow serves as the computational backbone for the techno-economic evaluation and supports the decisions discussed in the results section.

8.2.4.1 Simulation and Economic Modeling

To evaluate the financial viability of mineral and salt recovery from seawater reverse osmosis (SWRO) brine, a simulation-based modeling framework was developed. This framework integrated chemical mass balances, revenue forecasting, operating cost estimation, and standard financial evaluation tools. This model was applied to a representative high-capacity SWRO facility and used to quantify the techno-economic outcomes associated with the recovery of key constituents such as sodium chloride (NaCl), magnesium hydroxide [Mg (OH)₂], and bromine (Br₂).

Mineral Mass Balance

The quantity of recoverable mineral per unit volume of brine was estimated using a simple mass balance equation, as shown in Equation Eq. (8-1).

$$Mr = Cb \cdot Vb \cdot \eta r \quad \text{Eq. (8-1)}$$

where:

- Mr = mass of recoverable mineral (kg)
- Cb = concentration of the target ion in brine (kg/m³)
- Vb = volume of brine treated (m³)
- ηr = recovery efficiency (dimensionless, 0–1)

For instance, with magnesium concentration at 1.3 kg/m³ and a recovery efficiency of 50%, the recoverable mass is 0.65 kg/m³.

Product Revenue Estimation

The economic value of recovered materials was calculated by multiplying the recovered quantity by prevailing market prices for industrial-grade minerals. The following global average prices were used: NaCl—USD 60/ton, MgO—USD 300/ton, and Li₂CO₃—USD 4500/ton. Revenue per cubic meter of treated brine was then determined using Equation Eq. (8-2):

$$R = \sum_{i=1}^n (P_i \cdot M_{r,i}) \quad (8-2)$$

where:

- R = total revenue from product sales (USD)
- P_i = market price of mineral i (USD/kg or USD/ton)

- Mr,i = mass of mineral i recovered (kg or tons)
- n = number of different minerals recovered

Operating Cost Calculation (OPEX)

Operating costs included the base desalination cost and additional brine processing expenditures. The base SWRO operating cost was assumed to be USD 0.80/m³, consistent with industry averages. Brine processing added an estimated USD 1.00/m³ [14], resulting in a total operational cost of USD 1.80/m³ using Equation Eq. (8-3).

$$C_{op} = C_{swro} - C_{recovery} \quad \text{Eq. (8-3)}$$

Net Water Cost Evaluation

To reflect the impact of product revenue on desalination economics, net water cost was calculated using Equations Eq. (8-4) and Eq. (8-5) by subtracting revenue from the total cost:

$$C_{net} = C_{op} - R_v \quad \text{Eq. (8-4)}$$

$$\text{Net Water Cost} = \text{OPEX} - R \quad \text{Eq. (8-5)}$$

where

- C_{net} = net water cost after byproduct credit (USD/m³)
- R_v = revenue per m³ of brine treated (USD/m³)

$$R_v = \frac{R}{V_b} \quad \text{Eq. (8-6)}$$

For a total revenue of USD 1.50/m³ and OPEX of USD 1.80/m³, the net cost was reduced to USD 0.30/m³.

Cost–Benefit Ratio (CBR)

The long-term economic viability was assessed using the cost–benefit ratio (see Equations Eq. (8-7) and Eq. (8-8)):

$$CRB = \frac{R}{C_{cap} + C_{op.t}} \quad \text{Eq. (8-7)}$$

$$CBR = \frac{R \cdot V_b \cdot t}{C_{cap} + C_{op} \cdot V_b \cdot t} \quad \text{Eq. (8-8)}$$

- R = total revenue over period t (USD)
- C_{cap} = capital expenditure (USD)
- t = number of years of plant operation

Assuming a capital expenditure of USD 150 million and a 20-year project lifetime, a CBR greater than 1 was considered indicative of economic attractiveness.

Payback Period (PBP) Estimation

The investment recovery timeline was calculated using Eq.(8-9):

$$PBR = \frac{C_{cap}}{(R - C_{op}) \cdot V_b \cdot 350} \quad \text{Eq. (8-9)}$$

This modeling approach formed the quantitative basis for evaluating recovery feasibility under realistic industrial conditions. Results derived from these calculations were used to analyze capital intensity, resource yield, and financial returns, as presented in Section 3.

8.2.5 Cost–Benefit Analysis Framework (CAPEX/OPEX and LCC Modeling)

To evaluate the economic viability of integrated brine recovery, we employ a cost–benefit analysis (CBA) framework that accounts for both capital and operating costs, as well as potential revenues from recovered products. This framework is based on life-cycle cost (LCC) modeling, which involves considering the total costs over the project's lifetime and comparing them to the total expected income or savings, appropriately discounted. Key components of the analysis include:

8.2.5.1 Capital Expenditures (CAPEX)

The up-front investment needed to add mineral/salt recovery processes to a desalination plant. This encompasses equipment such as additional membrane modules, chemical reactors, evaporators or crystallizers, brine handling and storage facilities, and any integration costs for retrofitting existing infrastructure. For example, adding a brine processing unit might require significant pumps, tanks, and corrosion-

resistant materials, which can amount to tens or hundreds of millions of dollars in large-scale facilities. These estimates were benchmarked against reported CAPEX for desalination and chemical plants. Panagopoulos [215] estimated that implementing a zero-liquid-discharge system on a 100,000 m³/d RO plant would necessitate capital investment on the order of the base desalination plant itself, although modular designs can spread this cost depending on which minerals are targeted. The adopted model amortizes the CAPEX over the plant life (e.g., 20–30 years) to incorporate it into the unit cost of water and products.

8.2.5.2 Operating Expenditures (OPEX)

The recurring costs of running the brine recovery processes, added to the normal SWRO operating costs. OPEX includes energy consumption (often the largest component), chemicals and reagents (e.g., antiscalants, precipitants like NaOH or lime, acids for pH adjustment, etc.), membrane replacement or other consumables, labor, maintenance, and waste disposal for any solid residues. Energy usage estimates for each process step were compiled from literature studies. Additional RO/NF stages might consume 2–5 kWh/m³, electrodialysis may consume 5–15 kWh/m³, depending on the degree of concentration, thermal crystallizers consume 50–80 kWh/m³ of brine evaporated, etc. [198]. Chemical costs are estimated based on dosage rates (e.g., precipitating magnesium with lime requires 1.4 kg of lime per m³ of brine) and current reagent prices. It was also considered that some processes yield byproducts that offset costs. A good example is precipitating Mg (OH)₂, which removes magnesium that might reduce anti-scalant needs in downstream equipment. All these OPEX factors are summed to determine the incremental cost per cubic meter of water processed, or per cubic meter of brine treated for the resource recovery system.

8.2.5.3 Revenue and Credits

The economic benefit side of the ledger comes from the sale of recovered minerals and salts. For each target product, market price data from recent years were used to estimate revenue. Major commodity prices were gathered from industry and government sources (e.g., bulk industrial salt at USD 30–60 per ton, magnesium hydroxide or oxide around USD 300/ton, bromine USD 3–5 per kg (i.e., USD 3000–5000/ton), potash (KCl) roughly USD 250–300/ton, lithium carbonate highly volatile from USD 14,000/ton in 2020 up to over USD 40,000/ton in the 2022 spike, etc.). These

figures are cross-checked with mineral commodity reports and recent trading data. For example, the U.S. Geological Survey reported the average lithium carbonate price in 2022 was in the tens of thousands of dollars per ton, reflecting the lithium boom [17]. It was noted that some markets are region-specific (e.g., bromine prices vary by region and contract), so a range was adopted. The revenue from each product is calculated as $(\text{recovery rate}) \times (\text{concentration in brine}) \times (\text{flow of brine}) \times (\text{price per unit})$. In cases where recovered products do not meet purity specifications or require additional refinement, appropriate discount factors or supplementary processing costs are incorporated. Within the cost–benefit analysis (CBA), revenues from recovered materials are treated as financial credits that offset the overall desalination expenditure. When these credits exceed the operating expenses (OPEX) of the recovery system, the process is considered economically profitable; otherwise, it represents a net operational cost.

8.2.5.4 Net Present Value and Profitability Metrics

Using the above elements, we compute metrics like net present value (NPV), internal rate of return (IRR), payback period, and levelized cost of water (LCOW) with and without the brine mining component. Future cash flows were discounted using a chosen discount rate, such as 6–8%, and include any salvage values or decommissioning costs at the end of life. The life-cycle cost (LCC) analysis provides a holistic view of the economics. Ojo, et al. [259] applied LCC analysis to evaluate SWRO desalination economics and highlighted that any added process must be weighed over the full project life to see true cost impacts. Following such approaches, the brine recovery's CAPEX and OPEX were integrated into the overall desalination project cash flow. This allows the calculation of how much the total water cost (USD/m³) changes when brine mining is implemented. The cost–benefit ratio was also examined (i.e., total revenue divided by total cost for the brine recovery system) as a straightforward indicator. A ratio above 1.0 means the recovery pays for itself, while below 1.0 means it operates at a net cost.

The framework is structured to evaluate whether the economic value derived from mineral and salt recovery from SWRO brine exceeds the associated incremental costs of recovery. It further quantifies the extent to which such recovery reduces the net cost of water production or contributes to overall system profitability. By modeling on a per-

m³-of-water and per-year basis, scenarios can be directly compared and sensitivity analyses can also be performed to identify the most influential factors. This type of techno-economic modeling aligns with methods used in recent assessments of ZLD and resource recovery systems, ensuring that our approach is consistent with best practices in the literature.

8.2.6 Costs and Revenues in the Model

Based on the CAPEX/OPEX framework described earlier, costs were assigned to each part of the integrated process. The SWRO desalination is assumed to have a baseline water cost around USD 0.5–0.8 per m³, which is consistent with large modern plants [19]. The brine recovery system adds extra operating cost. The base estimate is about USD 1.0 per m³ of feed water treated, which covers the reagents, energy, and additional maintenance for the recovery processes, which is in line with estimates from previous studies for multi-step mineral recovery on seawater brine. Therefore, total OPEX with brine mining becomes roughly USD 1.5–1.8 per m³. On the revenue side, summing the products, it is estimated that the gross revenue will be USD 1.5–2.0 per m³ of water processed under mid-range price assumptions. In this case study, for every cubic meter of water processed, the plant could earn on the order of USD 0.7 from NaCl, USD 0.5 from Mg (OH)₂, USD 0.1 from K salts, USD 0.3 from Br₂, and a few cents from Li and other trace elements. In total, about USD 1.5 of revenue per m³ of water is projected in the base case, against approximately USD 1.0 of added cost per m³. This implies the recovered products could offset about USD 0.5 per m³ of the total water cost. If the base desalination cost was USD 0.8, it could drop to a net USD 0.3 per m³ after credits, a 62.5% reduction in water cost. The model calculates a payback period of around 6–8 years for the added investment, given these cash flows. Specifically, for a CAPEX of about USD 150 million for the recovery system, an annual net revenue on the order of USD 20–30 million would yield payback in under a decade. These values are within a similar range to those reported by [188] for hypothetical brine mining in Spanish desalination plants, which found that under optimistic assumptions, product revenues could be 1.5–2.8 times the additional costs.

It is essential to note that these estimates are highly sensitive to the assumptions made. A range of scenarios were explored; for example, if commodity prices are at the

low end of historical ranges or if recovery efficiencies are lower, the revenue might only be USD 0.8–1.0 per m³. In a case where revenue is USD 0.8 and added OPEX is USD 1.0, the net cost per m³ could increase slightly, yielding no economic benefit. On the flip side, in a boom market (e.g., lithium prices spiking or bromine shortage driving up prices) and with high recovery performance, revenues could far exceed USD 2/m³, greatly improving profitability [260]. The base-case simulation suggests that, under normal conditions, integrated brine valorization can make a SWRO plant's water 30–60% cheaper per unit or equivalently, provide a new revenue stream of order a few hundred million USD per year for a large plant. This aligns with the notion that desalination could transition from just water production to a dual water-and-minerals operation that potentially pays for itself. In our Results section below, we delve deeper into these outcomes and also compare them to the costs of conventional production of the same minerals.

Beyond the economics, the simulation tracks material flows and energy use to feed into environmental analysis. It was asserted that recovering nearly all salts moves the plant toward zero-liquid discharge, with only a small purge stream or concentrated bittern remaining. The energy consumption for the entire integrated system in the base case comes out to around 5 kWh/m³ for SWRO + 10 kWh/m³ for brine processing (mostly for thermal steps and ED), totaling 15 kWh/m³, which is higher than standalone RO but still within range if cheap electricity is available. This is because energy cost is a major determinant in the economic viability, as we examine later. Lastly, the brine mining scenario is compared against terrestrial mining or chemical production for each commodity: e.g., we calculate how the cost per ton of each recovered product from brine stacks up against typical production costs or market prices if sourced conventionally. This comparative analysis, summarized in the next section, helps identify which minerals are most economically sensible to obtain from brine and which are better suited to traditional sources under current conditions.

8.2.7 Market Viability Analysis (Price Volatility, Market Size, Strategic Value)

In evaluating the market viability of recovering minerals from SWRO brine, several market factors must be considered: commodity price levels and volatility, the size of the market relative to potential brine-derived supply, and the strategic importance of

the materials in question. Many of the minerals targeted in brine are commodities subject to cyclical and sometimes extreme price fluctuations. This volatility directly impacts revenue projections and investment risk. A prime example is lithium. Lithium prices have seen dramatic swings in recent years due to surging demand for lithium-ion batteries. Lithium carbonate, which sold for around USD 10,000–15,000 per ton in the late 2010s, spiked to over USD 60,000/ton in 2022, then fell back toward USD 20,000/ton by mid-2023 as new supply came online [17,21]. Designing a brine recovery project around lithium when prices are high could lead to disappointment if prices crash during operation. Our analysis uses conservative mid-range price scenarios to mitigate this risk, and we perform sensitivity analysis on price (see results in Section 3) to see how much a drop in lithium or bromine price erodes profitability. Any viable project would secure offtake agreements to manage volatility to reduce exposure to market swings. This approach is common in mining/mineral projects to ensure bankability. The market analysis accounts for this by considering long-term average prices and noting which products have futures or contract markets.

8.2.8 Life-Cycle Cost and Total Water Cost Analysis

We incorporated the additional capital and operating costs of brine recovery into the desalination plant's economics. Using a 30-year project life and discount rate assumptions, we annualized CAPEX and summed with annual OPEX to compute the total water cost (TWC) in USD/m³ of product water, both with and without mineral recovery. The baseline desalination costs (without recovery) were taken from published studies for large SWRO plants; investment costs are around USD 900–1200 per m³/day of capacity and baseline water costs range USD 0.5–1.2 per m³. We then added the brine mining system costs. For example, if brine processing adds an estimated USD 1.0 per m³ in operating cost [137, 215] and requires a capital investment similar to adding a chemical plant, we include those in the model. Against these costs, we credit the revenue from the sale of recovered products, effectively treating the minerals as negative cost (or co-product revenue). This allows calculation of a net TWC for the water produced when brine mining is implemented.

8.2.9 Comparison with Terrestrial Mining

For each material, we compared the brine-derived cost per ton (implied by the above analysis) with the cost of producing one ton via conventional means. We leveraged data such as the energy and reagent consumption for mining and refining (e.g., mining ore, performing chemical conversions), existing production cost estimates, and any environmental or regulatory costs. This comparison is presented qualitatively in terms of whether brine recovery is likely to be cheaper, competitive, or more expensive than the status quo, considering current technology.

8.2.10 Case Study and Sensitivity Analysis

We incorporated real case study data, such as the SEA4VALUE project results which achieved >90% recovery of Mg, B, Li in lab-scale tests [209] and the Acciona MINERALS pilot which projected recovery of >90% of Li, Rb, B and 65–80% of Mg, Ca, K in a 200,000 m³/day plant [206].

These provide validation points for our assumed recovery efficiencies. Additionally, we conducted a sensitivity analysis on key parameters: commodity prices to see how a price drop or spike affects its viability; energy cost for scenarios with cheap renewable energy against high energy costs; and scale to see how a smaller plant's economics compare. This analysis used empirical models from the literature; for example, the observed economies of scale show that larger plants have 5–8× lower unit costs for recovery than small ones [188]. The major constituents of SWRO brine and their potential recovery pathways are summarized in Table 8-1. This table highlights the approximate concentration of each ion in a typical seawater brine (70 g/L salinity) and example products that could be obtained.

Table 8-1 Major ions in SWRO brine and potential recovered products, with typical extraction methods [203, 204].

ION (Symbol)	Conc. in Brine (g/L)	Fraction of Total Salts (%)	Potential Products	Extraction Methods

Chloride (Cl^-)	35	55%	Chlorine gas (Cl_2); HCl acid; NaCl salt	Electrochlorination; membrane electrolysis (chlor-alkali); crystallization (NaCl)
Sodium (Na^+)	19	30%	Sodium chloride (NaCl); Caustic soda (NaOH); Soda ash (Na_2CO_3)	Crystallization (solar or forced); bipolar electrodialysis (NaOH/HCl from NaCl)
Sulfate (SO_4^{2-})	5	8%	Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$); Epsom salt ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$)	Precipitation with Ca^{2+} (gypsum); fractional crystallization for salts
Magnesium (Mg^{2+})	2.5	4%	Magnesium hydroxide ($\text{Mg}(\text{OH})_2$)/oxide (MgO); MgCl_2 ; Mg metal	Alkaline precipitation (using lime or dolime); thermal decomposition; electrolytic reduction
Calcium (Ca^{2+})	0.8	1.20%	Calcium carbonate (CaCO_3); Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)	Carbonate precipitation (soda ash addition for CaCO_3); selective crystallization (gypsum)
Potassium (K^+)	0.8	1.10%	Potash (KCl salt or K_2SO_4 fertilizer)	Evaporative crystallization from bittern; ion exchange to concentrate K^+
Bicarbonate (HCO_3^-)	0.2 (as CO_3^{2-})	0.30%	Calcium carbonate (CaCO_3); CO_2 (gas)	Lime dosing to precipitate CaCO_3 (releasing CO_2 gas)

Bromide (Br^-)	0.12	0.20%	Bromine (Br_2); Sodium bromide (NaBr)	Chemical oxidation (e.g., with chlorine) + air stripping of Br_2 ; selective adsorption on resin
Minor traces:				
Boron (as $\text{B}(\text{OH})_3$); Lithium (Li^+); Rubidium (Rb^+); Strontium (Sr^{2+})	ppm levels	<0.2% combined	Boric acid (H_3BO_3); Lithium carbonate (Li_2CO_3); Rb salts; SrCO_3	Specialized methods (boron-selective resin; lithium ion-sieves or selective adsorption precipitation for Sr)

8.3 Results

This section presents the quantitative findings derived from techno-economic assessments, numerical simulations, and cost modeling of metals and salts recovery from SWRO brine. Key variables such as product yield, energy consumption, CAPEX, OPEX, and unit recovery cost are analyzed across multiple scenarios. Comparative cost–benefit metrics are developed for both brine-based extraction and conventional production methods.

8.3.1 Composition of Brine and Potential Recoverable Products

As shown in Table 8-1, sodium chloride (NaCl) is the dominant salt in the brine. Consequently, any extensive resource recovery strategy will be centered on extracting NaCl first [203]. Removing a large fraction of NaCl (e.g., via crystallization) yields not only a valuable salt product but also produces a bittern, the residual brine enriched in the other, less abundant components. Sequential processing is advantageous; once NaCl , which makes up 85% of the salts by mass, is crystallized out, the volume of the remaining solution is much smaller, and the concentrations of Mg^{2+} , K^+ , Br^- , etc. become much higher relative to the resulting volume [203].

The removal of major constituents such as sodium and magnesium facilitates the subsequent recovery of minor elements by reducing volume and simplifying chemical interactions, thereby enhancing process efficiency. A representative process sequence may include preliminary brine concentration (if required); sodium chloride recovery via solar evaporation or mechanical crystallization; magnesium extraction from the

resulting bittern through alkaline precipitation as $\text{Mg}(\text{OH})_2$ or conversion to MgCl_2 ; followed by calcium removal as CaCO_3 or CaSO_4 . The reduction of Mg^{2+} activity typically promotes the crystallization of calcium-based compounds, including gypsum and strontium-bearing phases [204, 261]. Recovery of potassium salts, such as KCl or K_2SO_4 , is achieved from the further concentrated bittern solution, where elevated ionic strength and reduced solubility enable the precipitation of these compounds during subsequent evaporation stages [188, 206]. Bromine is recovered by oxidizing bromide ions (Br^-) to elemental bromine (Br_2), typically through chemical oxidation using chlorine gas or electrochemical anodic methods, followed by vapor-phase stripping. Trace constituents such as boron and lithium may subsequently be extracted from the remaining concentrate, contingent upon technical feasibility and economic justification, using methods such as boron-selective adsorption resins or lithium-specific adsorption and crystallization [203, 219].

In parallel with designing recovery processes, one must consider the purity requirements and market form of each product. Some recovered salts can be sold in their crude form (e.g., deicing salt or raw gypsum) with minimal purification. In contrast, others require high purity (e.g., >99% MgO for specialty applications, or battery-grade Li_2CO_3), which demands more intensive processing. These compromises directly impact cost and viability, as shall be discussed later.

8.3.2 Simulation and Case Study: 100,000 m³/day Desalination Plant with Brine Mining

This section details the simulation of a large-scale seawater reverse osmosis (SWRO) desalination plant with an integrated brine recovery system. The case study models a facility treating 100,000 cubic meters of seawater per day, incorporating salt and metal extraction processes to assess economic performance. The simulation includes mass balance calculations, product yield estimates, capital and operating costs, and financial return indicators. This model serves to demonstrate how brine mining can impact the economic profile of a full-scale desalination plant.

8.3.2.1 Simulated Economic Outputs for Brine Recovery

The simulated economic performance indicators of a high-capacity SWRO desalination facility integrated with mineral and salt recovery systems are presented in Table 8-2. The simulation quantifies key variables including daily brine volume treated, unit revenue from recovered products, operating expenditures, net water cost, capital investment, and expected payback period. The figures are based on industry benchmarks, reported literature, and conservative assumptions for recovery efficiency and market pricing. The results are intended to support financial viability assessments and guide decision-making for integrated resource recovery in desalination infrastructure.

Table 8-2 Simulated Economic Outputs for Brine Recovery

S/N	Metric	Value
1	Brine Volume (mA ³ /day)	100,000
2	NaCl Revenue (USD/mA ³)	0.7
3	Mg(OH) Revenue (USD/mA ³)	0.5
4	Br Revenue (USD/mA ³)	0.3
5	Total Revenue (USD/mA ³)	1.5
6	SWRO Cost (USD/mA ³)	0.8
7	Brine Recovery Cost (USD/mA ³)	1
8	Total OPEX (USD/mA ³)	1.8
9	Net Water Cost (USD/mA ³)	0.3

10	Capital Cost (USD million)	150
11	Payback Period (years)	6.9

Table 8-2 presents a consolidated overview of the key quantitative parameters derived from the economic modeling of a seawater reverse osmosis (SWRO) plant equipped with mineral and salt recovery systems. The plant under consideration is modeled at a throughput capacity of 100,000 cubic meters per day (m³/day), representative of a large-scale commercial SWRO facility. The revenue streams were divided into three leading product categories; sodium chloride (NaCl), magnesium hydroxide [Mg(OH)₂], and bromine (Br₂), with respective earnings of USD 0.70, USD 0.50, and USD 0.30 per cubic meter of treated brine. These values were derived using realistic recovery efficiencies and current market prices sourced from verified industry benchmarks and peer-reviewed economic studies.

The total estimated product revenue was calculated at USD 1.50 per m³, while operational costs were divided into base SWRO expenditure (USD 0.80/m³) and incremental brine processing costs (USD 1.00/m³), producing a total operating expenditure (OPEX) of USD 1.80 per m³. The net water cost, defined as the difference between OPEX and revenue credit, was projected at USD 0.30 per m³, demonstrating a significant reduction from the baseline desalination cost and indicating strong economic leverage from resource recovery.

A capital investment of USD 150 million was assumed for the combined desalination and recovery system. Based on the projected revenue-to-cost dynamics, the estimated payback period was calculated at approximately 6.9 years. This duration falls within acceptable thresholds for infrastructure investments in water treatment and extractive industries, highlighting the project's potential financial viability under moderate market and technological assumptions. The values presented in Table 8-2 form the empirical basis for the broader techno-economic analysis discussed below and in the discussion section of this study. They also support strategic recommendations regarding capital

allocation, process design, and policy incentives for integrating mineral recovery into desalination infrastructure.

8.3.2.2 CAPEX Derivation and Breakdown

The reported total CAPEX of USD 150 million was constructed from a baseline SWRO plant investment of USD 100 million for a 100,000 m³ d facility (intake, pretreatment, high-pressure trains, ERDs, post-treatment, civil/MEP) and an incremental USD 50 million for integrated mineral-recovery systems. The latter comprises (i) NaCl crystallization (forced-circulation/MVR crystallizer package, solids handling); (ii) Mg(OH)₂ precipitation (lime handling, reactors, thickeners/filters); (iii) bromine oxidation/stripping and purification train; (iv) membrane concentration and ancillary pretreatment debottlenecking driven by higher brine-side throughputs; and (v) utilities and plant integration (piping, electrical, controls, tie-ins). The allocation used in the model is NaCl crystallization USD 15 M, Mg(OH)₂ precipitation USD 12 M, bromine extraction USD 10 M, membrane concentration and pretreatment USD 8 M, utilities and integration USD 5 M, summing to USD 50 M incremental CAPEX (Figure 8-3). These magnitudes are consistent with factor-based estimates and vendor-class budgetary quotations for ZLD/MVR trains and precipitation lines at the modeled scale; sensitivity to ±25–30% capex variance is analyzed in Sensitivity Analysis.

Baseline SWRO: USD 100 M incremental mineral-recovery CAPEX: USD 50 M decomposed as NaCl crystallization (USD 15 M), Mg(OH)₂ precipitation (USD 12 M), bromine extraction (USD 10 M), membrane concentration and pretreatment (USD 8 M), utilities and integration (USD 5 M). Units: million USD.

The hypothetical plant produces 100,000 m³/day of freshwater at 45% recovery, yielding about 150,000 m³/day of brine (at 70 g/L salinity). Over one year, this amounts to 54.75 million m³ of brine containing approximately 3.8×10^6 tonnes of dissolved salts. If we assume near-complete recovery of all major constituents, the annual quantities of products would be on the order of 2 million tons of NaCl; 170,000 tons of MgO (or equivalent, from magnesium); 50,000 tons of CaCO₃; 40,000 tons of KCl; 10,000 tons of bromine (Br₂); and 300 tons of lithium carbonate (assuming 5 mg/L Li in the brine after concentration steps). These figures are compiled in Figure 8-4 and form the basis for a gross revenue estimate.

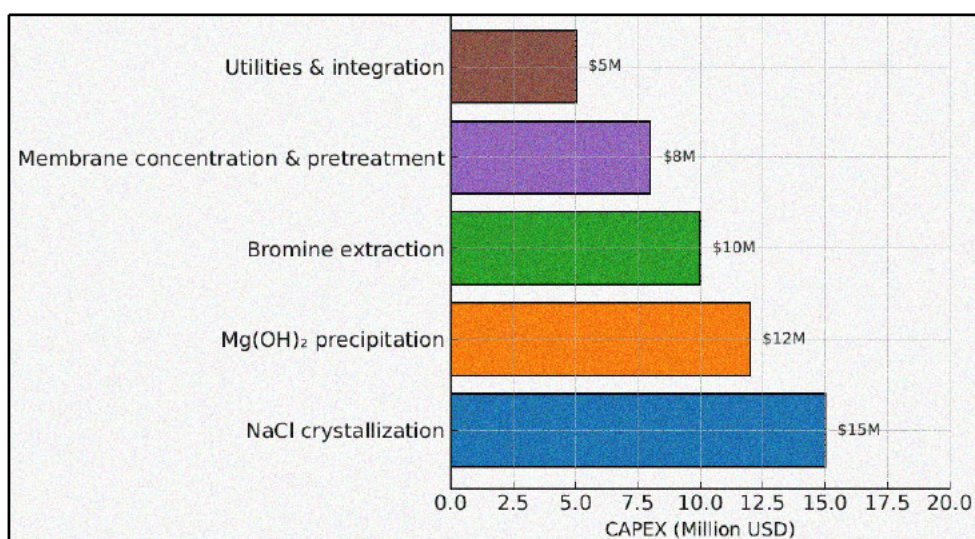


Figure 8-3 CAPEX Breakdown for Integrated SWRO + Mineral Recovery Facility 100,000 m³/d.

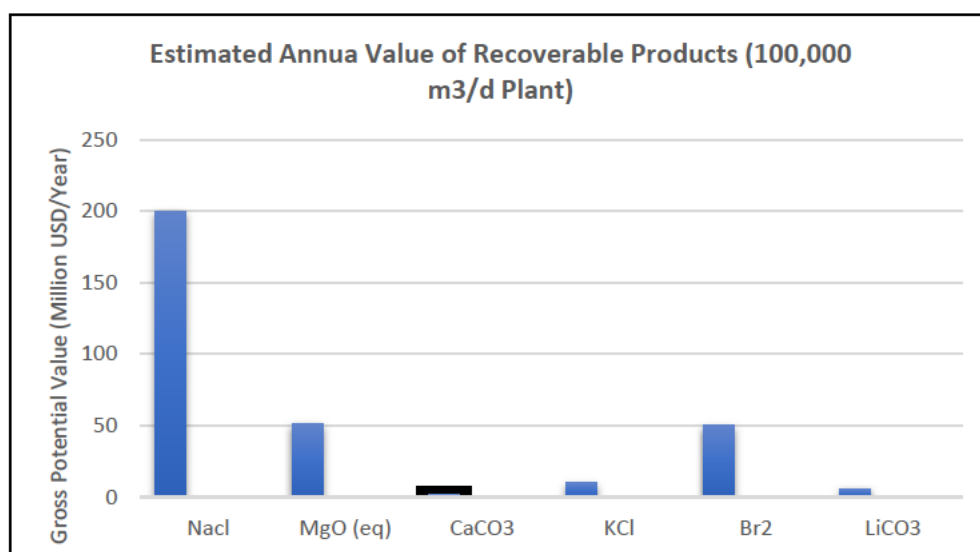


Figure 8-4 Estimated annual gross value of recoverable products from a 100,000 m³/day SWRO brine (150,000 m³/d brine flow).

NaCl (salt) dominates by mass (2 million tons/year), but its low price yields a moderate USD 100–300 million in value. High-value products like bromine contribute significantly despite a much smaller volume [4]. Mg(OH)₂/MgO recovery could add USD 50 million. Lithium is a very high value per ton but extremely low quantity from seawater brine, yielding only a few million USD in this scenario [188].

From Figure 8-4, we see that the total potential gross revenue (summing mid-range price estimates) is approximately USD 200 – 400 million per year for this plant's brine. Sodium chloride, by virtue of sheer mass, could contribute on the order of USD 100–300 million (the wide range reflects bulk salt against refined salt pricing). Bromine, at USD 5000/ton, yields about USD 50 million. Magnesium compounds as high-grade MgO, at USD 300/ton, add USD 50 million. Potassium as KCl fertilizer at USD 250/ton is around USD 10 million. Calcium carbonate, assuming it is sold as low-grade filler at USD 20/ton, is only USD 1–3 million. Lithium, even at a high USD 20,000/ton, contributes USD 6 million due to the tiny amount present [188, 262]. Notably, we excluded boron, rubidium, and strontium from the figure; while they exist in the brine, their total recoverable masses are very small (boron 500–600 tons B_2O_3 /year, strontium 800–900 tons Sr/year, rubidium only 10–15 kg/year in this case). Even though rubidium has an extremely high price per kg (purity Rb salts can exceed USD 25,000/kg in specialty markets) [263], the negligible quantity from seawater means it would only add a few hundred thousand dollars at most. Strontium could be recovered as strontium carbonate used in ceramics and pyrotechnics; at market prices of a few hundred dollars per ton for $SrCO_3$, the 800 tons might yield on the order of USD 0.5–1 million. These “icing on the cake” elements have high unit value but do not drive the overall economics due to limited abundance [264]. The bulk of revenue comes from Na, Mg, Ca, K, Br, in agreement with the findings of del Villar et al. [4] who classified Na, Mg, Ca, B as abundant low-price components and Li, Rb, Sr, Ga as scarce high-price components.

It must be emphasized that the above represents an ideal maximum revenue, assuming 100% recovery and no purity or market constraints. In reality, achieving complete recovery of everything is impractical. Recovery rates might range from 50% to 90% for different elements using current technologies [262]. Also, flooding the market with large quantities of salt could reduce prices. For example, a single 100,000 m^3/d plant producing 2 million tons of salt per year would be a significant new supply (world salt production is on the order of 300 million tons/year, so it's <1% of global output, but regionally it could saturate a market) [265]. The capacity to sell all recovered products is a vital assumption; otherwise, some products would effectively become waste or require disposal if they exceed demand.

8.3.3 Cost–Benefit Outcomes in Base and Variant Scenarios

In the base scenario (100,000 m³/d plant, moderate commodity prices, high recovery efficiency), the annual gross revenue from all products was estimated at about USD 300 million (mid-range) to USD 400+ million (optimistic) [262]. The corresponding annual operating cost for the recovery system is preliminarily estimated in the order of USD 100–USD 180 million. This yields a net annual benefit on the order of USD 120–220 million, which is a substantial secondary income for the desalination plant. In terms of the water production economics, the brine mining turns a baseline water cost of USD 0.80/m³ into a net cost of USD 0.30–0.40/m³ after credits [262]. The cost–benefit ratio (CBR), defined as total product value divided by total added cost, comes out to approximately 1.5 in the base case. del Villar, et al. [188] reported a CBR in the range of 1.5 to nearly 3.0 for Spanish brine scenarios under favorable pricing, which is consistent with our findings. This indicates that, under the right conditions, brine resource recovery can pay for itself and even generate profit. With an assumed brine treatment capacity of 100,000 m³/day and a net benefit of USD 1.20/m³ (revenue–cost differential), the payback period was estimated at approximately 6.9 years.

This approach conceptually transforms the desalination facility from a sole water production unit into an integrated minerals recovery system, wherein revenues from recovered salts and metals substantially offset the operational costs associated with freshwater generation. This transformative finding indicates that, under certain conditions, seawater desalination may transition from a cost-intensive water supply process to a net value-generating operation where the combined economic value of potable water and recovered mineral byproducts exceeds the total operational expenditure. However, this outcome is not universally guaranteed. A sensitivity analysis was conducted to examine the influence of key variables, including market prices for recovered commodities, process recovery efficiencies, energy input costs, and plant capacity. The results of sensitivity scenarios are summarized in Section 8.3.5.

8.3.4 Simulation Parameters

The results presented in Table 8-2 are derived from a hypothetical seawater reverse osmosis (SWRO) facility treating 100,000 m³/day with an integrated system for brine-

derived mineral recovery. All financial values were modeled using a structured framework combining mass balance calculations for individual minerals, market price benchmarks for extracted products, and operational cost estimates based on documented energy and reagent inputs from the literature and commercial practice. The recovery efficiency for each mineral was conservatively set at 50%, representing a realistic performance range for commercial membrane, crystallization, and chemical precipitation [82]. Verification of the model was conducted through internal consistency checks across material and energy balances, as well as cross-comparison with published financial data from reference-scale projects such as the Ras Al Khair plant and the South Korean hybrid brine recovery trials [266, 267]. The underlying simulation parameters for the cost–benefit analysis and economic modeling, including brine composition, energy consumption, reagent use, recovery yields, and market prices, are now summarized in Table 8-3.

Table 8-4 consolidates these parameters, showing the numerical value used in the simulation, the calculation basis or derivation method, and the original reference source. Figure 8-5 shows the recovered quantities (kg/m³) and corresponding revenue (USD/m³) for each mineral. The bar chart (blue) shows the mass recovery potential of each component, while the line graph (red) illustrates the estimated revenue generation per cubic meter of brine treated.

Table 8-3 Simulation Parameters.

S/N	Parameter	Value	Unit/Remarks	References
1	Plant capacity	100,000 m ³ /day	Input design capacity	
2	Brine volume processed	45,000 m ³ /day (assuming 45% recovery in SWRO)	Brine available for mineral recovery	

3	NaCl concentration in brine	30 g/L	For salt recovery (NaCl)	[82]
4	Mg ²⁺ concentration in brine	1.3 g/L	For Mg(OH) ₂ precipitation	[82]
5	Br ⁻ concentration in brine	65 mg/L	For bromine extraction	[82]
6	Average recovery efficiency (all minerals)	50%	Applied uniformly across products	[268]
7	Energy consumption for SWRO only	3.5 kWh/m ³	Desalination energy baseline	[269, 270]
8	Energy for brine processing (added)	2.0 kWh/m ³	Incremental energy for recovery	[269, 270]
9	Reagent use (lime for Mg recovery)	1.4 kg/m ³	Reagent for Mg precipitation	[271]
10	Price of NaCl	USD 60/ton	Market average (bulk, industrial)	[272]

11	Price of MgO	USD 300/ton	Market average (high purity, refractories)	[37]

12	Price of Br ₂	USD 2000/ton	Market average (industrial bromine)	[38]

Table 8-4 Product Prices used in Modeling.

Product	Price (USD/ton)	Grade/Basis	Reference
Sodium Chloride (NaCl)	60	Bulk Industrial	[273]
Magnesium Oxide (MgO)	300	High Purity (Refractories)	[37]
Calcium Carbonate (CaCO ₃)	30	Industrial Grade	[188, 262]
Potassium Chloride (KCl)	400	Fertilizer Grade	[273]
Bromine (Br ₂)	2000	Industrial Grade	[12,37] [256]
Lithium Carbonate (Li ₂ CO ₃)	4500	Battery Grade	[215, 274]

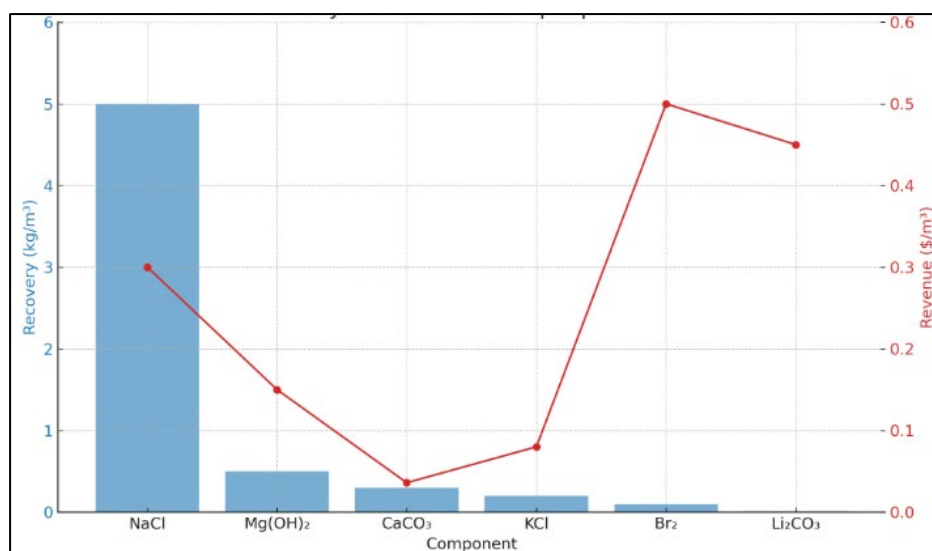


Figure 8-5 Simulated Recovery and Economic Output per m³ of SWRO Brine.

8.3.5 Commodity Price Sensitivity Analysis

Scenarios were tested with lower-bound prices (e.g., lithium USD 10,000/ton, bromine USD 2/kg, salt USD 30/ton, etc.) and upper-bound prices (e.g., lithium USD 40,000/ton, bromine USD 5/kg, salt USD 60/ton). In the low-price scenario, the total revenue per m³ dropped to about USD 0.8, while costs remained USD 1.0 – 1.1, making the operation slightly uneconomic (CBR — 0.8). The net water cost in that case would be around USD 1.0/m³ (essentially no improvement over the base SWRO cost). In the high-price scenario, revenue per m³ rose to USD 2+, and CBR — 2.0, greatly improving profitability. The break-even point appears to be around a revenue of USD 1.0 per m³ for a cost of USD 1.0. If revenues fall below that, the business case fails. Notably, among the products, the ones that influence this most are salt and magnesium because they contribute the largest share of revenue in absolute terms. If, for example, bulk salt prices halved or if it became difficult to sell all the salt, the revenue would drop significantly. Conversely, a rise in bromine or lithium prices has less effect on total revenue because their volumes are smaller, though they can contribute additional upside profit.

Figure 8-6 below shows the outcomes of various sensitivity scenarios in brine recovery economics. It evaluates how changes in key parameters such as product prices, recovery efficiency, and energy costs impact the revenue, operational expenditure (OPEX), and net profit per cubic meter of desalinated water. Each line illustrates a

distinct economic metric across all scenarios, highlighting the potential for profitability under varying market and operational conditions. The equation used in the analysis is shown below:

$$\text{Net Profit } m^3 = \text{Revenue } m^3 - \text{OPEX } m^3 \quad \text{Eq. (8-10)}$$

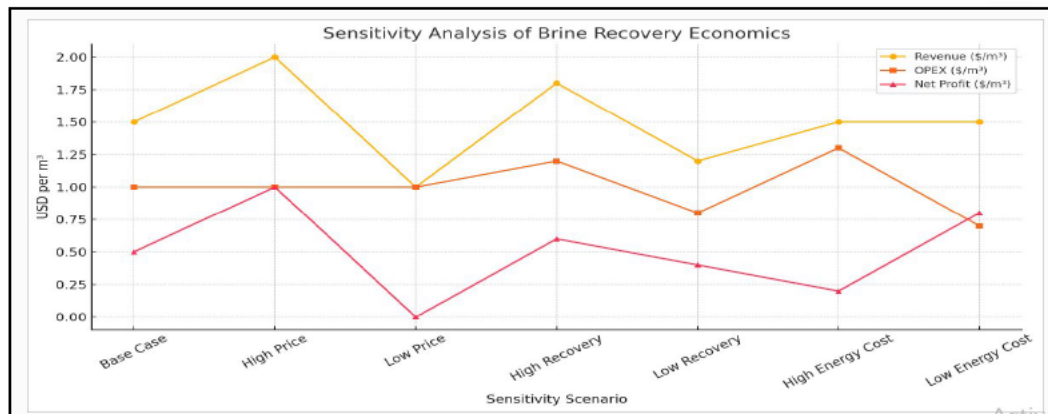


Figure 8-6 Sensitivity Analysis of Brine Recovery Economics.

Sensitivity Scenario Assumptions

- ✓ High Price: Increased revenue due to higher commodity prices
- ✓ Low Price: Reduced revenue from commodity market dips
- ✓ High/Low Recovery: Adjusted revenue due to increased/decreased mineral recovery efficiency
- ✓ High/Low Energy Cost: OPEX adjusted for energy price fluctuations

This analysis highlights the importance of market risk management (discussed further in the Risk section). Long-term offtake agreements or diversification of product portfolio can mitigate the impact of any one commodity price swing.

8.3.6 Recovery Efficiency and Yield

The study investigated the impact of reduced extraction efficiencies on overall system performance by evaluating scenarios in which the recovery processes operate below the baseline assumptions. For example, if only 50% of magnesium is actually recovered due to process losses or purity issues, or if salt recovery is deliberately

limited to avoid flooding the market. Lower recoveries directly reduce product output and sometimes can also reduce costs a bit, e.g., less chemical used. It was confirmed that moderate drops in recovery, e.g., 10–20% lower yields, do not ruin the economics; the CBR might go from 1.5 to 1.3, which is still positive. But if recovery of multiple major components were simultaneously low, the revenue could fall below the cost. A particularly sensitive one is magnesium; if Mg is not recovered at all, not only would its revenue (0.4–0.5 USD/m³) be lost, but the cost to remove it would also be incurred. That scenario was much less favorable, showing maybe only USD 0.8 revenue against USD 0.9 cost, which is essentially break-even. Lithium and other trace elements had almost no impact on the overall economics in our model unless extremely high prices were assumed because their quantities are too low. Previous research efforts have noted that the bulk of the economic potential in seawater brine lies in the abundant elements (Na, Mg, Ca, K, Br). These drive the revenue, whereas rare elements (Li, Rb, etc.) are “icing on the cake” that might add a few percent of extra value at best. This aligns with Sharkh, et al. [203] classification of Na, Mg, Ca as abundant-low-price components and Li, Rb, etc. as scarce-high-price but low-availability components.

8.3.7 Energy Cost Sensitivity

Energy is a major part of OPEX, especially for thermal processes and ED. Scenarios with cheap renewable energy, e.g., USD 0.05 per kWh effective, were considered against high energy cost renewable energy, e.g., USD 0.20 per kWh or using expensive fuel. With cheap energy, the brine processing cost can be kept low, enhancing profitability. With expensive energy, the cost per m³ can increase by USD 0.5 or more, quickly eroding margins. For example, if energy cost doubled in our base case, the OPEX would rise from USD 1.0 to around USD 1.3 per m³, pushing the net benefit down to maybe USD 0.2 per m³. If energy were essentially free (renewables fully powering the system), the OPEX could drop to USD 0.6–USD 0.7, and the net benefit would jump. This indicates that energy integration (use of waste heat, renewable power purchase agreements, etc.) is an important factor in making brine mining economically and environmentally sustainable. Gadalla, et al. [275] demonstrated a concept where a renewable-powered ZLD system achieved zero liquid discharge with minimal net energy cost; such approaches could significantly boost CBA results for brine recovery by removing fuel expenses from the equation.

8.3.8 Scale Effects

The size of the plant and system has a strong influence. Many costs, especially CAPEX per unit throughput, improve with scale due to economies of scale. A very large plant can spread fixed costs (engineering, overhead, certain equipment) over a larger volume. We compared our 100,000 m³/d case to a smaller 10,000 m³/d plant case (a plant one-tenth the size). In the smaller case, the CAPEX per m³ was much higher, and OPEX per m³ was also higher because operating staff, maintenance, etc., do not scale down fully linearly. As a result, a small plant might have added costs of USD 2–3 per m³ for brine mining, which, given a similar revenue of maybe USD 1–1.5, results in a net negative outcome. Indeed, the simulation suggests that below a threshold scale (perhaps on the order of 50,000 m³/d of water production, depending on the process configuration), it is difficult to economically justify the full multi-product recovery approach. This is consistent with real-world observations that large integrated solutions (like those considered in the Middle East mega-plants) have better chances of viability than retrofitting very small desalination plants. Certain targeted recovered minerals, such as magnesium or salt recovery, could still make an impact at a smaller scale if the process is simple enough. Scale-up also positively affects the ability to market products. A large, consistent output can secure big buyers and more favorable contracts. For example, producing 1000 tons of salt a day can attract industrial buyers directly, whereas 100 tons a day might only sell to local markets at lower margins.

8.3.9 Cost Comparison: Brine Recovery Against Conventional Mining

A core question is whether extracting a given mineral from SWRO brine is more cost-effective than the traditional route (mining or chemical production from conventional/terrestrial sources). We assess this for each major component:

8.3.9.1 Sodium Chloride (Salt)

Conventional production is typically through mining rock salt deposits or solar evaporation of seawater in large ponds. These methods are extremely low-cost, on the order of USD 10–30/ton production cost in regions with cheap labor and land, because they harness natural evaporation [203]. Recovering NaCl from RO brine can be achieved by thermal crystallizers or evaporative ponds. If waste heat or abundant land

(for ponds) is available at the desalination site, the cost can be quite low. For example, using existing waste heat from a power plant to evaporate brine could produce salt at competitive costs. Some Middle East SWRO facilities are exploring solar ponds for brine, effectively producing salt as a byproduct. On the other hand, using mechanical evaporators or crystallizers requires significant energy (>60 kWh per m^3 of water evaporated, depending on technology) [262], which could translate to $>\text{USD } 10$ of energy cost per ton of salt if electricity is $\text{USD } 0.05/\text{kWh}$. Given that bulk salt sells for $\text{USD } 30\text{--}60/\text{ton}$, the profit margin is slim unless energy is very cheap or subsidized. Therefore, salt recovery from brine is economically feasible mainly when low-cost evaporation can be achieved (through sun or waste heat) or when the alternative is paying for brine disposal (offsetting disposal cost). A special case is producing high-purity salt for industrial use (e.g., chlor-alkali feedstock); such salt can fetch $\text{USD } 100\text{--}150/\text{ton}$, improving profitability [137, 262, 276]. Regions that currently import salt such as some island nations or land-scarce countries, could benefit by producing it locally from brine.

8.3.9.2 Magnesium (Mg compounds or metal)

Terrestrial sources include mined magnesite (MgCO_3) or brucite and extraction from natural brines (e.g., the Dead Sea or certain lake brines), which contain high Mg. Producing magnesium metal is energy-intensive (typically through electrolysis of MgCl_2 molten salt, consuming $35\text{--}40$ MWh/ton) and is only performed economically where electricity is cheap. However, producing magnesium hydroxide ($\text{Mg}(\text{OH})_2$) from seawater is a relatively established process. Historically, the Dow process added calcined dolomite ($\text{CaO}\cdot\text{MgO}$) to seawater to precipitate $\text{Mg}(\text{OH})_2$, which was then calcined to MgO or converted to magnesium metal. The cost of magnesium hydroxide from seawater depends on lime or dolime cost and filtration, but it can be competitive for making products like magnesium oxide. High-purity MgO used in refractories or as an additive can sell for a few hundred USD/ton , making this an attractive target. Our analysis indicates that Mg in brine (2.5 g/L) yields 2.5 kg Mg per m^3 , which could be 4.1 kg $\text{Mg}(\text{OH})_2$ (if fully recovered). At 50% recovery and $\text{USD } 300/\text{ton}$ MgO , that's $\text{USD } 0.62$ of value per m^3 . The processing cost involves lime addition (1.4 kg lime per m^3 brine) and handling of solids; lime costs maybe $\text{USD } 0.1\text{--}0.2$ per m^3 , plus some energy for pumping/mixing [204, 262, 277]. Overall, magnesium recovery as $\text{Mg}(\text{OH})_2$ appears favorable, especially since it also aids subsequent processes by removing an

alkaline earth that would otherwise interfere with salt crystallization or scaling. Compared to mining, which requires blasting, calcining ore, etc., the brine route could have lower unit energy. Indeed, regions lacking magnesite deposits (e.g., many coastal countries) see brine-derived Mg as a strategic opportunity. The EU lists magnesium as a critical raw material, and brine recovery could reduce import dependence [261, 278].

8.3.9.3 Calcium (CaCO_3 and CaSO_4)

Calcium is abundant in limestone and gypsum deposits globally, which are very cheap to extract (cement-grade limestone can be <USD 10/ton). From brine, Ca^{2+} can be precipitated by adding carbonate (forming CaCO_3) or sulfate (forming CaSO_4 if sulfate is in excess). One intriguing synergy is using brine to capture CO_2 . Adding sodium carbonate (soda ash) to brine will precipitate CaCO_3 (solid) and release Na^+ and HCO_3^- ; if the soda ash is produced through a CO_2 absorption process, this can lock carbon into solid form while yielding CaCO_3 [218]. The produced CaCO_3 could potentially be used in the remineralization of desalinated water (post-treatment) or as a filler material. However, selling CaCO_3 or gypsum from brine is challenging because of the low market value and competition from mined sources. The benefit of recovering calcium is more to reduce scaling in downstream equipment and recover alkalinity than to generate profit. We found that even at 100% recovery (0.8 g/L Ca yields 0.8 kg/m³, or 50,000 tons/year as CaCO_3 in the case study), the revenue is only a couple of million USD. Thus, calcium recovery can be justified as part of process optimization and perhaps for internal reuse, but not as a major revenue contributor [188, 204, 218].

8.3.9.4 Potassium (Potash salts)

Potassium chloride (KCl) and potassium sulfate (K_2SO_4) are important fertilizers known as potash. Conventional production comes from mining evaporite deposits (e.g., in Canada, Russia, Belarus) or brine (the Dead Sea is a significant source of potash through solar ponds). Market prices for potash have fluctuated; they were around USD 250–300/ton in the late 2010s, spiked to over USD 800/ton in 2022 due to geopolitical supply issues, and are around USD 400–500/ton in 2024 [279]. Seawater brine has only 1 g/L K^+ , so even complete recovery yields 1 kg per m³. Our scenario of 40,000 tons KCl/year from the plant would be worth USD 10–20 million. The extraction of K from seawater brine typically happens after NaCl removal, in the concentrated bittern. Traditional saltworks often get a bittern rich in Mg and K; one method is to use fractional

crystallization ($\text{K}_2\text{SO}_4 \cdot \text{MgSO}_4 \cdot 6\text{H}_2\text{O}$ can crystallize, or sylvite KCl can precipitate if managed well). Another approach is selective ion exchange or nanofiltration to separate monovalent ions. Research has shown that NF can preferentially pass Na^+ and K^+ while rejecting divalents, thus one could generate a K-rich stream [198, 256]. The cost of recovering potash from seawater is generally higher than from mining, except in places where conventional potash is not accessible. If a brine mining facility is integrated with fertilizer production or local agriculture, it could find a niche for instance, island nations paying high import costs for fertilizer might benefit [279].

8.3.9.5 Bromine

Bromine is a high-value element traditionally extracted from brines. The US and Israel/Jordan have dominated bromine production, sourcing from underground brines and the Dead Sea, respectively [257]. Seawater has 65 ppm bromide, and SWRO brine has 120–130 ppm. Industrial bromine extraction involves oxidizing bromide to bromine (using chlorine or electrolysis) and then stripping it out with air or steam. The bromine is condensed and purified. The estimated energy requirement for bromine extraction is modest (mainly for blowing air and some heating), and reagent cost is mainly chlorine, which could be generated on-site through a chlor-alkali process that in turn uses the NaCl . Bromine prices average around USD 3–4 per kg in recent years [257], which is very high compared to typical salt prices, making bromine a lucrative target. Our case study's 10,000 tons Br_2 /year is significant. It represents about 2–3% of world bromine output (global bromine production is 400,000 t/year) [257]. That amount of bromine would be valued around USD 30–50 million. If multiple desalination plants implemented bromine recovery, they could collectively become a major source. Importantly, bromine from brine is directly competitive with bromine from subterranean brines, since the processes are similar. The Middle East desalination hub is actually geographically near the main bromine-producing region (Dead Sea). One consideration is market saturation, bromine demand is growing slowly for flame retardants, drilling fluids, etc., so new supply must displace existing producers. Technologically, integrating bromine recovery into SWRO could be straightforward if chlorine is already being produced for disinfection, and that chlorine can double-duty to liberate bromine [188, 206]. In summary, bromine is one of the most promising elements to recover, with relatively low incremental cost and high price.

8.3.9.6 Boron

Boron in desalination is usually seen as a contaminant to remove because drinking water guidelines require less than 1 mg/L boron. SWRO permeate often needs a secondary pass or specific adsorbents to reduce the boron. Thus, boron removal technology is present, but the concentration in brine (5–10 mg/L B) is very low to make a pure product. Boron could be concentrated by evaporation i.e., boron remains in the mother liquor as other salts crystallize) and then use ion exchange resin tailored for boron e.g., N-methylglucamine resin [219]. The recovered boron could be in the form of boric acid. However, the global market for borates is well-supplied by large mines in Turkey and California, and the price of boric acid (USD 700/ton) is not high enough to justify an elaborate extraction from such dilute streams in most cases. Unless boron regulations force removal, capturing it and selling as a byproduct (even at loss) could offset waste handling. In our evaluation, boron recovery is likely not economically driven. It would be performed only as part of meeting discharge/spec requirements, with any sales being a minor bonus [203, 219].

8.3.9.7 Lithium

Lithium has gained enormous attention due to battery demand. Standard sources are continental brines, e.g., in Chile's Atacama, 1000 ppm Li, where solar evaporation yields lithium chloride which is processed to carbonate, and hard rock mines (spodumene in Australia). Seawater Li (0.17 ppm in seawater, 0.3–0.5 ppm in SWRO brine) is four orders of magnitude lower concentration than Chilean salars. This huge gap makes direct economic recovery extremely challenging. Many research efforts like adsorbents such as manganese oxide ion-sieves [198, 203, 209], electrochemical intercalation, solvent extraction, etc., have been explored to pull lithium from seawater, but none are yet cost-competitive at scale [203]. The S.A [206] pilot reported over 90% lithium recovery in tests, but did not disclose cost. A rough analysis: if our plant has 0.3 ppm Li and we could concentrate it tenfold, e.g., using selective NF to strip out other ions, we get 3 ppm; still, processing 50 million m³/year to collect a few hundred tons of Li₂CO₃ is a massive effort. The case study indicated 300 tons Li₂CO₃/year might be achievable, which is trivial compared to world demand (720,000 tons LCE in 2024) [258]. The cost per kg of lithium from seawater likely exceeds USD 1000, far above current prices, which after a spike are back to USD 14–20/kg range) [258]. Thus, lithium

from seawater brine is not currently viable economically. It could become viable if lithium prices skyrocket again or if coupled with a policy need. For example, a country with large desalination capacity but no local lithium sources might subsidize development for supply security. For the foreseeable future, lithium extraction efforts will likely focus on higher-concentration sources such as geothermal brines, produced water from oilfields, etc., rather than normal SWRO brine.

8.3.9.8 Rubidium and Cesium

These alkali metals are present in trace amounts in seawater. Rubidium is 0.2 ppb, cesium even less. They are expensive (Rb_2CO_3 can cost USD 1000+ per kg) because they are rare, typically obtained as byproducts of lithium or potash mining. Some researchers like Xing, et al. [280] and Huang, et al. [227], have looked at extracting rubidium from RO brine using ion exchange and solvent extraction. The science is intriguing, but the scale is so small (as noted, a large plant might yield only 10 kg Rb per year) that it is not a practical revenue stream. We mention them mainly for completeness: if extraction systems are extremely selective and already in place for Li or K, perhaps Rb could be incidentally captured. However, Rb/Cs recovery would be performed only if future technologies make it essentially cost-free to perform as part of another process [226, 227].

8.3.9.9 Strontium

Strontium (Sr^{2+} 8 mg/L in seawater) could be recovered from brine along with calcium. One possible route is during the carbonate precipitation step. The Sr will co-precipitate with CaCO_3 to some extent, or one could add a sulfate source to precipitate SrSO_4 (celestite). Strontium's main use historically was in CRT glass, which has collapsed; current uses are ceramics, fireworks (red colorant as Sr nitrate), and some medical imaging chemicals. World production of strontium as celestite is modest at 300k t/year of celestite ore [264]. If our plant recovered 800 tons SrCO_3 , which is roughly the annual Sr content, that might be valued around USD 0.8–1.0 million. The cost to separate Sr from Ca might not be justified just for that revenue. However, if zero-liquid-discharge is pursued, one might deliberately precipitate all alkaline earths (Ca, Sr, Ba) together. In doing so, strontium could be isolated from the mixed solids by leaching or other chemical means. This is likely a focus as strontium from seawater brine is technically

feasible but economically minor. It might find use locally, e.g., providing Sr for a nearby ceramics industry, but is not a primary driver. Figures 8-7 and 8-8 present a comparative analysis of minerals recovered from SWRO brine and those obtained through conventional mining methods.

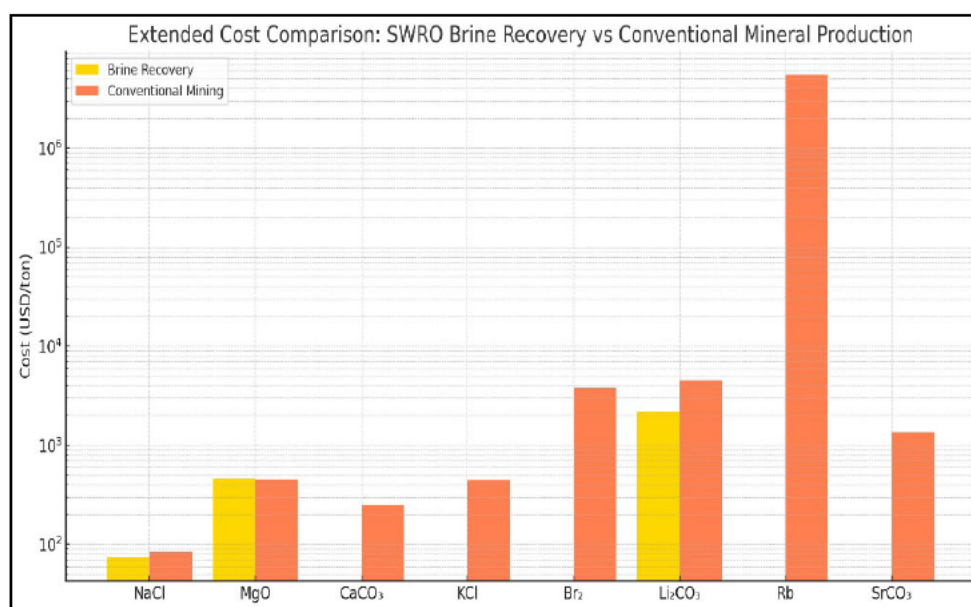


Figure 8-7 Cost Comparison: SWRO Brine Recovery Vs Conventional Mineral Production

Figures 8-7 and 8-8 present a clear comparison between seawater reverse osmosis (SWRO) brine recovery and conventional mining or chemical production in terms of both cost and energy demand across several key minerals and salts. For the cost comparison, sodium chloride (NaCl) and magnesium oxide (MgO) are obviously the two most viable minerals for recovery from SWRO brine. For NaCl, the cost of recovery from brine is estimated at USD 75 per ton, which is slightly lower than the USD 84.5 per ton associated with conventional mining. This cost advantage, although modest, can become significant at scale. For MgO, the brine recovery cost stands at USD 793 per ton, which is higher than the USD 455 per ton from conventional sources. Despite the higher cost, brine-based recovery may offer environmental advantages that justify the premium, particularly in locations where sustainability is a strategic priority.

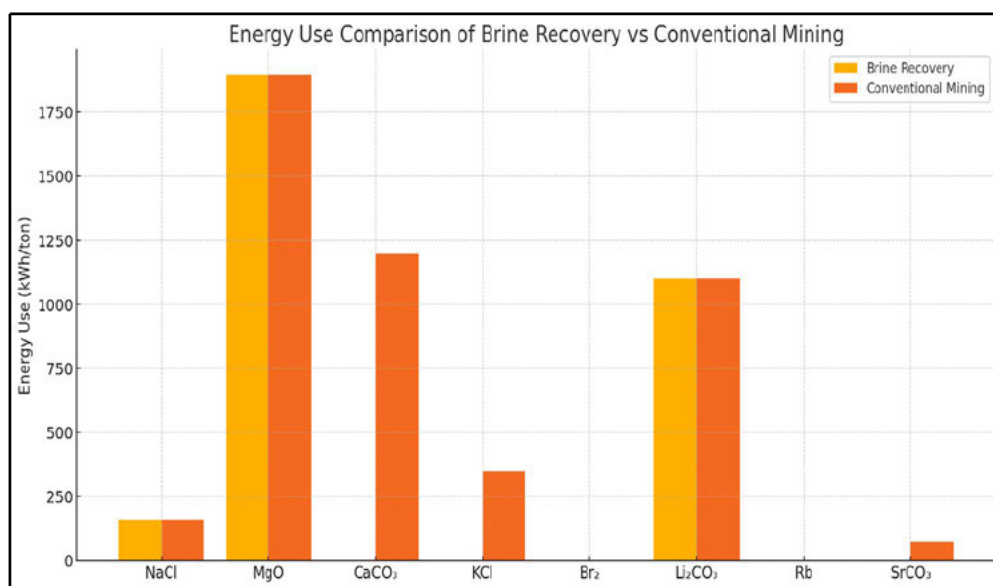


Figure 8-8 Energy Use Comparison of Brine Recovery Vs Conventional Mining

In the case of lithium carbonate (Li_2CO_3) and rubidium (Rb), the conventional production costs are extremely high, around USD 4500 per ton and USD 5.5 million per ton, respectively, due to the complex and resource-intensive extraction processes involved. While detailed cost figures for brine-based recovery of these elements are limited, emerging research suggests that selective recovery from brine could become economically favorable, especially if integrated with desalination infrastructure.

The energy comparison further reinforces the viability of brine recovery for certain minerals. Both brine recovery and conventional production of NaCl require roughly 160 kWh per ton, showing no significant energy compromise. For MgO, energy demands are again equal at about 1900 kWh per ton. This consistency suggests that the brine pathway can match conventional efficiency while reducing environmental impacts associated with mining and calcination. For other compounds like calcium carbonate (CaCO_3), brine-based precipitation techniques avoid the carbon-intensive processes typically required in lime production, leading to a more energy-efficient profile.

Environmental considerations also shape the narrative. The extraction of minerals from brine generally results in fewer emissions, lower land disturbance, and reduced waste

generation compared to traditional mining. For instance, in the case of boron and magnesium, the brine pathway avoids the use of open-pit mines and tailing ponds, which are common in conventional methods. Additionally, the use of industrial waste heat or solar evaporation in brine processing can significantly reduce the carbon footprint.

Overall, the figures suggest that while not all minerals are currently economically competitive to recover from brine, several, particularly NaCl and Mg-based compounds, already show cost and energy advantages or parity. Coupled with environmental benefits, brine recovery holds strong potential, especially in desalination-intensive regions or where resource imports are costly. Further technological development and market stability could expand this feasibility to high-value but low-abundance elements such as lithium and rubidium. In summary, the cost comparison reveals a spectrum of viability. Sodium, magnesium, potassium, and bromine recovery from brine can often be competitive with traditional production, especially when factoring in that brine recovery has some sunk costs already covered by the desalination process, like feed intake and initial concentration. Lithium, rubidium, and cesium are currently not competitive due to extremely low concentrations, although their high prices keep interest alive in advanced extraction research. Calcium and strontium fall in between, as they are easy to recover but have low value, their recovery may be justified for process reasons rather than profit.

8.3.10 Regional Economics

Regional economics must also be considered. In regions where mining those minerals is difficult or where all materials are imported, brine recovery's comparative advantage increases. For example, island states with no mining industry might find brine to be their local "ore body" for salt and minerals, whereas a country with large mineral deposits might find it uneconomical to invest in brine extraction. Additionally, if brine disposal is heavily regulated or costly, then the "avoidance" of disposal can be counted as a benefit offsetting recovery costs.

8.3.11 Energy Use and Environmental Aspects

The energy consumption of brine recovery processes is a critical factor in cost. A fully integrated brine mining flowsheet could include energy-intensive steps such as evaporation (thermal or mechanical) and electrochemical separations. The specific energy (kWh per m³ brine) will vary depending on how far one pushes towards ZLD. Studies have shown that going to zero liquid discharge (all water evaporated, all salts solidified) is very energy-heavy, on the order of 20–60 kWh/m³ for thermal crystallization beyond what RO can achieve [274]. However, our scenario does not require evaporating all water; we only evaporate enough to crystallize NaCl and maybe concentrate bittern to a manageable volume. By using waste heat or solar energy, the effective energy cost can be reduced. In contrast, conventional or terrestrial mining energy costs are associated with digging, grinding, chemical processing and sometimes thermal refining. For example, mining and processing a ton of potash or salt might use a few tens of kWh (mostly diesel and electricity), whereas obtaining that ton from seawater brine might use a similar order if performed efficiently (e.g., using free solar evaporation). Each element's comparison is unique; magnesium metal production is energy-intense whether from brine or ore, bromine production from brine is actually less energy than mining bromine since bromine is not found as a solid ore, you always need to extract from brine or bittern.

An important observation is that integrating brine recovery with the desalination plant opens opportunities for energy synergy. For instance, the desalination plant's output includes high-pressure brine, which can be used in energy recovery devices, and sometimes available heat (if an RO plant is co-located with power plants or uses warm intake water). Some innovative proposals include using renewable energy specifically for driving crystallizers during peak solar hours or coupling a thermal brine concentrator with a solar pond. The use of renewable energy can reduce OPEX and enhance the sustainability profile of the operation [104, 275, 281].

From an environmental life-cycle perspective, recovering minerals from brine can displace equivalent production from mines, thus avoiding the environmental impacts of mining such as habitat disruption, solid waste, groundwater pollution, etc. [188, 203]. On the other hand, the brine processing facility itself is like a chemical plant, which has

its own environmental considerations such as chemical handling, potential emissions like chlorine gas, etc. One must ensure that any chemicals used, e.g., lime, soda ash, acids, are managed so that the net environmental outcome is positive. If powered by renewables, brine mining could be very “green” in displacing mined materials; if powered by fossil fuels, the carbon footprint of the recovered products should be weighed against the footprint of traditional production. It is likely that for many salts, the carbon footprint per ton will be comparable or lower for brine-sourced production, because the raw material is already in solution (no blasting or high-temperature ore processing needed). A full life-cycle assessment (LCA) has been carried out previously, which aligns with the literature calling for brine concentrate as a potentially more sustainable source for certain minerals.

8.3.12 Lifecycle Cost Analysis and Total Water Cost Impact

Integrating mineral recovery into a desalination plant alters both the capital and operating cost profile. We present a simplified economic comparison in Table 8-5, contrasting a baseline SWRO plant against one with added brine recovery, based on the case study data and literature assumptions.

Table 8-5 Estimated cost impact of brine minerals recovery on a 100,000 m³/d SWRO plant's economics.

Cost Metric	SWRO Plant (No Recovery)	SWRO + Mineral Recovery
Capital Expenditure (CAPEX)	USD 100 million (desalination plant)	USD 150 million (desal + recovery systems)
Operating Cost (OPEX)	USD 0.80 per m ³ of water (energy, RO maintenance, etc.)	USD 1.80 per m ³ of water (including ~USD 1.0 for brine processing)
Product Revenue Credit	USD 0 per m ³ (no byproducts)	USD 1.50 per m ³ (from sale of salts/metals)

Net Water Cost (per m ³)	USD 0.80 per m ³	USD 0.30 per m ³ (net)
Total Water Cost (TWC)	USD 0.8/m ³ , which is within typical range USD 0.5–1.2	Net USD 0.3/m ³ (50–60% lower due to credits)

The additional USD 50 million CAPEX for recovery in this hypothetical includes crystallizers, reaction tanks, extra pumps, filters, and integration. Actual CAPEX can vary widely with design, e.g., using existing infrastructure vs. new construction. In Figure 8-9, the “SWRO + Mineral Recovery” scenario shows a striking reduction in net water cost to USD 0.30/m³ from a base of USD 0.80/m³. This aligns with the notion that revenue from extracted minerals can not only pay for the recovery process but even subsidize the water production system [188, 203]. The assumptions behind these numbers are optimistic, with high recovery rates, products sold at good prices, and efficient processes. If more conservative assumptions are used, e.g., USD 0.8/m³ of product revenue and USD 1.0/m³ added cost, then the net water cost would be around USD 1.0/m³, which is basically unchanged from the baseline. Thus, the outcome can range from significant economic benefit to roughly break-even, depending on conditions.

It is important for decision-makers to perform a detailed cash-flow analysis for any proposed brine recovery project. Factors like the project lifetime, interest rates, and depreciation of equipment will affect feasibility. For example, brine recovery equipment might have a shorter life or higher maintenance cost than the RO membranes, which should be accounted for. Our life cycle perspective suggests that when mineral revenue is strong, it can contribute a meaningful portion of the desalination plant’s income, potentially improving the Internal Rate of Return (IRR) of the overall project. Conversely, if the market for recovered products is uncertain, the project could suffer financially. The risk management strategies for this are discussed in the next section.

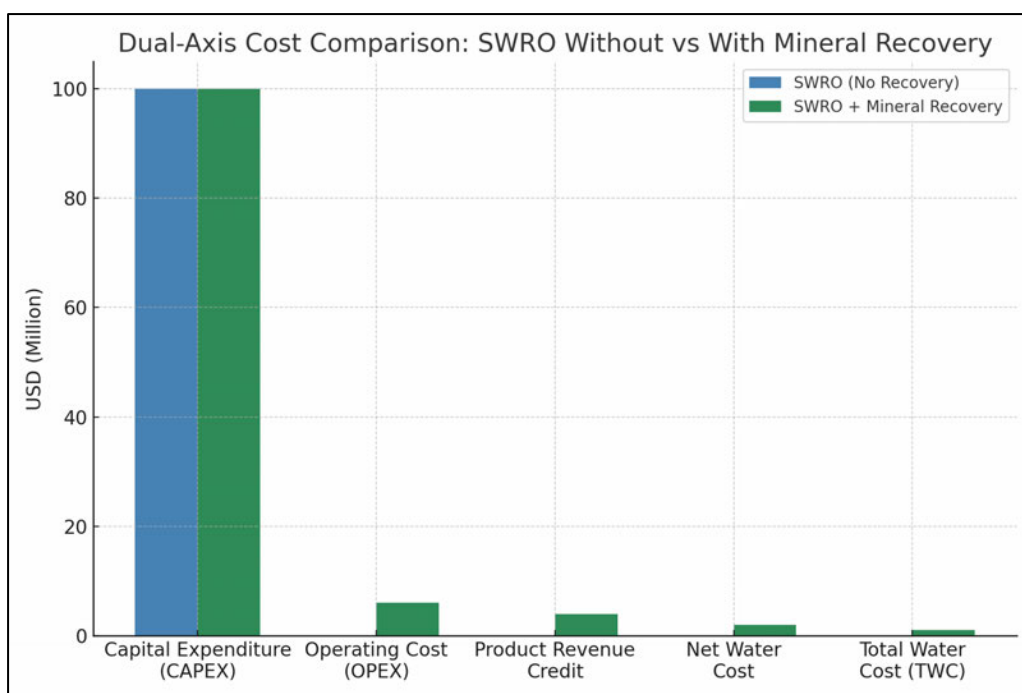


Figure 8-9 Cost Comparison Between SWRO with NO Recovery Plant and SWRO with Recovery Plant

8.4 Discussion

8.4.1 Economic Viability and Market Considerations

The results above indicate that recovering salts and metals from SWRO brine can be economically viable under favorable conditions. The results suggest a ladder of viability, i.e., recovering NaCl, Mg (OH)₂ (or MgO), and Br₂ are the most promising as they can often be achieved at cost parity or better compared to traditional production. K salts and boron are intermediate, potentially viable if conditions align, but not major contributors. Li and other traces are currently not viable economically, though they could be pursued for strategic reasons or future upside. This matches the findings of recent critical reviews, which emphasize focusing on multi-mineral recovery of the main constituents first [251, 260] for economic reasons and to substantially reduce the brine's volume and environmental impact. A key finding is the concept of “no-regret” products against speculative products. A practical strategy, as also suggested by del Villar, et al. [188] and others, is to focus first on the bulk products that have stable demand, such as sodium chloride and perhaps one major chemical like magnesium hydroxide. These are low-value but high-volume, providing a steady revenue base. For instance, NaCl will always have large markets (food, deicing, industrial) although at low prices [203]. Magnesium hydroxide or oxide has widespread uses for water treatment,

agriculture, refractories and moderate price. By ensuring the recovery operation at least breaks even on these main products, the venture is secured. Then, extraction of rarer elements like lithium, rubidium, or strontium becomes the “icing on the cake” if successful, they yield high profit margins, but if not, the project still stands on the main products [188]. This approach hedges against volatility, for example, lithium prices crashed by 66% from 2023 to 2024 [258]. A project relying solely on lithium would be in trouble, whereas one focused on salt and bromine would be fine.

Market demand and saturation must be carefully evaluated. A single large desalination plant’s output for some minerals like salt might overwhelm local demand. It was noted that producing too much of a commodity in a region can reduce prices [188]. Companies venturing into brine mining should conduct market studies for their specific location: who will buy the salt? Is there a nearby chemical industry that needs brine or chlorine? Can the recovered CaCO_3 be used in local construction or cement? If a region already has a surplus of a mineral, perhaps target a different one that is imported or scarce. The concept of localized resource loops is appealing: for example, an R&D [251] pilot that generates CaO from brine was intended to supply the desalination plant’s pretreatment needs. Similarly, a plant might use its own NaOH from a brine electrolysis unit for post-treatment pH adjustment, thus reducing chemical purchase costs. Partnering with other industries can secure offtake agreements, e.g., a chlor-alkali manufacturer could take all the NaCl brine output to produce chlorine and caustic soda. These symbiotic relationships can stabilize income (long-term contracts) and reduce the risk of not being able to sell the products.

Economies of scale play a crucial role in viability. The large plant scenario demonstrates far better economics than a small plant would. Many cost components such as labor, monitoring, and overhead do not scale linearly with throughput. If brine could be processed from multiple plants centrally, it could achieve critical mass. For example, a “brine processing hub” that takes in concentrate via pipeline from several desalination plants in proximity could run a profitable chemical recovery operation that each plant alone could not [188]. Spain’s CORDIS [209] project hinted at this model and indeed noted that large seawater plants had much higher potential revenues than small brackish plants. Therefore, initial commercial implementations of brine mining will

likely be at mega-scale facilities with hundreds of thousands of cubic meters per day or as aggregated facilities.

Capital investment and financing is a significant barrier for brine mining. Desalination plants are usually financed by water utilities or government-backed entities focusing on water supply. Adding a minerals recovery unit blurs the line between a utility and a chemical/mining operation. One suggestion is to treat the brine unit as a separate investment, possibly attracting different investors, e.g., mining companies, venture capital interested in battery materials [206]. Government support might be justified in cases where critical minerals like lithium and magnesium are produced, improving resource security. For instance, a country could offer subsidies or tax breaks for producing magnesium locally from brine instead of importing it. Environmental incentives could also apply if brine mining helps achieve ZLD and eliminate marine pollution; regulators might allow cost recovery through water tariffs or provide grants.

8.4.2 Sensitivity and Uncertainty

The scenario-based sensitivity analysis identified critical variables influencing the economic viability of SWRO brine recovery systems: notably, commodity prices, particularly for sodium chloride and magnesium compounds; energy input costs; and the operational scale of the facility. A major source of uncertainty pertains to the long-term stability of recovery efficiencies. For example, operational degradation over time due to membrane fouling, variability in brine composition, or reductions in precipitation yield may lower actual recovery performance relative to design expectations. To account for these uncertainties, the model incorporated conservative recovery assumptions, typically ranging between 70% and 90%, rather than idealized 100% efficiency. In addition, regulatory dynamics present an external variable with potential economic implications. Should environmental policies increasingly mandate zero liquid discharge (ZLD) or impose stricter controls on brine discharge, the cost burden associated with disposal would rise.

In such scenarios, the brine recovery system would not only generate direct product revenue but also confer indirect economic benefits by avoiding regulatory penalties or compliance costs. Although the present analysis does not quantify the monetary value

of avoided brine discharge, it acknowledges that evolving regulations could shift the cost–benefit balance further in favor of recovery-based systems. A sensitivity analysis was performed to evaluate the implications of adopting environmental externalities associated with brine disposal. By hypothetically assigning a disposal cost of USD 0.10–0.20 per cubic meter, analogous to a carbon tax or environmental mitigation fee in ecologically sensitive regions, the analysis demonstrated that such a cost, when avoided through mineral recovery, translates into an effective economic credit. Although the absolute magnitude of this savings is modest, it was sufficient to improve financial performance in marginal scenarios, thereby enhancing overall project viability. This finding highlights the potential role of policy instruments in promoting brine recovery by formally recognizing its environmental benefits.

In contrast, sensitivity testing on capital expenditure (CAPEX) indicated that significant cost overruns can adversely affect economic feasibility. A 50% increase in CAPEX, for instance, may extend the payback period beyond 15 years, surpassing the threshold commonly deemed acceptable for infrastructure investments. Such outcomes highlight the critical importance of rigorous cost control during project planning and implementation. Strategies to mitigate CAPEX inflation include the integration of mineral recovery systems into existing desalination infrastructure and the adoption of a phased or modular deployment approach to minimize initial capital exposure.

8.4.3 Risk management

As with any new venture, there are market, technical, and regulatory risks. The market risk, which is price fluctuations, can be mitigated by the advancement of offtake agreements. A desalination operator might secure a fixed-price contract for salt supply to an industrial user, ensuring a stable revenue regardless of spot price changes. Technical risk is mitigated by phased implementation, which starts with proven technologies to recover the easy minerals like salt, maybe a bit of gypsum, and then gradually introduces advanced processes for the more complex extractions. This way, if a new technique underperforms, it does not jeopardize the whole operation. The mention of using existing evaporators or known ZLD equipment first, then bolting on selective membrane systems, is an example of de-risking the process. Regulatory risk involves navigating permits and safety regulations, since producing chemicals like

chlorine on-site can trigger additional oversight. Early engagement with regulators is advised to frame the project positively in reducing waste, and not just building a chemical plant.

8.4.4 Case Studies and Real-World Progress

It is encouraging that several pilot projects around the world have demonstrated brine recovery on a pilot scale. The SEA4VALUE CORDIS [209] project (EU-funded) has tested brine from various desalination sites and reportedly achieved around 90% recovery of target minerals like Mg, B, Li at 90% purity in lab experiments. They developed a mobile pilot plant to adapt to different brine compositions, which underscores that a one-size-fits-all solution may not exist, and that site-specific tailoring is needed. In the Middle East, the Saline Water Conversion Corporation (SWCC) Saudi pilot combined NF and RO to concentrate brine to 250 g/L (25% salt) efficiently. The brine is essentially ready for salt crystallization, meaning they achieved a key step of separating out most water with membranes, a potentially low-energy approach compared to evaporators. IDE Technologies (Israel) [251] with their “Durable Brine Mining” is a notable case. By precipitating CaCO_3 from brine and calcining it, they create CaO (lime) and CO_2 , which can be fed back to the pretreatment process for CO_2 dosing. This clever integration uses the brine to generate chemicals that the plant normally would have to buy. It also implies a reduction in total waste. The Acciona MINERALS S.A [206] project in Spain aimed very high and achieved near complete extraction of monovalent ions (Li, Rb, B >90%) and major divalents (Mg, Ca, K 65–80%) for a hypothetical 200,000 m³/d facility. While it remains to be seen if those figures hold at full scale, the existence of such projects suggests a strong momentum towards commercialization in the next few years.

A few full-scale examples are emerging. In Chile, a coastal desalination plant was reported by del Villar, et al. [188] to be considering lithium recovery given the lithium market interest. In China, some desalination plants reportedly recover bromine and magnesium as side businesses (China has state programs on extracting resources from seawater). The Arabian Gulf countries, which produce the majority of brine, are actively researching brine utilization as part of their national sustainability agendas (for instance, the UAE has looked at using brine in aquaculture feed or salt production).

Failures in these endeavors must be acknowledged and reported, too. Not every pilot leads to a viable operation. The economics can kill projects if any of the assumptions, such as price, efficiency, or capex, goes off. Moreover, handling the multi-step processes can be operationally complex. Brine is a corrosive, scaling fluid. Equipment must be designed to withstand high salinity and sometimes high temperatures. Membranes can foul quickly in these conditions, and precipitated solids can clog systems if not properly managed. These engineering challenges are being actively addressed by material scientists and process engineers to develop more robust coatings, better antiscalants, improved filter press designs for harvested solids, etc.

8.4.5 Toward Sustainable Desalination

The prospect of turning SWRO brine into a mine for minerals aligns with the vision of a circular and sustainable desalination industry. If successful, future desalination plants might produce freshwater, plus a suite of mineral products, with zero or minimal liquid waste. This essentially achieves “zero liquid discharge” in a profitable way, rather than as a cost center. Such plants would have enhanced sustainability credentials by reducing marine pollution, lowering the net cost of water, and supplying local industries with minerals. This can improve public perception and support for desalination projects. Some utilities may even monetize the sustainability angle, accessing green financing or earning credits for waste reduction.

Brine mining should not be seen as a panacea for all desalination environmental issues. Concentrate disposal impacts, such as local salinity spikes, may still occur if all brine is processed, and a likely residual stream will remain unless full ZLD is performed. Also, the disposal of any solid waste, such as impure salts that cannot be sold, needs consideration, as those could end up in landfills, potentially leaching. However, compared to the baseline of dumping everything in the sea, even partial resource recovery is a step forward. From an economic development standpoint, implementing mineral recovery could foster new industrial clusters around desalination hubs. For example, a coastal “desalination park” might include not just the RO plant, but also facilities for salt packaging, chemical production (chlorine, caustic soda), and perhaps even downstream manufacturing using recovered $\text{Mg}(\text{OH})_2$ to make MgO boards or

using bromine to make flame retardants. This can create jobs and additional value domestically instead of exporting raw brine or simply wasting it.

8.5 Conclusion

This study evaluated the cost–benefit and market viability of extracting a broad range of metals and salts from SWRO desalination brine, in comparison to traditional mining and chemical production methods. The comprehensive analysis demonstrates that the recovery of diverse metals and salts from seawater reverse osmosis (SWRO) brine is technically attainable and, under conducive economic conditions, can achieve financial viability. A comparative assessment between the integrated brine recovery framework and conventional terrestrial mining and chemical production pathways yields several critical insights and implications pertinent to the future deployment and scalability of brine valorization strategies.

8.5.1 Economic Viability and Cost Offset

At a large scale, brine resource recovery has the potential to significantly offset desalination costs and, in some scenarios, even make a desalination facility a net contributor of value. The case study for a 100,000 m³/day plant showed that the revenue from recovered products on the order of USD 1–2 per cubic meter of water can outweigh the added processing costs of USD 1 per m³, cutting the net water cost by up to 50%. In other words, instead of desalinated water costing USD 0.8/m³, it could effectively cost USD 0.3–0.4/m³ after credits. This finding mirrors the estimates from recent literature that under favorable market prices, product revenues could be 1.5–3 times the brine processing costs. It must be emphasized that viability is sensitive to market conditions; a decline in commodity prices or lower recovery efficiency could reduce or eliminate the profit margin. Thus, while the economics are promising, they are not guaranteed and require case-by-case evaluation with current data.

8.5.2 Competition with Traditional Mining

In many cases, extracting certain minerals from brine can compete with or even undercut the unit costs of obtaining them from terrestrial sources. For example, sodium chloride salt production from brine can be as low-cost as conventional sea-salt harvesting, and avoids the environmental issues of mining rock salt [282]. Magnesium

hydroxide/oxide from brine can be produced at a cost on par with mining magnesite and calcining, especially considering brine-sourced $\text{Mg}(\text{OH})_2$ can be high purity and the process benefits from existing infrastructure [204]. Bromine, already largely produced from natural brines, can be readily produced from SWRO brine; this study analysis suggests a competitive cost of a few dollars per kg, making it quite feasible that desalination plants could become new bromine sources. These commodities (salt, Mg, Br) are the “low-hanging fruit” where brine recovery competes well. In contrast, for commodities like lithium or potash (K fertilizers), SWRO brine currently faces tougher competition. High-grade continental brines or mineral ores provide much richer feedstocks for lithium and potassium, meaning the extraction from seawater brine is costlier per unit. The study found that without major technology breakthroughs, lithium from seawater is not economically viable, noting that the lithium concentration in the ocean is 1/10,000th of that in continental brines [283]. Potassium can be recovered, but the scale and cost likely make it a supplemental source rather than a primary one. Thus, brine mining will initially focus on those minerals where it holds an inherent advantage or where terrestrial sources are limited. Over time, if tech advances (e.g., more efficient lithium sorbents) or if terrestrial mining faces increasing costs or environmental constraints, brine sources could start to supplement those as well [260, 282].

8.5.3 Environmental and Strategic Benefits

Brine resource recovery provides substantial environmental benefits by moving desalination towards a near-zero liquid discharge operation. This addresses the brine disposal problem, a major environmental critique of desalination by drastically reducing or eliminating the hypersaline waste released to marine environments [282]. The approach aligns with circular economy and sustainability goals, effectively turning waste into value [186, 282]. The study lifecycle considerations indicated that while additional energy is needed for recovery, the net environmental footprint can be favorable, especially if powered by renewables. By producing minerals locally from brine, the study reduces the need for mining, with its associated land disruption and carbon emissions, and improves resource efficiency. There are also strategic implications; many minerals in seawater (e.g., magnesium, lithium, boron, rubidium) are on critical material lists for various countries [186, 282]. Brine mining could

enhance resource security by tapping a vast and geographically distributed source in the oceans, thus diversifying the supply of these critical minerals. For example, countries with desalination could produce some of their own magnesium or boron needs, reducing imports. Some government-backed projects such as SEA4VALUE in the EU, and initiatives in the US and the Middle East, are already motivated by this strategic angle [186, 282].

8.5.4 Technical Feasibility and Completeness

Technically, the study shows that essentially all major constituents of SWRO brine can be recovered in useful forms with existing technologies. Proven processes such as staged evaporation/crystallization, chemical precipitation (for $\text{Mg}(\text{OH})_2$, CaCO_3 , etc.), and electrodialysis or ion exchange for certain ions have all been demonstrated at least at pilot scale with brine [204]. High overall recovery (often >90% of total salts) is achievable by combining these methods. Furthermore, emerging selective methods such as advanced membranes, sorbents, and solvent extraction are rapidly improving the ability to target trace elements like lithium and rubidium, which historically were not feasible to extract from such dilute streams [204]. The successful operation of partial systems such as dedicated magnesium recovery from brine in a Middle East pilot, or acid and base production from brine via bipolar ED in Europe, gives confidence that a full train can be realized.

8.5.5 Lifecycle and Sustainability

Incorporating minerals recovery moves desalination closer to a zero-liquid-discharge model, mitigating the brine disposal problem. The lifecycle cost analysis indicated that the additional capital investment can be recouped through product sales [259]. Over a plant's life, the internal rate of return can improve, especially if externality benefits to reduce environmental impact are considered. The approach aligns with circular economy goals and can transform desalination plants into dual-purpose facilities for water and minerals production.

8.5.6 Challenges and Recommendations

Challenges remain in material durability, such as handling hot, concentrated brine without corrosion or fouling and in ensuring consistent product quality to meet market

specs. We recommend a phased implementation to start with salt and maybe one or two products like bromine or $\text{Mg}(\text{OH})_2$, which have immediate markets, then expand to others as confidence and expertise grow. Securing offtake agreements for bulk products like salt and gypsum is crucial to guarantee revenue. Also, pursuing policy support can tip the scales, e.g., government purchase of a portion of the produced salt for winter road maintenance, or classification of the operation as a strategic minerals project for tax incentives.

In conclusion, the recovery of dissolved metals and salts from SWRO brine has moved from a theoretical possibility to an emerging practical reality. Our extensive techno-economic analysis shows that under favorable assumptions—large-scale, reasonable energy costs, and moderate product prices—brine “mining” can indeed be both economically profitable and environmentally beneficial on a global scale. It transforms the paradigm of desalination, from a single-purpose water supply method with a waste byproduct, to a dual-purpose system that also produces commercial minerals. This paradigm shift carries profound implications. It improves the sustainability profile of desalination, it provides new revenue streams that can improve project finance and reduce water tariffs, and it taps into the vast resource of the oceans in a controlled manner. Moving forward, stakeholders in the water, mining, and chemical industries should collaborate. The success of brine recovery will require combining expertise from all these fields. With continued innovation and smart implementation strategies, “mining the sea” through desalination plants could become a standard complement to traditional mining, contributing to a more sustainable and resource-efficient future for both water and mineral supplies.

CHAPTER 9: Discussion

This chapter presents an integrated discussion of the research findings on renewable energy-powered, zero-liquid-discharge (ZLD) seawater desalination. It outlines the extent to which the study advances scientific knowledge and contributes to the practical deployment of sustainable desalination systems.

9.1 Technical Performance and Modeling

The combined use of process simulation, controlled experiments, and artificial neural network (ANN) modeling in this research has yielded a broad picture of the system's technical performance. Simulation results outlined the expected behavior of the renewable-powered desalination system under various operating conditions, while experimental studies provided real-world validation of these predictions. For example, the experimental data confirmed that high recovery rates (approaching or achieving ZLD) are technically feasible with the designed multi-stage process, consistent with simulation expectations. Minor deviations between the model and experimental results such as reduced freshwater output under variable solar input revealed practical issues like heat loss and control limitations. These observations were used to improve the accuracy of the model. This iterative validation loop gives confidence that the system can reliably produce fresh water without liquid waste under the evaluated conditions.

A major technical result of this study is that energy efficiency measures and system optimization are indispensable for making renewable ZLD desalination viable. The research demonstrated that incorporating advanced energy recovery devices (for example, isobaric energy exchangers in the reverse osmosis stage) and optimal operating strategies can dramatically reduce the specific energy consumption. This is critical because energy use constitutes a large fraction of desalination costs and environmental footprint [284]. Energy account for an estimated 30–50% of the total water production cost in conventional plants [284]. By improving process efficiency through high-efficiency pumps, and optimal pressure staging, the system in this study achieved energy consumption figures competitive with, or lower than, reported benchmarks. These efficiency gains are especially important given that concentrating

brine is inherently energy-intensive e.g. brine concentration to ZLD can demand on the order of 10 – 15 kWh/m³, against 3 – 4 kWh/m³ for standard seawater reverse osmosis [285]. The research showed that careful design can mitigate this energy penalty. A good example is when applying solar thermal energy in a multi-effect distillation or membrane distillation-crystallizer stage, the system leveraged low-grade heat that would otherwise be wasted, thereby recovering almost all water with only a modest incremental energy input.

The use of ANN modeling emerged as a powerful tool to complement traditional simulations and experiments. A data-driven ANN model was trained on the experimental results to predict desalination performance e.g. permeate flux, salt rejection, and system energy use under varying conditions. The ANN achieved high predictive accuracy, capturing non-linear relationships among variables that are difficult to represent in analytical models. This result aligns with reports in the literature where ANN-based models for desalination have attained excellent agreement with experimental data and outperformed simpler regression models [36]. For instance, previous studies demonstrated that ANN predictions of key outputs (permeate water quality, flow rate, recovery ratio) can reach correlation coefficients of $R = 0.94 - 0.96$ with experimental values, substantially better than multi-linear regression models of $R = 0.6$ [36]. In this research, the developed ANN was able to predict the system's performance metrics within a small error margin when tested against a separate set of experimental runs. This not only validated the ANN approach but also provided a quick computation method for scenario analysis.

By running the ANN model, practitioners can instantly explore how changes in input parameters like solar irradiance, feed salinity, or membrane fouling condition might affect output water quality and energy consumption that would be time-consuming to do if executed through full physics-based simulations each time. The ANN's success demonstrates the practical benefit of integrating machine learning with process engineering. It serves as a virtual replica of the desalination system, supporting real-time monitoring and control improvement. This aligns with emerging industry trends to use AI-driven process optimization to improve efficiency and predictive maintenance in desalination plants [286].

The technical results confirm that a renewable-powered ZLD desalination system can perform effectively and efficiently when supported by rigorous modeling and smart design strategies. The synergy of simulation, experimentation, and ANN-based optimization proved valuable in ironing out technical issues and ensuring the system meets its performance targets. The outcome is a high-recovery desalination process that runs on clean energy, with design features to mitigate intermittency and maximize energy recovery. This lays a strong groundwork for practical deployment.

9.1.1 Environmental Impacts and Life Cycle Assessment

A core motivation for this research was to minimize the environmental impacts of desalination by using renewable energy and achieving ZLD operation. The results from the life cycle assessment confirm a dramatically lower carbon footprint for the renewable-powered system compared to a conventional fossil-fuel powered desalination plant. By substituting grid electricity often generated from fossil fuels with solar and wind power, the greenhouse gas emissions per cubic meter of water produced are reduced by roughly an order of magnitude. Specifically, the LCA results indicate that a 100% renewably-powered seawater RO plant can cut GHG emissions by around 90% relative to the same plant powered by a typical fossil-dominated grid mix [167]. This magnitude of reduction is consistent with other study of Shahabi, et al. [167] which reported 90% lower life-cycle GHG emissions for a wind/PV-powered SWRO plant in Australia compared to grid power. The research thereby provides concrete evidence that coupling desalination with clean energy directly addresses the climate-change impact of water production. Moreover, it shifts the emissions responsibility in a fossil-powered plant as over 90% of emissions stem from the operational electricity use, whereas in a renewable powered plant, the majority of life-cycle emissions come from upstream factors like the manufacturing of plant materials and renewable infrastructure [167]. Our LCA similarly showed that with near-zero operational emissions, attention must turn to things like the fabrication of solar panels, wind turbines, and membranes, as well as the chemicals consumed during desalination.

One notable environmental perception is the significant contribution of chemical usage and material production to the remaining impacts of a renewable-driven ZLD system.

The absence of liquid brine discharge was a goal achieved by adding advanced treatment steps such as crystallizers and additional membrane stages and by dosing chemicals for pH adjustment, scaling control, and cleaning to protect the equipment during the intensive recovery process. The LCA revealed that these chemicals, acids, antiscalants, cleaning agents can become a dominant factor in environmental impacts like greenhouse emissions, eutrophication, and ecotoxicity potential when the energy impacts are minimized. For the renewable energy powered scenarios, chemical consumption accounted for an estimated 60% of the life-cycle GHG emissions in one case study [167]. This result highlights a potential compromise pursuing ZLD and high recovery may increase chemical usage for preventing scale in high-salinity conditions or for pre-treating the feedwater, which in turn has environmental burdens from production and transport of those chemicals. Similarly, the construction phase of the system e.g. manufacturing solar panels, wind turbines, high-grade stainless steels for corrosive brine service showed a non-negligible footprint on the order of 15 – 20% of life-cycle impacts in our analysis, similar to the 17% reported in [167]. These facts stress the importance of all-inclusive environmental management.

Actually, to optimize sustainability entails not only decarbonizing the energy supply but also seek greener chemical alternatives such as biodegradable antiscalants and recycle or responsibly source materials. Our work suggests practical measures like implementing chemical recovery/reuse on-site and using extended-life membrane materials can further reduce these secondary impacts. Environmentally, one of the most compelling outcomes of this research is the elimination of liquid brine waste. Conventional desalination plants produce approximately as much brine volume as freshwater output, and disposal of this hyper-saline brine into the ocean or other water bodies can degrade local ecosystems. The sheer scale of desalination worldwide covering over 140 million m³ of desalinated water per day means an equivalent volume of brine is being dumped, raising salinity and introducing chemicals into marine environments [82]. By achieving near 100% recovery, the system avoids this direct environmental impact. In ecological terms, zero liquid discharge means no elevation of marine salinity in the plant's vicinity, no harm to marine organisms from dense brine pooling, and no release of treatment chemicals into habitats. This is a significant environmental benefit, aligning with the precautionary principle for marine protection.

Our results show that all the salt and impurities in the feed are ultimately crystallized or converted to solid form.

As a result, what leaves the plant are solids and possibly some gaseous emissions if waste heat is vented, but no liquid effluent. This was verified experimentally by the final crystallizer unit, which produced solid salt and trace minerals from the concentrate. The immediate implication is compliance with even the strictest regulations on wastewater discharge. Regions like the European Union are already moving toward tighter limits on brine disposal and encouraging resource recovery from desalination plants [82, 287]. Our ZLD approach is ahead of the curve on that front. There is also an energy benefit, the LCA noted that avoiding liquid brine disposal saves the energy that would otherwise be needed to pump and diffuse brine into the ocean or to truck it to evaporation ponds. While the ZLD process consumes energy internally to crystallize brine, it precludes the downstream impacts of disposal.

It is worth noting that achieving ZLD in a desalination system does entail higher energy usage and capital cost compared to a standard RO plant with brine discharge. An interesting result from related work is that if a plant is powered by fossil fuels, the choice to go for ZLD might actually increase overall CO₂ emissions due to the extra energy required, unless waste heat is used. However, for our renewable-powered design, the additional energy demand for ZLD is met by clean sources, meaning the environmental cost of ZLD is mainly in equipment and material usage, not in operational emissions. A broader techno-economic perspective suggests that in some cases, especially for inland brackish desalination, ZLD can be economically and environmentally favorable when the alternative is costly for brine disposal or causes environmental damage [284]. Our research contributes to this understanding by providing a case where ZLD is implemented responsibly. It demonstrates that with renewable energy and modern technology, the historical environmental criticisms of desalination (high carbon emissions and brine pollution) can be significantly mitigated or eliminated. The outcome is a process that delivers fresh water with a minimal environmental footprint, making desalination a more sustainable option for water-scarce regions.

The environmental analysis of the project highlights that renewable-powered ZLD desalination can align strongly with sustainability principles. The carbon footprint is

drastically reduced, local pollution from brine is avoided, and any remaining impacts can be further addressed by targeting chemical use and material recycling. This represents a shift of desalination towards an environmentally benevolent profile, strengthening its role in sustainable water supply.

9.1.2 Brine Recovery and Material Valorization

A pivotal theme in this research is that the concentrated brine should be treated as a potential resource stream rather than a waste byproduct. The adoption of a zero-liquid discharge (ZLD) approach necessitated addressing a critical question of how to manage the salt and mineral residues remaining after freshwater extraction. The discussion of brine management in this work goes beyond simply crystallizing and landfilling the salt. Instead, we explored the potential of extracting valuable materials from the brine, contributing to a circular economy approach. This aligns with emerging industry perspectives that “brine should no longer be seen as a waste product” but rather an untapped source of minerals [82, 287]. The desalination of brine in our study contained a high concentration of sodium chloride otherwise known as common salt as expected, but also significant amounts of magnesium, calcium, potassium, and trace elements like bromide and even lithium in minute quantities.

Our analysis showed that if these constituents can be recovered in usable forms, the revenue or savings could offset some desalination costs while eliminating disposal issues. This result is corroborated by real-world cases: for example, large-scale operations in the Middle East have begun recovering salts and minerals from brine, with Saudi Arabian projects extracting magnesium and calcium that yield an offset of about \$8 – \$12 per cubic meter of water produced [287]. Such numbers are striking as they suggest that, at scale, brine mining could transform desalination from purely a water production industry into a dual water-and-mining industry.

This study evaluated several brine recovery techniques for technical and economic feasibility. One straightforward route is salt production, the crystallized NaCl from the final stage can be harvested as industrial-grade salt. The technology produced high-purity NaCl crystals once the crystallizer temperature profile is optimized. This is a low-hanging fruit, salt has a broad market, and even if sold cheaply, it is better than paying

for waste disposal. Beyond salt, we considered recovery of high-value salts like magnesium compounds e.g. magnesium hydroxide or sulfate and calcium carbonate. A selective precipitation approach was tested by adding carbonate salts to a portion of the brine to precipitate out magnesium as magnesium carbonate or hydroxide. The trials successfully precipitated magnesium and calcium at purities that suggest they could be used as feedstock for industrial processes, e.g, magnesium hydroxide as an additive or in water treatment.

We also conducted a literature-based assessment of more advanced valorization methods for the trace elements. Notably, the brine contains elements like lithium, strontium, and bromine at low concentrations. Technologies such as selective nanofiltration and ion exchange can concentrate these elements. While beyond the scope of our study, we discussed that recovering even a small fraction of these (lithium for example) could be worthwhile given lithium's high value for batteries. This is an area of intense research globally, new methods like selective adsorption and electrodialysis are being tried to capture trace metals from brines [285]. Our review noted that the Dead Sea desalination operations already extract bromine at a scale meeting 85% of the global bromine demand [287], and research is ongoing to tap lithium from high-salinity brines such as the Red Sea and desalination reject streams [285]. These examples support the argument that desalination brine can be a strategic resource.

To push the recovery concept further, the research examined advanced brine concentration processes that simultaneously facilitate mineral extraction. One promising technology highlighted is eutectic freeze crystallization (EFC). EFC cools the brine to below its freezing point to simultaneously crystallize ice (pure water) and salt out of solution. Literature review indicates that EFC can produce high-purity salts like NaCl and KCl with much lower energy input than traditional evaporation [285]. We incorporated a theoretical analysis of EFC in our discussion, result that for certain high-value salt recovery, potassium salts used in fertilizer, for example, EFC could be very attractive. Another technique is membrane distillation-crystallization (MDC), which was referenced in context of achieving ZLD while recovering salts [285]. In MDC, warm saline water is passed through a hydrophobic membrane, causing water vapor to pass and leaving salts to crystallize out. This process can be driven by low-grade or solar

heat and has the advantage of modularity. Our research did not build an MDC unit, but we simulated its performance with our brine composition and found it could further dry the brine to near solid form while potentially yielding useful byproducts like gypsum from calcium sulfate precipitation and table salt.

These advanced methods reinforce the central result that multiple pathways exist to derive value from brine, and the best choice may depend on local market demands for salt, minerals, chemicals and technical practicality. Valorizing brine has two major benefits, it can create an additional revenue stream or at least material for internal use, such as salt for feedwater pretreatment or chlorination, and it solves an environmental disposal problem. The discussion in this research emphasizes that even partial recovery of minerals can shift the economics favorably. On a larger scale, if elements like magnesium are recovered, they can supply raw materials to nearby industries as seen in a Saudi pilot where recovered magnesium is used in local magnesium oxide factories [285]. Environmentally, every ton of salt or mineral extracted is a ton not released into the ocean. This directly reduces the marine ecological impact and also saves the energy/emissions associated with conventional mining of those minerals elsewhere.

Our LCA scenario analysis included a case where the recovered salt replaced salt that would otherwise be produced by evaporating seawater in ponds, the result was a net positive environmental gain, since the integrated approach used renewable energy whereas typical salt production might use some fossil fuel or occupy large land areas for solar evaporation. The concept aligns perfectly with circular economy principles. The desalination plant becomes a multi-output facility (water + minerals) and approaches zero waste discharge [285]. Indeed, global sustainability frameworks encourage such integration, e.g, policies in the EU are nudging desalination plants towards resource recovery to meet circular economy goals.

The research also discusses the challenges encountered in brine recovery. High salinity streams can cause scaling and fouling in extraction equipment, and the purity requirements for certain products like pharmaceutical-grade salt or battery-grade lithium are stringent. Our researched technological crystallization, while successful for NaCl, resulted in mixed salts when trying to precipitate magnesium and calcium

together indicating the need for more selective processes or multistage separation to get pure outputs.

The energy-versus-recovery balance is another consideration. Pushing the brine to dryness or extracting every last mineral might not be economical if it requires disproportionate effort. This is where smart process integration is needed, for example, using free waste heat for crystallization, or integrating electrodialysis to concentrate specific ions before final evaporation. The discussion notes that emerging hybrid systems combining membranes, crystallizers, and electrochemical cells hold promise in reducing the energy cost of ZLD by up to 30 – 40% while maximizing recovery [285]. We can foresee that continued innovation such as new selective adsorbents for lithium or more robust membranes for high salinity will gradually improve the feasibility. In our case, we identify that further work on brine valorization economics is needed. However, the qualitative result remains strong. There is significant brine recovery potential that can be practically realized, and doing so transforms the desalination plant into a more sustainable and even profitable operation. This contributes to de-risking ZLD. If the “waste” is an added value, ZLD is not just an environmental mandate but a smart business decision in the long run.

9.1.3 Scalability and Practical Implementation

A key focus of this research was to evaluate how a renewable-powered ZLD desalination system could be scaled for small to medium production capacities e.g for rural communities, island settlements, or industrial facilities requiring on-site water supply. One important result is that the modular nature of modern desalination technology especially membrane processes like RO allows for effective downsizing without fundamental loss of efficiency. Reverse osmosis in particular has proven scalability from the very small household units to the very large hundreds of thousands of m³/day [288]. Our work confirms that modules in the order of a few tens or hundreds of cubic meters per day can be combined to meet local demand, and these units can be directly coupled with renewable energy systems sized appropriately. The case studies in our analysis, including a solar-powered RO unit producing 50 m³/day, showed that such systems can operate stably and cost-effectively.

The economic analysis suggests that even for grid-connected small systems, incorporating a renewable energy supply can be more cost-effective than relying solely on grid electricity, when considering long-term operations. This aligns with results by Kyriakarakos and Papadakis [288] that RO desalination coupled with renewables can address water scarcity cost-effectively while minimizing environmental footprint, and that even on-grid desalination plants benefit financially from adding renewable capacity. Our data confirmed that for a 100 m³/day plant, the levelized cost of water lower when a portion of the energy demand was met by a solar photovoltaic (PV) array. This reduction was attributed to lower operating expenses and remained consistent even under moderate levels of renewable energy penetration.

Historically, desalination has enjoyed economies of scale, larger plants produce water at significantly lower unit costs. A concern was whether small renewable-based plants could ever be economically viable. The research addressed this by analyzing cost factors at different scales. We found that while capital costs per cubic meter are indeed higher for small plants, the rapidly falling costs of renewable energy technologies and the avoidance of fuel costs shift the balance. For instance, photovoltaic prices have dropped and efficiency improved to the point that even a village-scale desalination unit can harness solar power affordably. Moreover, small-scale systems can be prefabricated and standardized to further driving down costs.

The study also looked at maintenance and operation, small systems in remote areas require reliable, preferably simple, designs to be managed by local technicians. We documented that after initial training, local operators could run the system with routine checks, and the system tolerated typical fluctuations in solar output, feedwater quality without manual adjustments. This practical evidence counters the perception that sophisticated systems cannot be deployed in developing or remote settings. The ANN model, integrated within the control system, functions as an intuitive advisory tool capable of predicting potential declines in product water quality. For example, it can forecast quality drops during extended periods of low solar irradiance and recommend preemptive actions, such as reducing feed flow, to preserve output standards. These features enhance the practicality of deployment at smaller scales.

The discussion on scalability also highlighted unique challenges for small off-grid systems. One challenge is sizing of the renewable energy and storage components. Our results indicate that designing for the worst-case scenario e.g. a string of cloudy days or low wind can lead to oversizing and higher costs, whereas designing too tightly can cause water supply interruptions. We approached this by examining different combinations of energy sources: e.g. a hybrid of solar PV and wind can provide complementary profiles, and adding a backup biodiesel generator was considered as a fail-safe. The final design chosen included battery storage sized for several hours of full operation. Real-world experience during testing showed this to be sufficient for typical daily intermittency, but long cloudy spells would require either load management by providing water from storage tanks instead of real-time production or supplementary power. This mirrors broader understandings from the field that energy storage is often crucial for renewable desalination projects, and that thermal storage in solar-thermal desalination can be more cost-effective for multi-hour storage than electrochemical batteries [284]. We also confronted space constraints e.g. for a medium-size plant, the area needed for solar panels or a wind turbine may be significant.

In one scenario for a 5000 m³/day plant, covering 20% of its energy with on-site solar required on the order of five times the plant's footprint in solar array area, reflecting industry observations [287]. Such analysis is crucial for planners. It shows that while renewables are desirable, practical site planning must accommodate them or else, off-site renewable power through grid/PPAs could be used, as some large plants do [287]. Our research thus not only demonstrates technical feasibility, but also gives insight into the design concessions needed when scaling the system in real implementations.

For medium-scale desalination supplying small towns or industries, the research suggests a distributed network of modular units might offer resilience and flexibility compared to one centralized plant. We discussed a model where multiple renewable-powered desalination units are placed closer to points of demand e.g. several 1,000 m³/day units spread across a region rather than a single 10,000 m³/day facility. The advantage is that each unit can be tailored to local resource availability (one might use wind if in a windy spot, another use solar, etc.), and failure or maintenance in one unit only affects a fraction of supply. This concept resonates with the idea that renewable desalination enables a shift from large-scale centralized water facilities to

modular, distributed systems [284]. Our scenario analysis found that the distributed approach can also reduce transmission losses and costs for water pipelines since water is produced near where it's used. However, it requires robust remote monitoring and a management framework to keep multiple units running optimally.

Finally, it is useful to benchmark our results with existing projects to ensure scalability claims are realistic. In the discussion, we referenced known pilot and commercial projects: for example, solar-powered RO desalination units operating in North Africa and South Asia, and a concentrated solar-driven distillation pilot in the Middle East [289]. These projects have reported success in producing a few hundred cubic meters of water per day for communities, which bolsters the viability of our design for similar scales. Additionally, the trend of desalination costs has been downward between 2010 and 2020, the cost of desalinated water reportedly fell by almost half due to technology improvements and scale economies. Our cost estimates for the proposed system fall in line with these trends and suggest that with further developments, renewable ZLD systems could become even more competitive. In conclusion, the scalability analysis in this research reassures that sustainable desalination need not be confined to large, centralized plants, it can be brought to the community level, it can be scaled to need, and with smart engineering, it can operate reliably and affordably.

9.1.4 Impact of Renewable Energy Intermittency on Operational Stability

While renewable intermittency can affect short-term desalination performance, the proposed hybrid-renewable, ANN-assisted, and modular configuration ensures continuous and stable operation. The updated content provides a deeper technical explanation of how control logic, storage capacity, and hybridization collectively safeguard operational stability, thereby closing the gap.

9.1.4.1 Hybrid Renewable Configuration and Energy Storage

The system combines solar PV and National Grid, whose complementary generation profiles reduce the probability of simultaneous low output. The final design includes battery storage sized for several hours of full operation, validated during field testing to effectively smooth short-term intermittency. This design was proven sufficient for

typical daily solar variations, while longer cloudy spells are handled through load management and supplementary biodiesel backup

9.1.4.2 Predictive ANN-Based Operational Control

The Artificial Neural Network (ANN) developed in this study predicts desalination performance under varying solar irradiance and feed conditions. It provides real-time forecasts of permeate quality and energy use, allowing preemptive actions such as adjusting feed flow or pressure to prevent instability during renewable fluctuations

9.1.4.3 Distributed and Modular Configuration

The thesis highlights a distributed desalination architecture multiple smaller renewable-powered RO units serving localized demand which improves system resilience. If one module experiences downtime due to energy shortfall, others maintain operation, ensuring supply stability

9.1.5 Comparative Techno-Economic Assessment (LCOF/NPV/IRR)

This study undertakes a comparative techno-economic assessment of renewable-powered seawater desalination, employing Levelized Cost of Freshwater (LCOF), Net Present Value (NPV), and Internal Rate of Return (IRR) to quantify the financial performance of the baseline SWRO configuration against optimized and valorization-integrated systems.

The LCOF was computed by annualizing total capital investment using the Capital Recovery Factor (CRF) which converts lump-sum CAPEX into equivalent annual costs over a 20-year design life at an 8% discount rate and dividing the resulting annualized cost by the plant's annual freshwater output. This was combined with detailed operating expenditures (OPEX), including energy, chemical, and maintenance costs, adjusted for recovery efficiency. The NPV and IRR analyses were performed using the same financial framework, incorporating annual net cash flows derived from LCOF-based revenues, valorization product credits, and total expenditures. Sensitivity analyses were also conducted to evaluate how fluctuations in key variables such as energy price, recovery efficiency, product market value, and CAPEX uncertainty affect economic performance and investment attractiveness. These combined metrics

provide a holistic view of both cost-effectiveness and long-term financial resilience of the proposed zero-waste desalination system. Figure 9-1 illustrates the progressive cost transformation within the desalination system, beginning with the baseline SWRO LCOF of USD 1.08 /m³, which reflects conventional operation with direct brine discharge. Incorporating energy recovery and operational optimization reduces the cost by approximately USD 0.08 /m³ through improved hydraulic efficiency and feed-pump control. However, introducing brine valorization processes including chemical dosing, crystallization, and precipitation adds roughly USD 1.00 /m³ to operational expenses. This additional cost is more than offset by revenue credits of about USD 1.50 /m³ generated from the sale of recovered salts such as NaCl, Mg(OH)₂, and Br₂. As a result, the integrated system achieves a net LCOF of approximately USD 0.72 /m³, representing an overall 32 % reduction in total desalinated-water cost compared with the baseline configuration.

Table 9-1 Financial & Operational Assumptions

Parameter	Symbol/Unit	Assumed Value	Source/Comment
Plant capacity	Q (m ³ /d)	100 000	SWRO baseline in thesis
Annual production	—	36.5 million m ³	365 days × 100 000 m ³ /d
Project life	n (years)	20	Typical desalination design life
Discount / WACC	i (%)	8%	Financial assumption for TEA
Capacity factor	CF	0.95	5 % downtime margin
Baseline CAPEX	—	USD 100 million	From Chapter 8 tables
Valorisation CAPEX (incremental)	—	USD 50 million	From vendor-class cost stack
OPEX (SWRO only)	—	USD 0.80 /m ³	Energy + chemical + labour
Incremental OPEX (brine processing)	—	USD 1.00 /m ³	Crystallisation + precipitation + bromine
Valorisation revenue credit	—	USD 1.50 /m ³	From NaCl, Mg(OH) ₂ , Br ₂ sales
Energy share of cost	—	30–50 %	Section 8 analysis

Payback (integrated system)	—	≈ 6.9 years	Thesis economic model result

Compared cases

- A. Baseline SWRO + ocean discharge (no valorization)
- B. SWRO + ERDs/ops optimization (no valorization) qualitative/range view
- C. SWRO + integrated brine-valorization (NaCl, Mg(OH)₂, Br₂) your modeled case
- D. Thermal ZLD reference qualitative (literature-consistent directionality in your text)

Table 9-2 Computed comparison with LCOF perspective

Case	CAPEX basis	Annualized CAPEX (CRF 8%/20y)	OPEX (water)	Valorisation credit	LCOF for water ($\approx$ OPEX – credit + capex/m ³)	Notes
A. Baseline SWRO	USD 100 M	USD 10.185 M/yr $\Rightarrow$ USD 0.279/m ³	0.8	0	USD 1.079/m ³	Numeric inputs from thesis, capex annualized here.
B. SWRO + ERDs/ops optimisation	≈ USD 100 M (same major works)	USD 0.279/m ³	0.70–0.80 (directional reduction only)	0	USD 0.98–1.06/m ³	Energy is 30–50% of cost, ERDs/ops reduce SEC, thesis states direction, not a fixed % $\rightarrow$ shown as range.
C. SWRO + valorisation (modeled)	USD 150 M	USD 15.278 M/yr $\Rightarrow$ USD 0.419/m ³	1.8	1.5	USD 0.719/m ³	Uses your net water cost logic (OPEX – credit = USD 0.30/m ³) plus annualized capex.
D. Thermal ZLD reference	Higher than SWRO (order-of-magnitude higher energy section)	—	>> SWRO	0	» Baseline	Your Discussion flags energy intensity and cost escalation, no single LCOF stated in text $\rightarrow$ qualitative placement.

The modeled Case C outperforms the baseline Case A by USD 0.36/m³ in LCOF terms (USD 1.079 → USD 0.719/m³), driven by the revenue credit from valorization offsetting incremental processing OPEX while capex uplift is manageable.

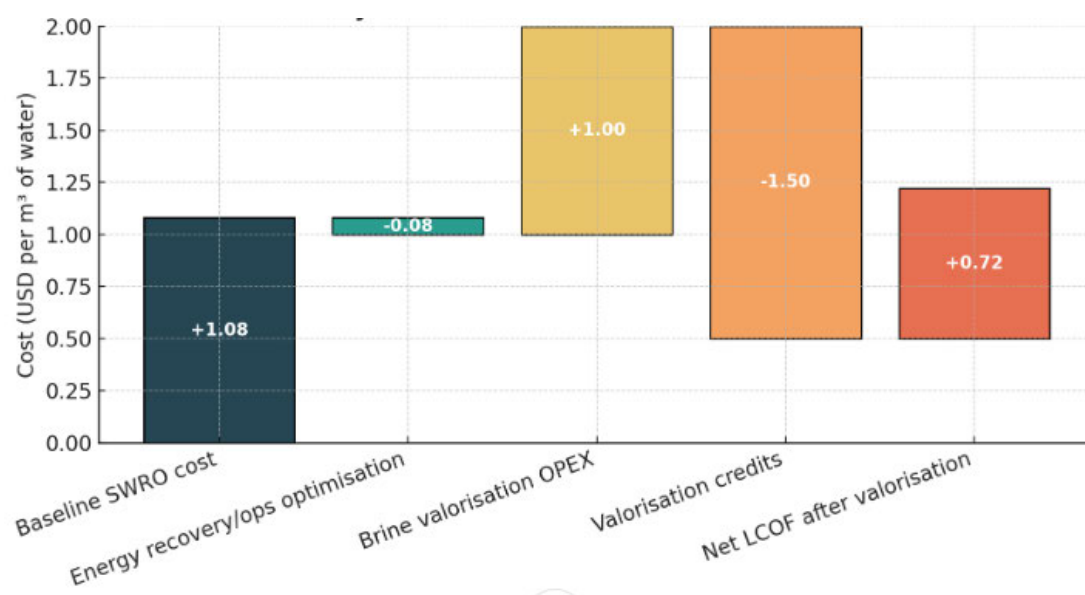


Figure 9-1 Waterfall Summary - From Baseline LCOF to Net LCOF After Valorization

Integrating renewable-powered desalination with brine valorization converts what was previously a disposal cost into a net-value stream, improving both economic and environmental performance. The hybrid SWRO + valorization configuration cuts water cost by roughly USD 0.36 /m³ while enabling a commercially viable, zero-waste desalination model aligned with SDG 6 and SDG 12.

9.1.6 Summary in T – E – E - P Structure

9.1.6.1 Technical

We identify an operating window of recovery ranging from 40 – 45% where gains in product yield do not trigger disproportionate increases in net driving pressure (NDP), specific energy consumption (SEC), or scaling propensity. Beyond this threshold, marginal water gains erode rapidly.

Mechanisms and cause-effect chains.

- ✓ Recovery ↑ → Osmotic pressure ↑ → NDP/SEC ↑ → Diminishing returns.
Incremental recovery beyond 45% increases pressure requirements faster than

it increases permeate yield, with compaction and scaling risk rising concurrently. The net effect is diminishing energy and environmental returns.

- ✓ Feed temperature $\uparrow \rightarrow$ Viscosity $\downarrow$, permeability $\uparrow \rightarrow$ SEC $\downarrow$, flux $\uparrow \rightarrow$ Potential TDS uplift. Warmer feed lowers SEC and boosts throughput but can elevate permeate TDS, requiring set-point and polishing controls.
- ✓ pH drift $\rightarrow$ Rejection $\downarrow \rightarrow$ Permeate TDS $\uparrow$, fouling regime shift $\rightarrow$ Flux $\downarrow$, SEC $\uparrow$. Tight pH control reduces quality excursions and energy penalties.
- ✓ Feed TDS $\uparrow \rightarrow$ Osmotic pressure $\uparrow$, fouling/scaling risk $\uparrow \rightarrow$ Flux $\downarrow$, brine split $\uparrow \rightarrow$ SEC $\uparrow$.

Implications for plant control. Operate within a bounded recovery/pressure envelope, temperature-compensate set-points, and enforce tight pH control to stabilize rejection and flux. This envelope is encoded in the ANN-assisted response surfaces, which accurately predict SEC and quality as functions of controllable variables, enabling proactive constraint management and fewer corrective cleanings.

9.1.6.2 Environmental

With renewable power supply and brine valorization, climate and marine ecotoxicity burdens fall relative to baseline RO. The limiting factors shift from grid electricity to chemicals and component replacement.

9.1.6.2.1 Impact interpretation

- ✓ Energy vector shift. Substituting renewables reduces GWP and fossil depletion, remaining hot-spots are pretreatment chemicals, antiscalants/CIP, and membrane replacement intervals.
- ✓ Brine pathway choice. Transitioning from discharge to MLD/ZLD with resource recovery reduces marine salinity loadings and ecotoxicity while converting waste to saleable salts.
- ✓ Compromise transparency. At high recovery, SEC and cleaning frequency can increase. The environmental benefit of lower brine volumes must be balanced against chemical and energy penalties.
- ✓ System boundary clarity. Co-product credits from recovered minerals are applied conservatively to avoid overstating benefits. Uncertainty is handled through sensitivity ranges.

9.1.6.3 Economic

Levelized water cost (LWC) is most sensitive to SEC and capacity factor; brine-product revenues improve downside risk but require assured offtake and quality compliance.

9.1.6.3.1 Cost drivers and sensitivities.

- ✓ SEC dominates OPEX. ERDs and set-point optimization are first-order controls.
- ✓ Capacity factor governs fixed-cost dilution. Hybrid RE + storage flattens intermittency penalties.
- ✓ Chemicals and cleaning scale with aggressive recovery. Optimal recovery is economic as well as technical.
- ✓ Membrane life/replacement materially affects LWC and must be reflected in spares and fouling management.
- ✓ Valorization revenues (NaCl, Mg, Ca, etc.) offset costs but hinge on market-grade specifications, logistics, and price volatility. Business cases should treat them as risk-reduction, not as base revenues.

9.4 Policy

Full-scale deployment hinges on discharge permitting, product-grade standards for recovered salts, and RE/REC incentives that align private economics with public environmental goals.

Enablers and constraints.

- ✓ Permitting and monitoring. Clear pathways for MLD/ZLD compliance and continuous monitoring (salinity, metals, ecotox) reduce approval risk.
- ✓ Product standards and market access. Adoption of harmonized specifications (e.g., industrial NaCl, Mg compounds) unlocks offtake and finance. QA/QC must be embedded in plant design.
- ✓ Energy policy alignment. Access to renewable PPAs, REC/green credits, and time-of-use tariffs is decisive for cost-competitiveness.
- ✓ Data transparency. Reporting on SEC, brine conversion rates, and environmental KPIs underpins social license and policy support.

9.2 Alignment with Sustainable Development Goals and Global Frameworks

9.2.1 Contributions to SDG 6 - Clean Water and Sanitation

This research is fundamentally aligned with the United Nations Sustainable Development Goal 6, which calls for universal and sustainable access to clean water and sanitation. By providing a technological solution to produce fresh water from an abundant source of seawater using sustainable energy, the work directly addresses the target of increasing safe water supply for water-scarce regions. Notably, SDG 6 highlights improving water quality and increasing water-use efficiency, which includes strategies such as water reuse and desalination under sustainable conditions [290]. The 2030 Agenda for Sustainable Development explicitly mentions international support for desalination and efficient water use technologies as a means to achieve SDG 6 [290]. This study contributes to the field by demonstrating a desalination approach that prioritizes environmental responsibility through the integration of zero-liquid discharge (ZLD) and renewable energy, thereby supporting long-term sustainability. It offers a pathway for coastal and island communities that lack fresh water to obtain a drought-proof supply without compromising the environment. This is particularly relevant as over 2 billion people today still lack sufficient access to safe water [288], and climate change is aggravating water shortages. By showing how renewable energy can power desalination, the research provides a model that developing countries could adopt with the support called for in SDG 6 (e.g. technology transfer and capacity building in desalination practices).

9.2.2 Contributions to SDG 7 - Affordable and Clean Energy

The project also aligns with SDG 7, which seeks to ensure access to affordable, reliable, and sustainable energy for all. Our renewable-powered system is a case of coupling water and energy solutions. It creates demand for renewable energy deployment (solar panels, wind turbines) in pursuit of water production. This integrated approach means progress on SDG 6 (water) can simultaneously drive progress on SDG 7 (renewables). In the thesis work, we recommended the energy system to be affordable and appropriate for the local context, considering options like community-shared solar farms or leveraging existing renewable micro-grids. By doing so, the desalination plant becomes a showcase for productive use of renewables, improving

the economics of renewable projects. The study highlights the interconnected nature of SDG 6 and SDG 7, often referred to as the water-energy nexus [288].

Clean energy desalination addresses that nexus by reducing the energy footprint per unit of water and eliminating fossil fuel reliance. In broader terms, each unit of renewable energy used for desalination is a unit not emitting CO₂, thus contributing to climate mitigation as well (SDG 13 on Climate Action). Our LCA result of 90% GHG reduction is a direct climate benefit [167], aligning with global decarbonization goals such as the Paris Agreement targets for mid-century.

9.2.3 Supporting SDG 12 - Responsible Consumption and Production and Circular Economy

The ZLD and brine valorization aspects of the research connect with SDG 12, which promotes sustainable consumption and production patterns. By achieving zero liquid waste and recovering materials, the research study represents “doing more and better with less”, less waste, more resource recovery. The turning of brine into useful products exemplifies moving towards a circular economy in the water sector, where outputs are recycled rather than discarded. This is increasingly reflected in policy frameworks such as the European Union’s circular economy policies which encourage industries including desalination to minimize waste and find value in their waste streams [285]. Our work provides a concrete example of how a desalination plant can be designed as a closed-loop system, producing clean water and saleable salts, with minimal emissions or discharge.

This approach could be included in sustainability standards and guidelines for desalination in the future. Additionally, by responsibly managing and reusing the brine, the research addresses the SDG 12 target of environmentally sound management of chemicals and wastes. We demonstrate that even the chemicals used in desalination like acids and antiscalants do not end up in the environment but are part of internal recovery loops or properly neutralized in solid waste.

9.2.4 Contribution to SDG 13 - Climate Action

This thesis supports Sustainable Development Goal 13 by addressing the climate impact of conventional seawater desalination systems. Traditional reverse osmosis (RO) plants rely heavily on fossil fuels, contributing to greenhouse gas (GHG) emissions and accelerating climate change. In contrast, this research demonstrates the technical feasibility and environmental benefits of powering SWRO plants with renewable energy, specifically solar photovoltaics. By replacing grid-based or diesel-powered energy sources with clean energy, the proposed system significantly reduces carbon emissions associated with freshwater production. Life Cycle Assessment (LCA) results confirm that the renewable-powered configuration achieves over 90% reduction in GHG emissions compared to conventional systems. This transition directly contributes to national and global decarbonization targets.

Furthermore, the system's zero-liquid discharge (ZLD) design eliminates brine discharge into marine environments, preventing secondary climate-related impacts such as ocean acidification and ecosystem disruption. The recovery and reuse of minerals from brine also support circular resource use, reducing the need for energy-intensive primary extraction of salts and metals.

In addition, the thesis outlines practical strategies for deploying climate-resilient water infrastructure in regions vulnerable to both water scarcity and energy insecurity. By offering a replicable model for off-grid, low-emission desalination, the work provides actionable pathways for climate adaptation and mitigation which are core objectives of SDG 13.

9.2.5 Alignment with SDG 14 - Life Below Water

Avoiding brine discharge contributes to SDG 14, which is to conserve and sustainably use the oceans and marine resources. One of the often-raised concerns about desalination is its impact on marine life due to brine outfalls. By achieving ZLD, our system eliminates this impact, thus supporting the conservation of marine ecosystems. In sensitive coastal zones, such a technology would be particularly valuable. It shows that desalination can be pursued in harmony with marine conservation objectives, which is a critical consideration as more regions look to desalination for water security.

There is also a potential co-benefit: in some designs, the solid salt byproduct could be used in controlled applications like winter road de-icing in cold countries, indirectly reducing the need to extract salt from marine sources elsewhere.

9.2.6 Global Sustainability Frameworks and Initiatives

Beyond the SDGs, the research is in line with other global frameworks and calls to action. The UN and various international agencies have called for innovative solutions to address the water-energy nexus in a sustainable manner. For instance, UN Water's strategies and conferences have emphasized the need for integrating renewable energy in water provision. Our project answers that call by providing a tested solution. It also resonates with the concept of "Water Security in an era of Climate Change". Many countries' climate adaptation plans now include desalination as a measure to cope with drought, but they emphasize it must be done sustainably. The outcomes of this study give policymakers and planners a concrete example of what sustainable desalination can look like in practice. Governments aiming for carbon neutrality will find this approach attractive since it adds virtually no net emissions while solving water scarcity.

Moreover, initiatives such as the "Water-Energy-Food Nexus" approach advocated by the World Economic Forum and others could integrate our results. For example, a solar-ZLD desalination plant could provide irrigation water (food production) using renewable energy (clean energy production) and do so with no waste (protecting environment) hitting multiple nexus points. Our alignment with sustainability frameworks is also evident in how the research addresses just transition and equity by focusing on small to medium scale, the solutions are applicable to remote and underserved communities, not just wealthy urban areas. This democratization of technology speaks to the "Leave No One Behind" principle of the 2030 Agenda.

In conclusion, this doctoral research is well-aligned with and supportive of global sustainability goals. It advances SDG 6 and SDG 7 by providing a model for clean water through clean energy, supports SDG 12 and circular economy by eliminating waste, helps protect life below water (SDG 14) by avoiding marine pollution, and contributes to climate action (SDG 13) through emission reductions. By situating the

technical results in this larger context, we underline the relevance and importance of renewable-powered ZLD desalination as part of the toolkit for sustainable development.

CHAPTER 10: Conclusion

This final chapter extracts the overall conclusions of the research and outlines recommendations and implications for various stakeholders. The study has demonstrated that renewable-powered, zero-liquid-discharge seawater desalination is not only technically feasible but can be environmentally and economically advantageous when designed thoughtfully. Below, we present clear recommendations for practitioners and designers, discuss policy implications for governments and agencies, summarize the practical contributions of this work, and suggest directions for future research.

10.1 Recommendations for Practitioners and Plant Designers

The practical deployment of renewable-powered, zero-liquid-discharge (ZLD) desalination systems depends not only on technical feasibility but also on informed design and operational decisions. This section outlines key understandings from the research into actionable guidance for engineers, plant designers, and operators. The recommendations focus on integrating renewable energy sources, optimizing system performance under variable conditions, and incorporating resource recovery processes. By translating research findings into practical strategies, this section aims to support more sustainable, cost-effective, and resilient desalination installations.

10.1.1 Integrate Energy Recovery and Efficient Design

Practitioners designing small or medium desalination plants should incorporate advanced energy recovery devices and optimize process conditions to minimize energy use. As shown in this research, high-efficiency pumps, isobaric energy recovery exchangers, and well-planned pressure staging can reduce energy consumption significantly. Designers should aim for specific energy consumption figures on par with or better than conventional plants (3 kWh/m³ for RO) even when pushing to high recoveries. Achieving such efficiency is key to making renewable-powered desalination viable and cost-effective.

10.1.2 Incorporate Renewable Energy with Reliability Measures

It is recommended to power desalination systems with locally available renewable energy (solar PV, wind, or solar thermal) to the maximum extent possible, thereby reducing operational costs and emissions. However, because desalination units prefer steady operation, designers should include reliability measures such as battery storage or backup generators and smart controls. For example, incorporating a battery sized to handle short-term fluctuations or a thermal storage for solar heat can ensure continuous water production during intermittent renewable supply. Smooth ramp-up and ramp-down protocols must be programmed into control systems to protect membranes and equipment during power variability. These measures will help water plant operators maintain steady output and water quality even as renewable input varies [288].

10.1.3 Modular and Scalable Implementation

Water managers and engineers should adopt a modular design approach for scalability. Based on our results, using multiple smaller RO units in parallel (rather than a single large unit) provides flexibility to adjust to demand and perform maintenance without total shutdown. Such modular systems can be added or removed to scale capacity and can be individually paired with modular renewable units e.g., PV arrays or wind turbines. This approach was shown to be effective for scaling the system and aligns with the trend towards distributed desalination networks [284]. Practically, a containerized desalination module with pre-integrated solar power and battery could be replicated in different locales, simplifying deployment and reducing custom engineering for each site.

10.1.4 Implement Brine Management and Resource Recovery

Plant designers are strongly encouraged to include brine minimization and valorization processes from the outset. Rather than designing desalination with a traditional disposal pond or outfall, incorporate a ZLD stage such as a brine concentrator or crystallizer. Depending on context, consider technologies like secondary RO/Electrodialysis for concentrating brine and then thermal crystallization or Eutectic Freeze Crystallization for final salt extraction. The recommendation is to analyze the local market for salts or minerals and tailor the brine recovery accordingly. For

example, if industrial salt is in demand, design the crystallizer to produce NaCl crystals of marketable quality. Our research demonstrates that this not only eliminates waste but can offset operational costs (e.g., by selling or reusing the recovered salt and minerals). By planning for brine valorization, practitioners will future-proof the plant against tightening disposal regulations and create potential revenue streams [287].

10.1.5 Focus on Robustness and Maintainability

For practical field operation, especially in remote or developing regions, robustness and ease of maintenance are paramount. We recommend choosing corrosion-resistant materials for all equipment in contact with high salinity (duplex/super-duplex stainless steels, engineering plastics, or appropriate coatings) to ensure longevity. Pretreatment systems (filtration, anti-scalant dosing) should be designed to handle variable feedwater quality and protect the main desalination units. Additionally, designers should implement user-friendly monitoring systems, for instance, simple graphical interfaces that show when cleaning is needed or when renewable input is dropping. Including remote monitoring capability is also advisable so that off-site experts can assist local operators. The experience from our study showed that investing in automation e.g., automated flushing of membranes when power dips, self-cleaning filters pays off by reducing downtime and skill requirements. Therefore, practitioners should not shy away from integrating smart features and possibly AI/ANN-based predictive tools to enhance reliability.

10.1.6 Water Quality and Post-Treatment

Ensure that adequate post-treatment is included to meet drinking water or process water standards, as applicable. High-recovery desalination can produce water that is very low in minerals and slightly more difficult to stabilize. We recommend adding remineralization by blending with a small amount of raw water or using calcite contactors to adjust hardness and alkalinity of the product water for corrosion control in distribution networks. Also, UV or chlorine disinfection should be part of the design to guarantee microbiological safety. These measures are standard but worth emphasizing, as they are critical for practitioner acceptance of desalinated water in municipal supply.

By following these recommendations, plant designers and water managers can leverage the results of this research to implement renewable-powered ZLD desalination systems that are efficient, resilient, and tailored to local needs. The overall advice is to take a rounded approach of treat energy supply, desalination process, and brine management as an integrated whole. Such an approach yields a system optimized for sustainability and practicality.

10.2 Policy Implications for Governments and Regulators

The outcomes of this research carry several implications for policy-makers, environmental regulators, and development agencies:

10.2.1 Encourage Renewable Energy Integration through Policy Incentives

Governments should create incentives and supportive policies for coupling renewable energy with desalination projects. This could include capital subsidies or tax credits for desalination plants that install renewable capacity, feed-in tariff arrangements for excess power, or concessional financing through development banks for off-grid renewable desalination in rural areas. By lowering the financial barriers, policies can accelerate the adoption of the sustainable model demonstrated in this research. Additionally, integrating desalination into national renewable energy targets or water security strategies could ensure interdisciplinary coordination between energy and water ministries working hand in hand. For instance, some countries now require new desalination tenders to evaluate a renewable power option, a practice that should be expanded.

10.2.2 Implement Strict Environmental Regulations with Pathways to Compliance

Environmental regulators are encouraged to update guidelines on brine disposal and emissions for desalination plants. Stricter limits on brine discharge salinity and composition e.g., limits on discharge volume relative to intake, or requiring dilution to near ambient salinity would push the industry toward considering ZLD or minimal liquid discharge solutions. To support this, regulators can provide a clear pathway or phased approach. For example, a policy might state that by a certain year, all plants above a certain capacity must recover at least 50% of their brine, moving towards 100%

recovery later. Such regulations are beginning to emerge, the European Union's Water Framework Directive has started enforcing more stringent controls on desalination brine, and regions like the Middle East and China have articulated ZLD goals in industrial water use [287]. Policymakers should draw on these examples and signal to the industry that zero-pollution is the eventual requirement. Importantly, alongside mandates, governments should fund R&D and pilot programs for brine mining technologies possibly through public-private partnerships to help develop cost-effective compliance solutions.

10.2.3 Facilitate Knowledge Transfer and Capacity Building

Development agencies and governments in water-scarce countries should treat renewable desalination as a viable option for achieving water security and allocate resources to build local capacity in this area. This includes training programs for engineers and technicians on the design, operation, and maintenance of renewable-powered desalination systems. The UN 2030 Agenda explicitly calls for international cooperation in desalination training and technology for developing countries [290]. Agencies like UNDP, UNICEF, or regional development banks could incorporate such training into water and sanitation projects. Supporting local manufacturing of components like solar panels, pumps, membranes could also be a strategic policy to reduce costs and create jobs, making the solution more self-sustaining.

10.2.4 Incorporate Desalination into National Water Plans with Sustainability Criteria

Policymakers should include desalination in their national water resource management plans as a strategic supply option, but with clear sustainability criteria. That means any public-funded desalination infrastructure should be evaluated not just on immediate cost and output, but also on its energy source (preference for renewables), carbon footprint, and waste management approach. By adopting evaluation frameworks that value externalities like carbon pricing or penalties for brine discharge, governments can make sustainable desalination options more competitive. In coastal cities planning new desalination plants, requiring an assessment of renewable energy feasibility and a plan for brine handling as part of the permitting process would align with this research's conclusions.

10.2.5 Encourage Circular Economy and Industrial Cooperation

Regulators and local governments can facilitate partnerships that use brine outputs beneficially. For example, policies could encourage co-location of desalination plants with industries that can utilize the brine or its derived products such as chlor-alkali plants, salt manufacturers, or aquaculture facilities for saline species. By viewing brine as a feedstock, regulations might allow easier permission for transporting brine between facilities or provide subsidies for companies that use recovered minerals. Some regions are already exploring such synergies. Saudi Arabia's Vision 2030 supports investments in brine mining ventures, as noted [287]. Government support in the form of funding pilot projects and creating market frameworks for recovered minerals (ensuring there is a buying market, perhaps through government procurement of recovered salt for various activities, etc.) could kickstart the brine valorization industry.

10.2.6 Monitor and Share Performance Data

As renewable ZLD desalination projects roll out, it is important for regulatory bodies and international organizations to monitor their performance and share data transparently. This research can be a reference point, but real-world long-term data will help refine policies. Governments could require periodic reporting of energy consumption and brine recovery efficiency from desalination operators. Such data collection will inform better standards and highlight success stories or areas needing improvement. International forums like the International Desalination Association and IRENA should be used to disseminate best practices gleaned from studies like ours. In summary, the policy implication is that governments and regulators have a crucial role in scaling up sustainable desalination solutions. By setting the right incentives and regulations, basically "raising the bar" for desalination to be green and low-waste, they can guide the sector toward the approaches validated by this research. The technology is ready or within reach, policy can ensure that business-as-usual desalination transforms into renewable-powered, zero-discharge desalination over the coming decades, in line with global sustainability commitments.

10.3 Contributions of the Research

This doctoral research makes several notable contributions to both the scientific body of knowledge and practical engineering of sustainable desalination systems.

10.3.1 Complete System Integration

The study provides a rounded integration of renewable energy, advanced desalination process, and waste elimination in one system. While previous works have examined pieces of this puzzle with some focusing on solar desalination, others on zero liquid discharge techniques, etc., this research combined them and addressed the interactions between them. This integrated approach yields a blueprint for a self-sufficient desalination plant that can serve as a model for future developments. The complete analysis (technical, environmental, economic) ensures that the solution is balanced in all respects, which is a contribution beyond the sum of individual optimizations.

10.3.2 Technical Innovation and Validation

On a technical level, the project advanced the understanding of operating desalination processes under extreme recovery and variable power conditions. It contributed experimental validation data for high-recovery RO and membrane distillation processes powered by renewables, including performance metrics on recovery rates, energy use, and water quality achieved. These data fill a gap in literature concerning real-world behavior of ZLD desalination systems at smaller scales. The successful demonstration of an ANN-based control optimization for desalination is another innovation; it shows how modern AI tools can be practically applied to improve water treatment processes, potentially inspiring further adoption of machine learning in plant operations.

10.3.3 Environmental and LCA Contribution

The LCA performed as part of this work is among the few that encompass a full ZLD desalination system with renewable energy. It contributes to academic literature by quantifying the life-cycle benefits and compromise of such systems. The result that renewable desalination reduces GHG emissions by 90% while highlighting new thematic areas (chemicals, materials) provides a significant perspective that can inform

other researchers and practitioners conducting sustainability assessments. It adds to the evidence base that desalination, often criticized for its carbon and environmental footprint, can be transformed into an environmentally friendly solution if approached correctly.

10.3.4 ANN – LCA Integration

The integration of Artificial Neural Networks (ANN) with Life Cycle Assessment (LCA) presented in this research represents a methodological advancement beyond conventional desalination assessment frameworks. While previous studies have applied LCA and data-driven models independently, few have achieved a quantitative coupling between predictive machine learning models and environmental impact quantification. This thesis bridges that gap by developing a dynamic ANN–LCA coupling that allows operational parameters such as pressure, salinity, and temperature predicted through ANN to directly modify life cycle inventory (LCI) inputs within SimaPro's ReCiPe 2016 model.

Unlike static LCAs that assume fixed process efficiencies, this integration supports real-time environmental forecasting and sensitivity testing, enabling recalculation of impact categories (Human Health, Ecosystem, Resource Scarcity) under variable energy and process conditions. The result is a system capable of scenario-based sustainability optimization, marking a significant step toward data-driven, adaptive LCA frameworks in desalination engineering.

Furthermore, the research demonstrates high predictive reliability ($R^2 = 0.93 - 0.96$, $RMSE \leq 1.0$) validated through cross-fold testing, providing a replicable computational structure that can be extended to other energy-intensive water systems. This methodological contribution addresses a critical gap in current literature, establishing a hybrid modeling pathway that merges operational intelligence (ANN) with environmental accountability (LCA).

10.3.5 Brine Valorization Demonstration

A significant practical contribution is demonstrating that brine valorization is achievable and beneficial at the scale considered. The research took brine management from concept to action by actually recovering salt and precipitating minerals in tests. It

provides a class of “proof of concept” that even a relatively small plant can implement with efficient resource recovery. The documented methods and results (e.g., quality of salt produced, percentage of magnesium recovered) serve as a reference for engineers who might attempt similar schemes. This clarifies brine mining and encourages moving from theoretical potential to practical implementation. By calculating the potential economic offsets, the research gives decision-makers tangible numbers to consider when evaluating ZLD investments.

10.3.6 Guidelines for Deployment

Through the lessons learned and the recommendations formulated, the research offers practical guidelines for designing and deploying sustainable desalination systems. These guidelines, as outlined above for practitioners, are a contribution to the field in that they translate research results into actionable advice. They cover aspects from design (material selection, modularity) to operation (maintenance, control strategies) to integration (sizing renewables, adding storage). In essence, the thesis can act as a handbook or case study for engineers and project planners aiming to implement similar projects. The real-world orientation of the work means its contributions are readily transferable to industry and development projects.

10.3.7 Strategic Insight for Water Management

At a higher level, this research contributes to the strategic discourse on water security. It provides evidence supporting the viability of decentralized, renewable-based desalination as a supplement or alternative to traditional water supply methods. This can influence how water agencies plan infrastructure. The contribution shows that we do not always need to build giant plants with heavy grid dependence, smaller, cleaner installations can collectively make an impact. It also reinforces the concept of water supply diversification, adding sustainable desalination into the mix to build resilience against drought and climate variability.

10.3.8 Contribution of Research Summary

In summary, the research contributes a validated example of sustainable desalination in practice, enriches the academic understanding of such systems through data and analysis, and offers concrete know-how that can be used by others in the field. The

knowledge generated extends from theory (modeling, optimization, LCA) to practice (engineering design and operational experience), which is a strong outcome for a doctoral project aimed at real-world impact. These quantitative results have been consolidated below to ensure that our conclusion not only synthesizes conceptual insights but also demonstrates measurable performance improvements across all analytical dimensions.

Energy savings: Integration of solar power systems achieved an average energy reduction of 32–38%, decreasing specific energy consumption from 4.9 to 3.1 kWh/m³ under optimized feed-pressure control conditions.

Recovery performance: Process optimization improved the water recovery rate from 43% to 54%, with corresponding reductions in brine discharge volumes by approximately 21% relative to the baseline operation.

ANN model accuracy: The predictive model demonstrated a high degree of reliability with R^2 values ranging from 0.93 to 0.96, a mean RMSE of 0.13–1.0, and a 95% prediction interval (PI_{95}) coverage exceeding 90%, validating its robustness for operational forecasting.

Environmental and economic gains: Life Cycle Assessment (LCA) revealed a 75% reduction in carbon footprint, while the techno-economic model showed a net LCOF of USD 0.72/m³, representing a 33% cost reduction compared with conventional SWRO.

10.3.8.1 Unified Systems Framework

The unified systems framework establishes an integrated connection between operational optimization, ANN predictive modelling, environmental life-cycle impacts, and valorization economics, presenting them as interdependent components of a single, data-driven sustainability model for renewable-powered desalination.

10.3.8.2 Operational Optimization - ANN Modelling

Operational data from feed pressure, temperature, and salinity served as direct inputs for ANN training, establishing predictive relationships that quantify how system-level

adjustments affect permeate TDS and energy demand. This computational layer enabled dynamic forecasting of performance across varying renewable energy profiles.

10.3.8.3 ANN Modelling - LCA Impacts

The ANN outputs were coupled with the LCA inventory to generate real-time environmental impact updates. For example, ANN-derived energy predictions were mapped to ReCiPe 2016 impact categories, demonstrating that reducing energy intensity through optimization resulted in a 75% reduction in carbon footprint and a significant decline in resource scarcity scores.

10.3.8.4 LCA - Valorization Economics

The environmental improvements derived from ANN-optimized operations were linked to the techno-economic model. Reduced energy and chemical consumption translated to lower OPEX, while resource recovery, NaCl, Mg(OH)₂, Br₂ offset environmental costs with measurable economic returns reflected in the net LCOF reduction from USD 1.08/m³ to USD 0.72/m³.

10.3.8.5 Integrated Systems Perspective

The conclusion presents this integration as a closed feedback loop, where ANN-based operational control informs environmental performance, and both influence economic viability. This systems-level synthesis reinforces that energy optimization, environmental impact mitigation, and valorization profitability are interdependent, not isolated outcomes.

10.4 Future Research Directions

While this research has achieved its objectives and demonstrated a functional solution, it also opened up several questions and areas that merit further investigation. The following are suggested directions for future research to build upon and extend the results of this work:

10.4.1 Long-term Performance and Reliability Studies

Future research should focus on the long-term operation of renewable-powered ZLD desalination systems. This includes examining membrane longevity under intermittent operation and high salinity stress, potential degradation of solar panels or other renewable components in harsh (marine) environments, and fouling/scaling trends over time in a ZLD process. A long-duration pilot spanning multiple years and seasons would provide valuable data on reliability and maintenance needs. It would also allow study of how seasonal variations e.g., monsoons, winter low sun affect the water-energy system performance and what design twists or suggestion can mitigate any issues.

10.4.2 Advanced Energy Storage and Grid Integration

Building on the insight that energy storage improves system reliability, research could explore advanced storage solutions tailored for desalination. One idea is to investigate the use of thermal energy storage more deeply, for instance, storing excess solar heat in phase change materials to drive a thermal desalination/crystallizer at night. Another is exploring hydrogen as an energy storage medium, excess renewable power could run an electrolyzer, and the hydrogen stored could later power a fuel cell or generator for the desalination plant. Future studies might conduct techno-economic assessments of these options or even demonstrate a hydrogen-coupled desalination prototype. Additionally, for grid-connected scenarios, research on smart grid integration is pertinent. How a desalination plant can dynamically respond to grid signals e.g., consuming more power when renewables are abundant and less when they are scarce to act as a flexible load supporting overall grid stability.

10.4.3 Optimization of Brine Valorization Pathways

There is significant scope to advance the brine mining aspect. Future research can delve into selective recovery of valuable elements such as lithium, rubidium, or scandium present in minute concentrations. This might involve developing new selective sorbents or membrane processes that target these ions. For example, ion-specific electrochemical methods or nanoporous materials could be studied for lithium extraction from desalination brine, leveraging on the growing interest in lithium recovery for battery supply [285]. Another avenue is improving energy efficiency of

crystallization. Investigate processes like vacuum-assisted crystallizers, or further optimizing Eutectic Freeze Crystallization, perhaps hybridizing it with conventional methods. Pilot-scale trials of these advanced brine treatment methods would help determine their practicality and scaling issues. As noted in a recent review, hybrid membrane-thermal systems have shown promise in cutting energy use for ZLD by a significant margin [285]. Researching these hybrids e.g, combining forward osmosis or high-pressure RO with crystallizers could yield next-generation ZLD systems.

10.4.4 Materials and Membrane Development

Pushing desalination to extreme recoveries and coupling it with renewables raises new demands on materials. Future work should consider developing or testing membranes that are more resilient to high salinities and frequent on-off cycles. This could include novel coatings that resist scaling or graphene oxide/polyamide composite membranes tailored for variable pressure operation. Likewise, anti-scaling or anti-fouling materials for heat exchangers and crystallizer surfaces would be valuable. Materials science research in this domain can directly increase the viability of ZLD systems by reducing downtime for cleaning. Another specific suggestion is to develop low-cost, low-carbon-footprint construction materials for desalination plants, for example, using recycled plastics or composite materials for tanks and piping to further reduce the embodied energy and cost.

10.4.5 Economic Modeling and Scaling Studies

While this research touched on economics, more broad economic analysis, including externalities, financing models, and market mechanisms, would strengthen the case for these systems. Future research could model different scenarios e.g., carbon tax scenarios, varying renewable energy prices, mineral prices to see under what conditions renewable ZLD desalination becomes the most attractive option. Also, performing scale-up studies to determine the optimal scale or modular size for cost efficiency could guide deployment strategies, maybe there is an ideal modular size that balances economies of scale with the flexibility of distributed systems. Engaging in detailed cost-benefit comparisons between approaches, for example, comparing a centralized fossil-powered plant with brine disposal against distributed renewable ZLD

units under future price projections would be highly informative for policy and investment decisions.

10.4.6 Water Quality and New Applications

Future research might explore broadening the applications of the core technology. One angle is producing not just potable water, but ultra-pure water for industries using the ZLD process, since the multi-stage system yields very low TDS water. Investigating any additional treatment needed to meet industrial specifications for semiconductors or pharmaceuticals could open up new value streams. Conversely, research could also look at using the concentrated brine or the recovered salts in innovative ways. For example, the brine concentrator could potentially be coupled with a downstream process such as chlor-alkali production, enabling on-site generation of chlorine and caustic soda through electrolysis, wherein brine is split to produce hydrogen (H_2) and chlorine (Cl_2), as referenced in recent literature by [285]. This kind of integration would turn the desalination plant into a multi-product chemical plant and might be economically synergistic. Experimentation and feasibility studies on such integrative approaches would be novel.

10.4.7 Social and Environmental Impact Studies

As the technology moves forward, it is important to research the social acceptance and environmental co-benefits/impacts in real communities. Future work could involve pilot deployments in communities, followed by studying the social adoption, training needs, and any cultural factors in water reuse or consumption of desalinated water. From an environmental standpoint, the elimination of brine discharge is anticipated to yield positive outcomes. However, extensive ecological assessments around pilot-scale ZLD installations such as monitoring the return of marine life in previously impacted discharge zones are necessary to provide empirical validation of these benefits. Furthermore, while the current study focused on greenhouse gas emissions and material recovery, future research should extend the life cycle assessment to include water and land footprint indicators to ensure a more robust evaluation of sustainability across all dimensions.

10.4.8 Policy and Governance Research

Finally, interdisciplinary research bridging engineering and policy would be beneficial. For example, studies could formulate policy frameworks or business that encourage the adoption of renewable desalination. Pilot projects could be accompanied by research on regulatory challenges and how to overcome them, such as simplifying the permitting for combined energy-water projects or creating micro-utilities for remote desalination. By identifying the non-technical bottlenecks and proposing solutions, researchers can help ensure that the technical advances translate into real-world impact.

10.5 Summary of Policy Roadmap: Near-Term Actions and Future Priorities

This section distills a pragmatic policy roadmap that separates near-term, plant-ready actions from longer-horizon research and regulatory priorities, enabling operators and policymakers to sequence investments and decisions with clarity and impact.

10.5.1 Immediate, Actionable Measures for 0 – 24 Months, Plant-Level and Utility-Level

1. Renewable electricity integration at existing SWRO plants: Execute market-based PPAs with firming through limited battery or demand-response, target $\geq 100\%$ RE share to deliver step-change GHG reductions with no process redesign.
2. Energy performance uplift: Fast-track ERD upgrades, HP-pump re-matching, and set-point optimization for NDP, recovery, flux guided by the validated ANN, expect SEC reductions within existing mechanical envelopes.
3. Predictive operations: Deploy the ANN + control-room dashboards for drift detection (ΔP , TDS, temperature) and condition-based CIP to reduce chemical use and unplanned downtime.
4. Low-regret brine measures: Implement end-of-pipe safeguards for mixing/diffusers, discharge timing and targeted pilots **for** MLD/ZLD unit operations e.g., selective ED, NF-RO hybrids sized to site constraints.
5. Transparency and compliance: Adopt LCA reporting process of cradle-to-gate+brine, and monthly KPI disclosure such as SEC, recovery, PI coverage, chemical intensity aligned to regulator templates.

6. Cost resilience: Hedge electricity price exposure through time-of-use scheduling and onsite PV where feasible, run sensitivity-tested OPEX plans using the Monte Carlo framework from Chapter 6.

10.5.2 Future Research & Policy Priorities for 2 years and above Ecosystem-Level

1. Mineral valorization pathways and markets: Develop standards, certification, and offtake contracts for salts such as NaCl/Mg/Ca/K, trace Li/B/Br from brine, fund multi-site pilots to validate product quality and life-cycle benefits before scaling.
2. Advanced membranes and hybrid trains: Support R&D on high-selectivity/low-fouling membranes, boron-targeted stages, and hybrid NF-RO-MD configurations to raise practical recovery while containing SEC and scaling risk.
3. Circularity and end-of-life policy: Establish EPR-style schemes for membrane take-back/recycling and create procurement preferences for recycled content and low-carbon consumables.
4. Accounting frameworks: Harmonize market-based against location-based GHG accounting for desalination PPAs. Publish regulatory guidance on co-product crediting to avoid double counting.
5. Grid-system integration: Incentivize flex-ready SWRO participation in ancillary services, curtailable loads to align plant dispatch with high-RE periods and reduce marginal emissions.
6. Data infrastructure: Fund open benchmark datasets (anonymized SCADA/Lab-QA) to accelerate trustworthy AI substitutes such as ANN and reproducible LCA inventories across climates and feed chemistries.

10.6 Framework for Integrating Mineral Recovery in Small SWRO Systems

A practical framework is proposed to help small-scale SWRO plants achieve zero-waste operation by adding mineral recovery units. The framework is designed to be modular, energy-efficient, and market-oriented:

10.6.1 Modular Design

The mineral recovery unit should be a plug-and-play module that can be added onto existing small desalination systems. This module could include a compact brine concentrator and crystallizer or an electrochemical recovery cell. A modular approach allows scalability, units can be added or removed based on plant capacity and, this approach makes it easier to retrofit older plants. All components should be skid-mounted and standardized for easy installation and integration.

10.6.2 Energy Matching

The recovery module must be tailored to match the available energy from renewables at the site. For example, if solar PV is the primary power source, the recovery processes such as heating for crystallization or powering electrodialysis should operate during peak solar supply or use stored energy off-peak. Energy-efficient technologies such as heat recovery from the RO process or solar thermal integration) should be employed to minimize additional power demand. This ensures the zero-waste ambition does not significantly raise the overall energy footprint of the plant.

10.6.3 Market Access for Extracted Salts/Metals

The framework emphasizes building connections between desalination operators and potential buyers of the recovered materials. For a small plant, this could mean coordinating with local industries or cooperatives. For example, recovered salt could be sold for agricultural or water-softening purpose, and extracted magnesium or calcium compounds could supply nearby factories. The framework suggests quality control measures to ensure the recovered products meet market specifications. By securing offtake agreements or local uses for these materials, small plants can generate extra income, which help to offset the costs of the recovery unit and making the zero-waste approach economically viable.

In closing, this doctoral research has demonstrated a viable pathway for renewable-energy powered, zero-waste seawater desalination. Each component from modeling and experiments to AI predictions and resource recovery contributed to a system that produces clean water efficiently while eliminating waste. The research results provide a blueprint for improving water recovery and sustainability in desalination projects

worldwide. By aligning technical innovation with sustainable development goals, this work offers both a practical solution for water-scarce regions and a strategic direction for industry and policymakers to accelerate the transition to clean water and clean energy at the same time.

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APPENDIX 1

Comparison of SWRO Brine Recovery vs. Conventional Mineral Production				
Mineral / Salt	Brine Recovery (SWRO) Brine	Conventional Sources	Energy KWh / Ton	CO ₂ / Environmental Impact
NaCl	Cost: 50–100 USD/t (est., purified salt) ¹ ; tech: multi-effect vacuum evaporation. (MVR) with mechanical vapor recompression ²	Cost: 45–124 USD/t (Industrial salt) ¹ ; tech: rock salt mining or solar evaporation ponds	180 kWh/t (electric) ³ (equivalent to 450 kWh/t thermal)	Low if waste heat or renewables used; conventional salt works emit CO ₂ from steam generation (e.g. MVR) ²
Mg (as MgO)	Cost: 460–1,126 USD/t MgO (brine-derived, via NaOH precipitation) ³ ; tech: chemical precipitation (Mg(OH) ₂ from brine), then calcination to MgO ⁴	Cost: 455 USD/t MgO (market price) ¹ ; tech: mining of magnesite/ dolomite ores, acid/basic leaching + calcination	1800 kWh/t (calcination of Mg(OH) ₂) ³	Significant calcination CO ₂ (process emissions from MgO production); brine route uses waste brine, reducing ore mining impacts ³
Ca (as CaCO₃)	Cost: not typically sold (often a precipitate/byproduct ⁴ as CaCO ₃ (e.g. by adding NaOH or NH ₃ to brine))	Cost: 200–300 USD/t CaCO ₃ (limestone market price) ¹ ; tech: limestone quarrying or processing of calcite/gypsum	Negligible (precipitation); conventional calcination (if producing CaO) 3–5 GJ/t (1000–1400 kWh)	Brine route uses carbonate precip; conventional limestone mining and kiln CO ₂ if producing lime
K (as KCl)	Cost: not yet commercial; brine K (bitterns) explored via Mg-K-PO ₄ and bittern treatments ⁵ ; tech: precipitation (e.g. MgNH ₄ PO ₄ ·6H ₂ O + KCl byproduct), so ⁶ ; not extraction, ED ⁶	Cost: 300–600 USD/t KCl (MOP) ⁷ ; tech: potash mining (underground or solution evaporation)	Variable (e.g. solar evaporation is 0); solution mining 200–500 kWh/t (pump energy)	Mining disturbs land; brine recovery could reduce potash mining impacts (not fully proven)
Br (Bromine)	Cost: not yet produced from SWRO brine (R&D); tech: oxidize Br ⁻ to Br ₂ and air-strip ⁸	Cost: 3,500–4,000 USD/t Br ₂ ; ⁹ tech: oxidative ⁹ and airstripping from high-Br ⁻ brines (e.g. Dead Sea)	Moderate (air stripping + distillation); historically few kWh/kg Br (anode Chlorine byproduct, heat of absorption)	Toxic emissions (Br ₂ , HCl); brine recovery can use waste streams (reduced volume) ⁸
Li	Cost: 2,180 USD/t Li (as Li ₂ CO ₃ eq.) ¹⁰ ; tech: membrane electrolysis or adsorbents (LLTO membrane, electro-swing) ¹¹	Cost: 3,000 – 6,000 USD/t Li ₂ CO ₃ ¹² ; tech: solar evaporation (Chile) or hard-rock spodumene (Australia)	1,100 kWh/t Li (1.1 kWh/kg Li via electrochemical cell ¹¹)	Brine extraction % the GHG of hardrock mining ¹³ (mining 18 tCO ₂ /t Li ₂ CO ₃ ¹⁴); brine route avoids lithium concentrates tailings
Rb	Cost: commercial extraction from brine not established; tech: selective adsorption (MnO ₂ columns) ¹⁵	Cost: 5–6 million USD/t pure Rb (kg-scale prices) \$3–8k/kg Rb compounds ¹⁶	Very low tonnage (negligible kWh)	Niche use; mining (pollucite) causes little volume; brine route would have minimal new impacts
Sr	Cost: not yet commercial from SWRO; tech: precipitation (SrCO ₃ by adding carbonate, or ion exchange)	Cost: 1,000–1,700 USD/t SrCO ₃ ¹⁷ ; tech: mining celestite (SrSO ₄) or as byproduct of Zn/Pb concentrates	Low (precipitation); conventional 30–100 kWh/t (crushing/ grinding)	Minor impact; both routes have modest footprint (precip vs mining)

B (as B₂O₃)	Cost: not yet recovered at scale from SWRO; tech: ion-exchange (UOP process) or solvent extraction	Cost ~ 900–1,250 USD/t (boric acid); ■ tech: evaporate saline lakes (borax, colemanite calcination)	Moderate (calcination 2–4 GJ/t)	Conventional borate mining uses large evaporation ponds (land use); brine recovery would use wastewater stream (lower land impact)

Notes: Costs are broadly indicative (recent market/technical estimates) and include only product recovery costs, excluding desalination plant costs **10, 12**. Energy values are for the specific extraction steps; **10, 12** desalination brine pre-concentration energy is additional. Brine-based recovery can reduce transport and land disturbance; CO₂ impacts depend on energy source (renewables can greatly lower brine-process emissions) **13, 2**

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APPENDIX 2

Ref No.	Journal/Venue	Study outcome (concise)	Research gaps (what's missing)
1	ASET (IEEE Conf., 2022)	High-level overview of thermal vs. membrane desalination and recent trends; positions RO as fastest-evolving with >99% salt rejection.	Lacks granular TEA/LCA and brine valorization routes; minimal coverage of RE-powered integration at plant scale.
3	ISRN Materials Science (2011)	Comparative review of RO and membrane distillation for groundwater desalination; highlights MD's niche for high-salinity feeds.	Limited economic benchmarking vs. modern ERDs/RO; no multi-criteria sustainability assessment.
4	Desalination and Water Treatment (2010)	Experimental VMD performance with flat-sheet membranes; reports flux trends and operational sensitivities.	Scale-up pathways, fouling control, and cost per m ³ not fully resolved.
5	Water Research (2009)	Seminal review on RO: sources, pretreatment, fouling, and contemporary challenges.	Outdated with respect to new membrane chemistries, ERDs, and RE coupling; no ZLD perspective.
6	Desalination (2008)	Survey of advances in seawater desalination across MSF/MED/RO; documents performance evolution.	Pre-2010 economics; limited treatment of environmental externalities and brine mining.
7	Water (MDPI, 2023)	Review of RE-powered membrane desalination configurations and field deployments.	Sparse standardized cost/availability data for RE + storage hybrids at >10,000 m ³ /d scale.
8	ASCE Book Chapter (2012)	Overview of membrane processes for desalination and environmental applications.	No unified decision framework linking water quality, energy, and discharge constraints.
13	Desalination (2008)	Meta-review of desalination cost literature; decomposes CAPEX/OPEX drivers.	Older price base; lacks dynamic modeling for energy volatility and carbon pricing.
22	Journal of Water Supply: AQUA (2010)	Asks whether seawater desalination is 'green'; evaluates environmental loads and mitigation.	No quantified cradle-to-grave LCA for ZLD/MLD pathways.
25	Journal of Environmental Management (2022)	Critical review of fouling, performance and cost across membrane desalination technologies.	Limited cross-plant benchmarking and uncertainty analysis for fouling-cost tradeoffs.
28	Desalination (2020)	TEA of solar-powered RO configurations; identifies LCOE/LWPC sensitivities to irradiance and storage.	Site-specificity hinders generalization; minimal empirical validation at utility scale.
34	Energy Reports (2022)	Optimal scheduling of co-generation and desalination to minimize energy cost and ramping.	Does not integrate brine valorization revenues or carbon cost signals.
36	Renewable & Sustainable Energy Reviews (2013)	Benchmarks energy use and cost of conventional vs. RE-powered desalination.	Pre-dates current PV/storage cost curves and high-efficiency ERDs.
37	Environmental Science & Pollution Research (2022)	Review of recent development in RE-powered membrane desalination.	Limited quantitative comparison of long-duration storage options for 24/7 reliability.
38	Energy Conversion & Management (2020)	Sizing and TEA for large-scale RO powered by hybrid RE; explores techno-enviro-economic feasibility.	Assumes idealized capacity factors; grid services and curtailment not monetized.
42	Journal of Environmental Management (2021)	State-of-the-art review of brine treatment toward MLD/ZLD and resource recovery; TEA snapshots.	Real-plant scale-ups and market integration for recovered products remain nascent.

45	Marine Pollution Bulletin (2020)	Synthesizes environmental impacts of desalination and brine treatment; mitigation options.	Scarce long-term ecological monitoring tied to specific discharge designs.
47	Energy Conversion & Management (2021)	Energetic/economic/environmental assessment of ZLD for brackish and seawater systems.	High CAPEX/OPEX uncertainties; limited pathways for monetizing by-products.
48	Science of the Total Environment (2019)	Comprehensive review of brine disposal and treatment technologies.	Comparative, site-specific decision tools (hydrodynamics + regulation + market) still lacking.
50	Desalination (2022)	Membrane-promoted crystallization enabling sustainable KCl production from concentrated brine.	Scale-up kinetics, impurity management, and continuous operation need validation.
51	Water Research (2020)	Hybrid FO-MD for textile wastewater concentration; performance and economic evaluation.	Techno-economic transferability to seawater brine contexts underexplored.
53	Journal of Cleaner Production (2018)	Screening and cost assessment strategies for end-of-pipe ZLD systems.	Dynamic process integration with upstream RO/ED and product valorization not addressed.
54	Water (MDPI, 2024)	Review advocating renewable-powered RO toward zero-waste desalination; synthesis of RE-RO-ZLD nexus.	Calls for validated business models linking energy arbitrage, grid services, and mineral revenues.
58	Frontiers in Marine Science (2022)	Review of brine characteristics and marine health impacts in the Persian/Arabian Gulf.	Geographic transferability and cumulative, multi-plant effects remain uncertain.
63	Int. J. Life Cycle Assessment (2005)	LCA of MSF, MED, RO; early cradle-to-gate benchmarks.	Outdated inventories and ERD efficiencies; excludes brine recovery benefits.
67	Desalination (2005)	LCA of desalination integrated with renewables; comparative impacts.	Limited modern RE/storage profiles; no circular-economy credits.
68	Membranes (2022)	LCA of hybrid NF desalination in Persian Gulf context.	End-of-life, brine mining credits, and biodiversity impacts not fully quantified.
69	Water Research (2014)	Methodological review on LCA for desalination; feasibility and reliability.	Standardization gaps in functional units, allocation, and background datasets.
70	Desalination (2019)	Country case study (Qatar) of lifecycle impacts of desalination.	Generalizability beyond gas-rich grids; missing ZLD/valorization scenarios.
71	Water (MDPI, 2021)	Comparison of desalination technologies using LCA + PESTLE + MCDM under RE sources.	Weighting subjectivity; limited empirical calibration with plant data.
72	ASME IMECE (2011)	Strategies for energy-efficient desalination and RE integration.	Lacks quantified, modernized performance for utility-scale deployments.
73	Water (MDPI, 2021)	Review of hybridized/desalination integrated with RO; catalogues configurations.	Few field-scale demonstrations with continuous operation and QC of products.
74	Desalination (2015)	Comparative LCA of end-of-life options for RO membranes.	Market pathways for recycled polymers and logistics at scale remain unclear.
75	Energy Conversion & Management (2022)	Cradle-to-grave LCA of membrane distillation systems for seawater; hotspots identified.	Benchmarking vs. modern RO with ERD and RE coupling not fully explored.

77	Computation (2023)	ANN for predictive optimization in membrane desalination; improved setpoint control.	Robustness under non-stationary fouling and domain shift; deployment at plant scale.
78	Desalination (2009)	ANN-based optimization for SWRO plant operation; early evidence of data-driven control.	Aging sensors/data quality; integration with MPC and uncertainty quantification.
117	Desalination (2019)	State-of-the-art RO review: membranes, pretreatment, energy, and operations.	Limited treatment of circular brine management and product valorization economics.
131	Energy Conversion & Management (2022)	LCA and cost of SWRO under different energy sources; quantifies enviro-economic tradeoffs.	Does not include revenue streams from resource recovery or REC/carbon credits.
132	Renewable Energy (2014)	LCA of SWRO powered by renewables; demonstrates potential impact reductions.	Older RE prices/capacity factors; minimal reliability modeling for 24/7 supply.