

**IMPROVEMENT ON SEAWATER REVERSE OSMOSIS
DESIGN INTEGRATED WITH SOLAR PV SYSTEM**

BY

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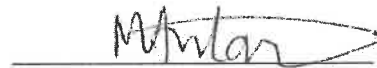
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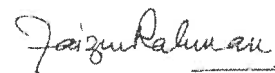
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Dedicate to My Parents, My Sisters, My Brothers

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	V
TABLE OF CONTENTS	VI
LIST OF TABLES.....	IX
LIST OF FIGURES.....	XI
LIST OF ABBREVIATIONS.....	XIII
ABSTRACT	XVIII
ملخص الرسالة	XX
CHAPTER 1 INTRODUCTION	1
1.1 Background	1
1.2 Desalination Technologies	3
1.3 Reverse Osmosis	5
1.4 Photovoltaic System (PVs) Powered RO Desalination	7
CHAPTER 2 LITERATURE REVIEW	9
2.1 Introduction	9
2.2 Reverse Osmosis Desalination System	9
2.3 Reverse osmosis System Powered by Photovoltaic System as Renewable Energy.....	23
2.4 Research Objectives	27
CHAPTER 3 METHODOLOGY	29
3.1 RO Modeling	29

3.1.1	Solution-Diffusion (Non-Porous) Model	31
3.1.2	Osmotic Pressure.....	33
3.1.3	Flow and Mass Balance	35
3.1.4	Concentration Polarization	37
3.1.5	Temperature Correction Factor and Pressure Drop	40
3.1.6	RO System Performance	41
3.1.7	RO System Discretization.....	42
3.1.8	RO System Assumption	43
3.1.9	Product Cost of Desalted Water for SWRO System	43
3.2	Photovoltaic PVs Modeling	45
3.2.1	Incident and Absorbed Radiation	46
3.2.2	Electrical Model for PVs System.....	48
CHAPTER 4 VALIDATION.....		50
4.1	Validation Against Literature Studies	50
4.1.1	Junghin. K, Seungkwan. H [27].....	50
4.1.2	Geraldes V, and Nuno E, [51]	53
4.1.3	Yawei. D et al [29].	56
4.2	Validation Against Software WAVA	58
CHAPTER 5 MATERIAL AND CONFIGURATION		62
5.1	SWRO System Configuration	63
5.2	Stand-Alone Photovoltaic System Configuration	68
CHAPTER 6 RESULTS AND DISCUSSION		72
6.1	Effect of Operating Parameters on SSP Performance.....	72
6.1.1	Average Water Flux and Recovery Ratio	72

6.1.2	Seawater Density	77
6.1.3	Eight Membranes Inside the Pressure Vessel	79
a.	Constant Permeate Flow Rate (Q_p).....	79
b.	Constant Avg Water Flux (J_w)	82
6.1.4	SSP Combined with Internally Staged Design (ISD).....	84
a.	SSP Combined with ISD Under Standard Seawater Condition	86
b.	SSP Combined with ISD Under Harsh Seawater Condition.....	91
6.1.5	Flux Distribution within Pressure Vessel for SSP-ISD Configuration.....	96
6.2	Sizing the PV _s system to Powered SWRO	99
6.2.1	Electrical Load Demand	101
6.2.2	Simulation and Optimization Result.....	102
6.3.	Unit Product Cost of desalted water for SSP-ISD configuration	105
CHAPTER 7 CONCLUSION		108
REFERENCES.....		111
VITAE		117

LIST OF TABLES

Table 1.1:	Desalination Process Applicability [3]	4
Table 4.1:	Comparison of permeate salinity and SEC obtained by thesis model against study [27]	51
Table 4.2:	FilmTec SW30HR-380 properties [53]	54
Table 4.3:	Case 1, validation at feed pressure 54.5 bar, inlet feed velocity 0.186 m/s, feed salinity 38 kg/m ³ (38,000 mg/L), 14 pressure vessels, and temperature 20 °C.....	55
Table 4.4:	Case 2, validation at feed pressure 63.4 bar, inlet feed velocity 0.178 m/s, feed salinity 38 kg/m ³ , 11 pressure vessels, and temperature 20 °C.....	56
Table 4.5:	Case 3, validation at feed pressure 71 bar, inlet feed velocity 0.192 m/s, feed salinity 38 kg/m ³ , 9 pressure vessels, and temperature 20 °C.....	56
Table 4.6:	Parameters for the RO Desalination Model [29]	57
Table 4.7:	Comparison of UPC obtained by thesis model against study [29]	57
Table 4.8:	Feed water input values for two cases	59
Table 5.1:	FilmTec Spiral-Wound Reverse Osmosis Membrane Characteristics [27, 53, 29, 62]	67
Table 5.2:	Parameters for the RO Desalination Model [27, 29, 46]	68
Table 5.3:	Specification of Canadian Solar Maxpower CS6U-340M module [55].....	69
Table 5.4:	Specification of Trojan SSIG 12 255 Battery [57]	71
Table 6.1:	Power consumption for 1 pressure vessel of SSP7 & Single pass (single stage)	76
Table 6.2:	Fixed design parameters used for Avg water flux & RR effect on SSP7 & Single pass (single stage) performance.....	77
Table 6.3:	Density effect on SSP7 performance	78
Table 6.4:	Fixed design parameters used for seawater density effect on SSP7 performance	78
Table 6.5:	SEC and permeate salinity value for the SSP RO design at different split for 7 & 8 membranes and at constant permeate flow rate 80 m ³ /day.....	82

Table 6.6:	SEC and permeate salinity value for the SSP RO design at the different split for 7 & 8 membranes and at constant Avg water flux rate 12.81 LMH	84
Table 6.7:	SSP performance under different ISD configurations for standard seawater conditions	87
Table 6.8:	Design parameters used with standard seawater conditions to evaluate SSP-ISD performance	89
Table 6.9:	Design parameters used with harsh seawater conditions to evaluate SSP-ISD performance	91
Table 6.10:	SSP performance under different ISD configurations for harsh seawater condition	93
Table 6.11:	Electric load worksheet calculation for 10,000 m ³ daily purified water....	102
Table 6.12:	Optimum configurations of PV _s panels, converter, and batteries for the nine SSP-ISD designs for Dhahran.....	104
Table 6.13:	Unit product cost of desalted water for SSP-ISD configuration for Dhahran	106

LIST OF FIGURES

Figure 1.1: Desalination process contribution globally [4].	4
Figure 1.2: Contaminant removal by RO membrane [3].	6
Figure 2.1: ERD classification [11].	11
Figure 2.2: ERDs configuration used in RO plants a Pelton wheel, b- Turbocharger, c- DWEER, and d- Pressure exchanger [11].	12
Figure 2.3: SEC as a function of membrane water permeability in different cases for SWRO [13]	14
Figure 2.4: SEC as a function of membrane water permeability in different cases for BWRO [13].	15
Figure 2.5: Single pass (Single stage) RO configuration [27].	17
Figure 2.6: Full Two-pass RO configuration [27].	18
Figure 2.7: Partial Two-pass RO configuration [27].	18
Figure 2.8: Split Partial Second Pass (SPSP) RO configuration	19
Figure 2.9: Internally staged design RO configuration [19].	20
Figure 2.10: Permeate flux distribution with different ISD configurations using Filmtec membrane at case one [31]	21
Figure 2.11: Schematic design of Split partial single-pass (SSP) [27].	23
Figure 2.12: Schematic design of a PV/RO system with concentrating mirrors [39]	26
Figure 3.1: Spiral-wound RO module from company Dupont water solution (Filmtec).	30
Figure 3.2: Diagram of a spiral-wound RO module.	30
Figure 3.3: Schematic of osmotic pressure prevent water flux [47].	34
Figure 3.4: Simple schematic of RO module [46].	35
Figure 3.5: Concentration profile under steady state condition [47].	37
Figure 3.6: One dimension discretize segment on rectangle flow channel [29]	43
Figure 4.1: Validation of SEC at different split ratios.	52
Figure 4.2: Validation of product quality at different feed salinity.	53
Figure 4.3: WAVE RO design software from Dow [52].	58

Figure 4.4: Validate Permeate quality (Cp) at each membrane case 1 and 2	60
Figure 4.5 : Validate Permeate flow (Qp) at each membrane case 1 and 2	61
Figure 5.1: A schematic diagram of the PV-SWRO system	62
Figure 5.2: Split partial single-pass configuration (SSP) [27]	63
Figure 5.3: Schematic design of single-pass split partial (SSP) [27]	64
Figure 5.4: Configuration of single pass (single stage) [27]	64
Figure 5.5: Configuration of a Split partial second pass (SPSP) [27]	65
Figure 5.6: ISD membranes combination inside pressure vessel [32]	66
Figure 5.7: Canadian Solar Maxpower CS6U-340M 340W [55].....	69
Figure 5.8: Trojan SSIG 12 255 Battery [57].....	71
Figure 6.1: SWRO performance for SSP7 and conventional single-pass system depending on average water flux and recovery ratio (RR)	74
Figure 6.2: SEC for the SSP RO design at the different split for 7 & 8 membranes and at constant permeate flow rate 80 m ³ /day	81
Figure 6.3: SEC for the SSP RO design at the different split for 7 & 8 membranes and at constant Avg water flux rate 12.81 LMH	83
Figure 6.4: SSP-ISD Performance under standard Seawater conditions with 12 average water flux and recovery ratio (RR) ranged from 35% to 45%.....	90
Figure 6.5: SSP-ISD Performance under harsh Seawater conditions with 12 average water flux and recovery ratio (RR) ranged from 35% to 45%.....	96
Figure 6.6: Flux distribution within Pressure Vessel under harsh Seawater conditions with 12 LMH total average water flux and 45% recovery ratio (RR)	99
Figure 6.7: Monthly average solar radiation and clearness index on the horizontal plane for Dhahran City	100
Figure 6.8: Monthly mean ambient temperature data for Dhahran City	100
Figure 6.9: Schematic diagram for, a) SSP-ISD 2 _{hr} 4 _{hf} 1 _i b) SSP-ISD 070.....	103
Figure 6.10: Optimization result for SSP-ISD 2 _{hr} 4 _{hf} 1 _i design.....	104
Figure 6.11: Optimization result for SSP-ISD 601 design	104
Figure 6.12: Monthly total electrical production by PV panels for SSP-ISD 2 _{hr} 4 _{hf} 1 _i design	105
Figure 6.13: Cost breakdown for the UPC	107

LIST OF ABBREVIATIONS

TDS	Total dissolved solids, mg/L
ppm	Part per million
RO	Reverse Osmosis
SWRO	Seawater reverse osmosis
PV _s	Photovoltaic
PV _{ro}	Pressure Vessel
WHO	World Health Organization
US EPA	United States Environmental Protection Agency
Å	Angstrom
SEC	Specific Energy Consumption, kWh/m ³
ERD	Energy Recovery Device
Q_f	Feed flow, m ³ /day
Q_p	Permeate flow, m ³ /day
Q_c	Concentration flow, m ³ /day
C_f	Feed Salinity concentration, mg/L
C_p	Permeate Salinity concentration, mg/L
C_c	Concentrate Salinity concentration, mg/L
RR	Recovery Ratio

Re_j	Salt Rejection percentage, %
HPP	High pressure pump power, kW
P_f	Feed pressure, bar
P_p	Permeate pressure, bar
P_d	Pressure drop, bar
TCF	Temperature correction factor
FF	Fouling factor
CPF	Concentration polarization factor
A_w	Membrane water permeability, L/m ² .h.bar
B_s	Salt permeability, m/h
π_f	Feed osmotic pressure, bar
π_p	Permeate Osmotic pressure, bar
J_w	Water flux (Solvent), L/m ² . h
J_s	Salt flux (solute), mg/m ² .h
A_m	Effective membrane area, m ²
FF	Fouling factor
k	Mass transfer coefficient, m/s
K	Friction factor correction parameter
D_s	Salt diffusivity m ² /s
Sh	Sherwood number
Re	Reynolds number
Sc	Schmidt number
d_H	Hydraulic diameter, m

μ	Viscosity, kg/m.s
ρ	Density, kg/m ³
v	Cross-flow velocity, m/s.
T_{sea}	Sea water temperature, °C
I	Incident radiation, W/m ²
I_T	Total radiation incident, W/m ²
I_b	Direct radiation, W/m ²
I_d	Diffuse radiation, W/m ²
β	Collector tilt angle, degree
ρ_g	Reflectance of Ground
R_b	Ratio of direct radiation to horizontal surface
$\emptyset$	Latitude, °N
δ	Declination angle, degree
ω	Average hour angle, degree
θ_1	Incidence angle, degree
I_{ET}	Extra-terrestrial radiation, W/m ²
G_{SC}	Solar constant, W/m ²
k_t	Clearness index
$(\tau\alpha)$	Transmittance-absorptance of PV
V_{mp}	Maximum power voltage, V
I_{mp}	Maximum power current, A
P_{mp}	Maximum power, kW
ζ_{mp}	Maximum power efficiency
a	Ideality factor

I_L	Light generate current, A
I_o	Diode reverse saturate current, A
R_s	Series resistance, Ω
R_{sh}	Shunt resistance, Ω
T_c	Cell temperature, $^{\circ}\text{C}$
S	Absorbed radiation, W/m^2
ref	Reference conditions
UPC	Unit product cost, $\$/\text{m}^3$
CC_{total}	Total capital cost for SWRO system, $\$/\text{year}$
OC_{total}	Total operation cost for SWRO system, $\$/\text{year}$
Ir	Interest rate, %
y	RO plant lifetime, year
CC_{SWIP}	Capital cost of the seawater intake, $\$$
CC_{hpp}	Capital cost of the pressure pumps, $\$$
CC_{ERD}	Capital cost of the energy recovery device, $\$$
CC_m	Capital cost of the membranes and pressure vessel, $\$$
C_m	Membrane price, $\$$
n_m	Number of membrane element inside the pressure vessel
n_{PV}	Number of pressure vessel
C_{PV}	Pressure vessel price, $\$$
OC_m	Operation cost for membrane replacement, $\$$
OC_e	Operation cost for energy, $\$$
OC_{insure}	Operation cost for insurance, $\$$
OC_{labor}	Operation cost for annual labor, $\$$

OC_{ch}	Operation cost for chemical supply, \$
OC_{main}	Operation cost for maintenance, \$
C_e	Electricity cost, \$/kWh
f_c	RO plant load factor
NPC	Net present cost, \$
LCOE	Levelized cost of energy, \$/kWh

ABSTRACT

Full Name : [Sohayb Omar Hamdi Badandi]
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Saudi Arabia is heavily reliant on desalination, which accounts for over 70% of the country's potable water system and is recognized as the largest seawater desalination countries worldwide. Among various desalination technologies, reverse osmosis (RO) has the lowest specific energy consumption, and further improvements in SWRO design can effectively reduce energy consumption or improve product water quality and hence the overall economics. This study utilizes MATLAB software to thoroughly investigate the recently innovated Split Partial Single-Pass (SSP) SWRO design, and the impact of various operating parameters and harsh seawater condition on the SSP Design. Moreover, a novel design combining SSP with Internal Staged Design (ISD) utilizing three types of membranes with different characteristics has been examined, resulting in a 1% increase in the optimal recovery ratio, a 6.6% improvement in water quality with SSP-ISD 313 configuration, and a 1.5% reduction in SEC with SSP-ISD_{2hr 4hf 1i} configuration. Additionally, the SSP-ISD configuration successfully alleviates flux distribution imbalances, mitigating fouling and scale formation.

Finally, HOMER simulation software has been utilized to determine the optimal size for a stand-alone PV system to power SWRO with a 10,000 m³/day product water capacity, resulting in a 8,942-kW PV array, along with 2,761-kW inverter, and 22,533 batteries. the

unit product cost (UPC) for SSP-ISD 2_{hr} 4_{hf} 1_i has the lowest value at 1.42 \$/m³ and it has annual saving amount \$2,700,000 instead of SSP-ISD 601, and \$700,000 as compared to standard SSP-ISD 070 design at 100,000 m³/day production capacity.

ملخص الرسالة

الاسم الكامل: صهيب عمر حمدي بدندي

عنوان الرسالة: تحسين في تصميم نظام التناضح العكسي لمياه البحر وربطها بنظام الطاقة الشمسية الكهروضوئية

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: مايو 2023

تتبع المملكة العربية السعودية بشكل كبير على تحلية مياه البحر، والتي تمثل أكثر من 70 ٪ من نظام المياه المحلاة في البلاد، وهي معترف بها كأكبر دول تحلية مياه البحر في جميع أنحاء العالم. من بين تقنيات تحلية المياه المختلفة، تتميز تقنية التناضح العكسي (RO) بأقل استهلاك محدد للطاقة، ويمكن أن تؤدي التحسينات المستمرة في تصميم نظام تحلية مياه البحر بالتناضح العكسي (SWRO) إلى تقليل استهلاك الطاقة بشكل فعال أو تحسين جودة المياه المنتجة (تقليل الملوحة) وبذلك التكلفة الكلية. تستخدم هذه الدراسة برنامج الماتلاب (MATLAB) لدراسة تحلية مياه البحر بالتناضح العكسي باستخدام نظام المرور الواحد مع تدوير جزء من المياه الناتجة إلى خط التغذية المبتكر مؤخرًا (SSP) في ظل معايير تشغيلية مختلفة وظروف مياه البحر شديدة الملوحة. علاوة على ذلك، تم فحص تصميم جديد يجمع بين نظام المرور الواحد مع تدوير جزء من المياه الناتجة إلى خط التغذية (SSP) والتصميم الداخلي المرحلي (ISD) باستخدام ثلاثة أنواع من الأغشية بخصائص مختلفة، مما أدى إلى 1٪ زيادة في نسبة الاسترداد الأمثل، وتقليل الملوحة بنسبة 6.6٪ باستخدام تكوين (SSP-ISD 313). وتخفيض الاستهلاك المحدد للطاقة بنسبة 1.5٪ مع تكوين (SSP-ISD2hr 4hf 1i). بالإضافة إلى ذلك، فإن التصميم الجديد (SSP-ISD) يوازن بنجاح في توزيع التدفق داخل الأغشية، مما يؤدي إلى تخفيف الترسبات والتكلسات على أسطح الأغشية.

أخيرًا، تم استخدام برنامج محاكاة (HOMER) لتحديد الحجم الأمثل لنظام الكهروضوئية لتشغيل نظام تحلية مياه البحر بشكل مستقل وبسعة إنتاجية 10,000 متر مكعب / يوم، مما أدى إلى تكوين ألواح كهروضوئية بسعة 8,942 كيلو واط، مع محول بسعة 2,761 كيلو واط، وعدد 22,533 بطارية. وحدة التكلفة لكل متر مكعب للتكوين-SSP (ISD2hr 4hf 1i) هي الأقل بقيمة $1.42 \text{ \$/m}^3$ وبتوفير سنوي 2.7 مليون دولار بدلا من التكوين SSP-ISD

(601) و 700,000 دولار بدلا من التكوين الأساسي (SSP-ISD 070) بوحدة إنتاج 100,000 متر

مكعب/يوم.

CHAPTER 1

INTRODUCTION

1.1 Background

Every day, more and more people require fresh water, and many places around the world are running out. One of the best ways to solve this problem is to get rid of the salt water. Seawater, which is found in the oceans and accounts for around 97% of the water on Earth. Approximately, 70% of the earth's freshwater is in the form of frozen water and the remaining 30% is found in groundwater, streams, and moisture. Despite the Large amount of the water in the world, less than 2.6% of the 1380 million km³ of water on the planet is potable water, which can be used with routine water treatment [1]. Desalination offers a solution to utilize the enormous amount of saline water resources known as seawater or brackish water.

In recent years, the desalination process has taken considerable steps in many dried regions, such as the Middle East. Over the past ten years, the cost of producing water has steadily decreased, extending its use.

As of now, more than 183 countries are using one of the desalination technologies. KSA and the UAE depend on water desalination for more than 70% of their fresh water systems. Based on the IDA yearbook [2], with a total installed production capacity of

around 88.9 million m³/day (23,485 million gal/day), there will be over 18,214 desalination plants operating by the end of 2019.

More than 50% of the world's inhabitants live near the seashores [3], and in several arid regions of the earth, like Australia, the Middle East, and North Africa, with over 75% of the population living along the coast. Hence, seawater desalination is a logical solution for sustainability and can meet the increasing demand for water in coastal locations. Additionally, it is projected that Brackish water desalination would rise in capacity, particularly for untapped brackish water in inland regions.

Recently, large-capacity desalination plants have become a trend in seawater desalination, which provide coastal towns all throughout the world with a constant increase in water supplies.

The salt content of water is often measured using total dissolved solids (TDS) in milligrams per liter (mg/L) or parts per million (ppm) units. Water with a maximum TDS value of 500 mg/L (500 ppm) has been approved as safe by both the World Health Organization (WHO) and the United States Environmental Protection Agency (US EPA) as potable (fresh) water under safe drinking water circumstances. Brackish water is defined as having a TDS concentration of at least 500 mg/L but not more than 15,000 mg/L. Seawater from the ocean is considered to be a natural water source if the TDS level is above 15,000 mg/L. For instance, the typical TDS concentration in the Pacific Ocean is 35,000 mg/L.

1.2 Desalination Technologies

Reverse osmosis (RO) and thermal evaporation (distillation) are the two primary treatment methods used to desalinate sea and brackish water on a large scale.

In thermal distillation, evaporation is used to separate freshwater from saline sources. In reverse osmosis desalination, semipermeable membranes are utilized to create freshwater from saline water under high pressure. In order to overcome the osmotic pressure that builds across the semipermeable membrane and is proportionate to the salinity/salinity difference across the membrane in the source water, pressure energy, which is a main driving force in RO desalination, is required.

Two other technologies commonly applied for the low salinity compared to the thermal and RO desalination system, are ion exchange (IX) and electrodialysis (ED). An electrical current applied directly separates the salt ions from the supply water in electrodialysis.

An overview of the most affordable separation method for source water salinity that requires distillation is presented in Table (1.1) [3]. The most effective desalination technique is often chosen for processes with overlapping concentration ranges after conducting an economic analysis for the particular desalination project.

Table 1.1: Desalination Process Applicability [3]

Separation Process	The concentration range for cost-effective Application, mg/L
Thermal process	20,000 - 100,000
RO separation	50 – 46,000
Electrodialysis	200 – 3,000
Ion Exchange	1 – 800

In 2016, approximately 65% of the global desalination installed systems are RO desalination plants while 28% are thermal desalination plants, as shown in Figure (1.1) [4]. Because the energy recovery and membrane separation processes have been continually improved over the past few decades, the percentage of RO desalination installations has gradually increased.

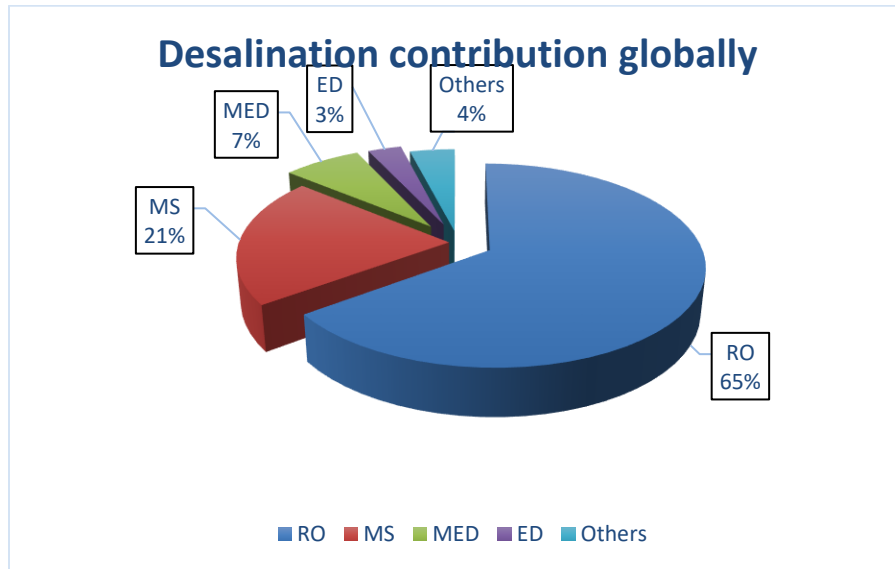


Figure 1.1: Desalination process contribution globally [4].

1.3 Reverse Osmosis

The most used technique is reverse osmosis (RO) for desalination due to its effectiveness in removing impurities, dissolved solids, and contaminants from seawater or brackish water, it removes substances like salts, organic material, germs, and viruses by forcing water through a particular impermeable, usually polymeric membrane sheet while rolls of membrane sheets are coiled into a cylinder in a spiral wound arrangement, which is extensively used in the industry. Each long pressure vessel contains several membrane components, where the membrane layer is incredibly thin and selectively permits water to permeate or flow through while blocking other substances from doing so depending on their size, shape, and charge.

Water species or dissolved solids that does not permeate typically gets more heavily concentrated with salts and other chemicals, which is referred to as concentrate. In general, pollutants larger than water molecules will not pass through. RO technology can remove up to 99% of dissolved solids, including salts, minerals, bacteria, and viruses. This makes RO a popular method for many countries, particularly in areas with a lack of water, like North Africa, Southeast Asia, and the Middle East. RO plants can produce large quantities of fresh water, sufficient to meet the needs of large populations, industries, and agriculture, with a relatively small footprint (World Bank, 2021) [5]. RO systems can also be used on a small or large scale because they are made up of separate parts.

Figure (1.2) [3] shows according to each filtration technique, the sizes and types of pollutants that RO membranes can remove. In terms of physical size, 1 (Angstrom) Å is the lowest size that the RO membrane can reject from being permeated. Usually, pre-treatment is required before exposing the water source to the RO membrane, to remove bigger particle-size ions that can plug the membrane surface and affect the steady desalination process.

The energy consumption and water production costs are the main reason for more rapid improvement in RO desalination than other desalination technologies used over the past three decades.

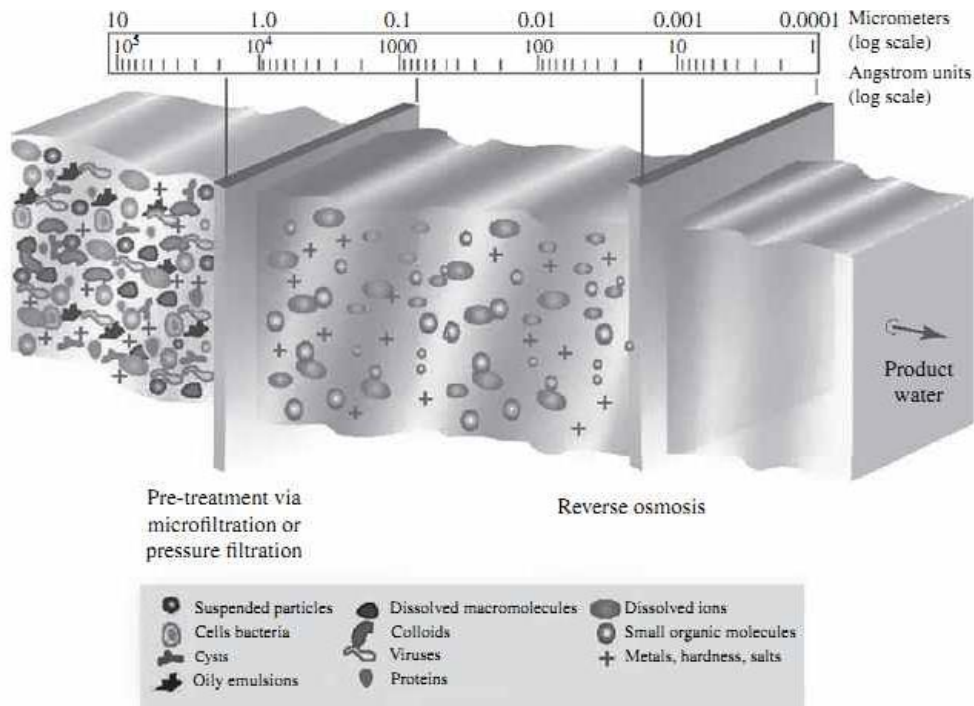


Figure 1.2: Contaminant removal by RO membrane [3]

1.4 Photovoltaic System (PV_s) Powered RO Desalination

Photovoltaic (PV_s) panels produce energy directly from sunlight using an electrical process that happens naturally in particular types of materials known as semiconductors. Solar energy liberates electrons in these materials, which are induced to flow through an electrical circuit, powering electrical devices or transmitting electricity to the grid. PV_s panels may be used to power everything from calculators and traffic signs to residences, commercial organizations, and industrials, the photovoltaic converts lighting into electrical through D.C. current by taking advantage of the photoelectric effect. A PV_s system consists of solar panels, an inverter, and batteries that store excess energy for later use, it has become a fast-growing business and keeps reducing its cost-effectiveness.

RO plants typically rely on fossil fuels or grid electricity. Recently, there has been growing interest in integrating renewable energy sources like photovoltaic (PV_s) systems with RO plants to create sustainable and environmentally friendly water supply systems. By combining these two technologies, long-lasting water supply systems can be created that are beneficial for both people and the planet.

However, PV-powered RO plants also face challenges. The effectiveness of the RO system may be impacted by solar energy's sporadic nature, requiring a hybrid system with batteries or a backup generator to provide power when there is low sunlight or high demand [6]. Additionally, the initial cost of installing a PV_s system can be higher than other energy sources, but the long-term savings and benefits of using a renewable source of energy can justify the investment, particularly in areas with high energy costs and limited access to grid electricity (World Bank, 2021) [5].

PV-powered RO systems can offer a sustainable solution to water scarcity in water-scarce regions by reducing dependence on fossil fuels and grid electricity. The use of PV systems can lower the costs of running RO plants, make the water supply more reliable in remote and off-grid areas, and provide a steady source of energy to improve the RO system's stability. However, the intermittent nature of solar energy and the initial cost of installing a PV system remain challenges that require hybrid solutions and careful consideration.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Reverse osmosis (RO) desalination is a common way to turn salt water into drinkable water. Seawater is put under a lot of pressure, which forces it through a semi-permeable membrane and gets rid of the salts and other impurities in the water. RO desalination requires a lot of energy, which makes it an expensive way to get fresh water. But as the need for freshwater grows and natural water sources are used up, RO desalination is becoming a more important technology.

Desalination by reverse osmosis (RO) has become a promising answer to the problem of water scarcity on a worldwide scale. The general use of RO desalination is, however, significantly hampered by its high energy needs. To cut costs and carbon emissions, RO desalination system efficiency and energy consumption must be improved

2.2 Reverse Osmosis Desalination System

Most RO desalination systems need a lot of energy to run, which is the main reason why they are so expensive. The amount of energy needed for RO desalination is usually between 2 and 5 kWh/m³ of water made [7-8]. Seawater RO (SWRO) plant-specific energy

consumption (SEC) reduced from 8 kWh/m³ in the early 1980s to roughly 2.6 kWh/m³ in more recent years [9]. There is still room for improvement in terms of reducing the energy consumption of the SWRO process because the minimal amount of energy needed to desalinate seawater with a salinity of 35,000 mg/L is around 1.07 kWh/m³ at 50% recovery [10]. With its many advantages over conventional desalination methods, including no phase change, low energy consumption, modularity, adaptability, and minimal installation space, RO has advanced significantly in recent years [11]. Spiral-wound module-type membranes are used in the majority of RO desalination plants since they are able to provide an optimal balance of membrane fouling management, packing density, and pure water permeability [12].

The high energy use is mostly caused by the high pressure that is needed to push water through the semi-permeable membrane. This pressure is usually between 55 and 80 bar [13]. Improvements in energy efficiency in RO desalination have been achieved through a variety of methods. The utilization of energy recovery devices (ERDs), breakthroughs in membrane characteristics, and system design innovations are a few of these techniques.

ERD devices can function by collecting the energy that is normally wasted during the desalination process and converting it into usable form so that it may be used to power other parts of the system when compared to a typical plant without ERDs, the greatest energy savings in SWRO plants with ERDs can reach up to 60% [14]. The author [15-16] discussed the energy recovery devices (ERDs) used in RO desalination systems. They highlighted the different types of ERDs, including Pelton wheels, turbochargers, and isobaric, Figure (2.1) classified the ERDs into two groups, centrifugal and isobaric. The

authors concluded that the isobaric ERDs are more efficient and are widely used in commercial RO desalination systems because of their higher efficiency around 97% and smaller size than Centrifugal ERD which can reach 82% transfer efficiency only.

In the last decade, Isobaric ERDs have taken the place of Centrifugal ERDs in many RO facilities. the resulting decrease in energy consumption for the same capacity [17-18]. Figure (2.2) shows different ERDs configurations that are used in RO plants. The Pelton wheel and the turbocharger are depicted in figures (2.2a, 2.2b), respectively. DWEER and a pressure exchanger are seen in Figures 2.2c and 2.2d, respectively. As opposed to the conventional method of allocating smaller-size pumps to the individual RO trains, which serves several RO trains, high-pressure pumps (HPP) have an efficiency of up to 85%. Multistage centrifugal pumps have an increase in efficiency with size (pump flow), which is a practical upper limit for centrifugal pump efficiency and explains the energy savings brought on by using larger pumps [19].

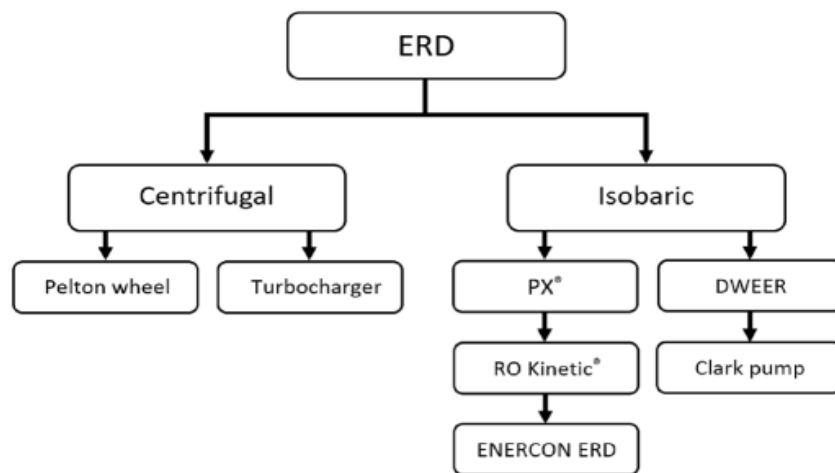


Figure 2.1: ERD classification [11]

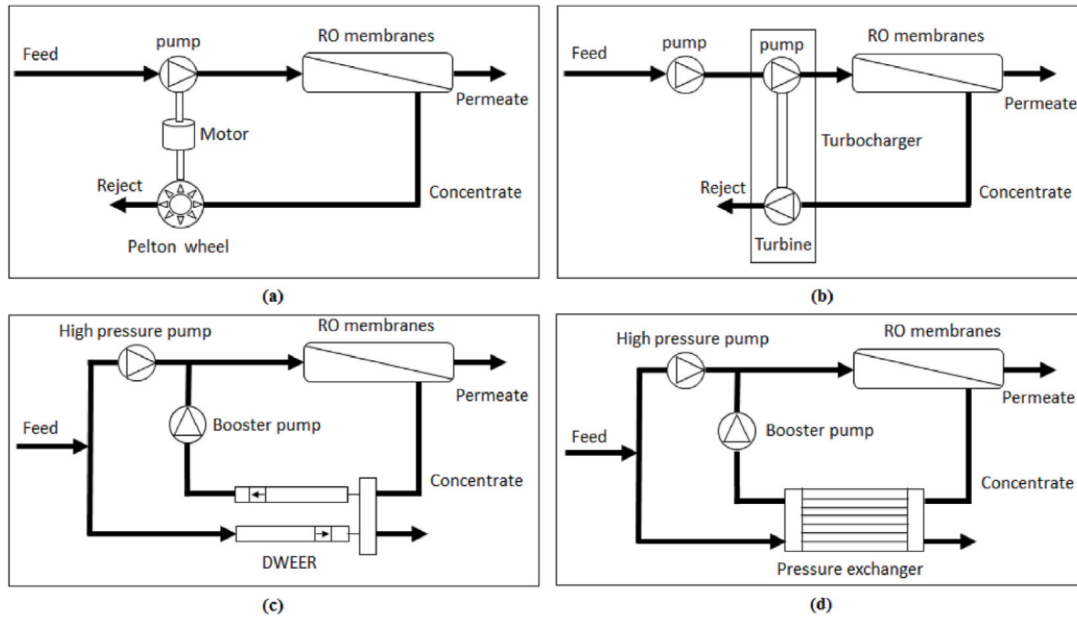


Figure 2.2: ERDs configuration used in RO plants a Pelton wheel, b- Turbocharger, c- DWEER, and d- Pressure exchanger [11]

According to a study that was conducted by Ghaffour et al. (2014) [20] many developments in membrane properties have occurred since the 1980s, by increasing membrane surface area, salt rejection, permeability, and improving membrane life. Also, the Recovery Ratio (RR) of seawater RO (SWRO) plants has increased from 25% in the early 1980s to approximately 45% in more recent years for 35,000 mg/L seawater salinity. The development of high-performance membranes is primarily responsible for this progress and helped to lower the pressure drop while simultaneously increasing the water flux.

The fouling propensity and permeate quality of RO membranes are greatly impacted by the membrane's material, thickness, and surface charge. Surface modification has been used to create fouling-resistant RO membranes by enhancing hydrophilicity,

lowering surface roughness, and lowering concentration polarization at the membrane's surface [21]. the usage of thin-film composite (TFC) membranes plays an important role because of the high rejection rate and a lower fouling tendency than other types of membranes [13], TFC is one of the most important advancements in membrane properties and has evolved to become the industry standard for use in modern RO desalination systems, which has contributed to an increase in the systems' overall energy efficiency.

However, Even though creating a membrane that is resistant to fouling is still one of their biggest challenges, more creative approaches to reducing membrane fouling are likely to be discovered shortly [21]. Other than feed salinity, factors such as membrane compaction, degree of surface fouling, temperature, recovery, and age influence the necessary applied pressure [22], and membrane fouling results in a decrease in membrane permeability with time. It is necessary to increase the applied pressure to operate at the same fixed flux.

Some researchers study out the effects of raising the membrane's water permeability LMH/bar in specific energy consumption (SEC) under different cases, and all of them found that a negligible reduction in the SEC as the water permeability surpasses 3 LMH/bar for SWRO and 8 LMH/bar for BWRO due to fast increases in required hydraulic pressure to overcome the high feed-concentrate osmotic pressure, especially at the rear membranes [13] as shown in Figure (2.3-2.4). In 2009, Kim et al. proposed a temperature management mechanism for the feed water temperature [23] to optimize the RO desalination process. According to research, increasing the feed water's temperature from 15 to 40 °C can increase permeate flow by 57%.

According to Cohen-Tanugi et al. (2014) [9], the water permeability of modern RO membranes is effective "high enough" and getting close to the performance thresholds established by external mass transfer rates or thermodynamic restrictions. The requirement for greater membrane selectivity later highlighted in a review by Werber et al. [24] in 2016. These studies demonstrated that improving membrane water permeability is less likely to increase energy efficiency, especially for SWRO.

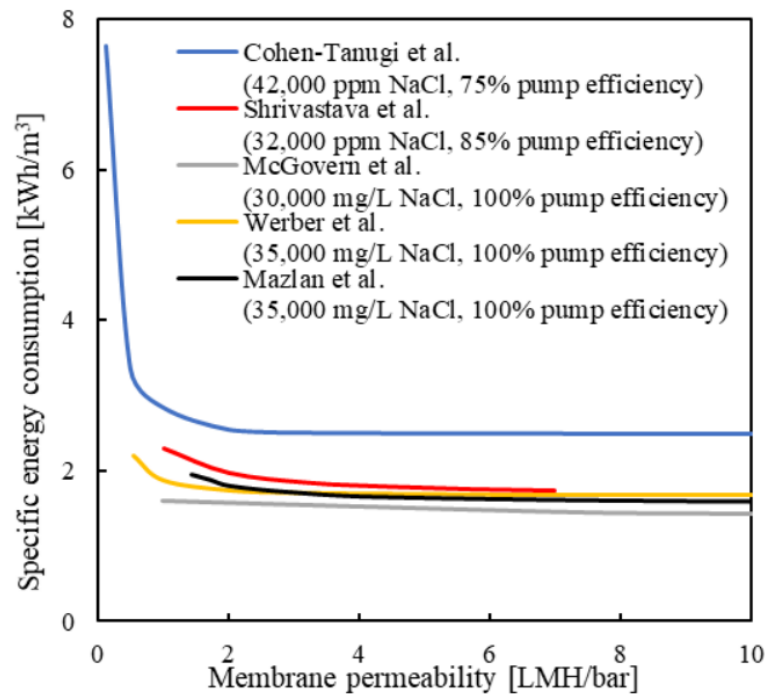


Figure 2.3: SEC as a function of membrane water permeability in different cases for SWRO [13]

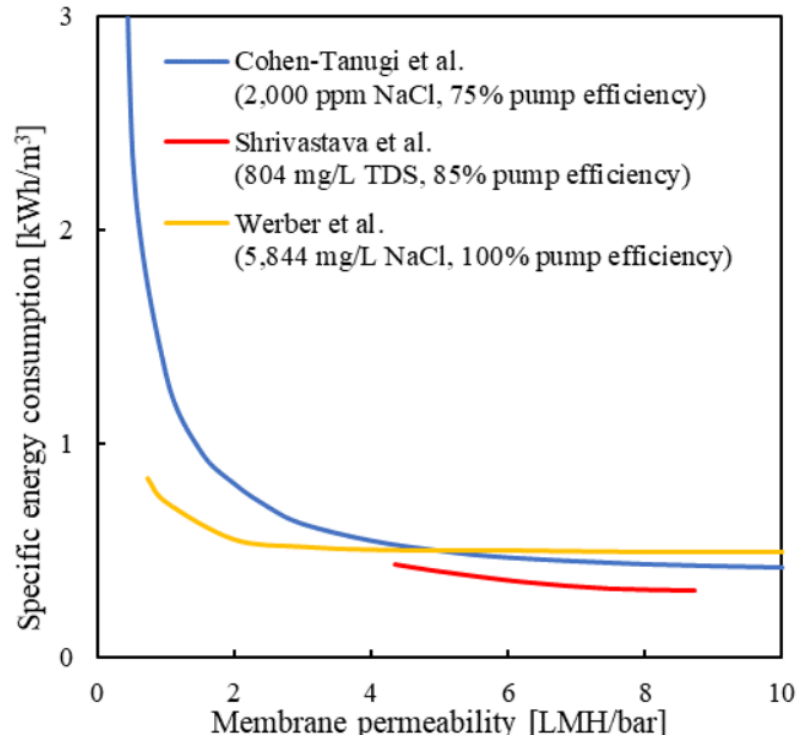


Figure 2.4: SEC as a function of membrane water permeability in different cases for BWRO [13]

In RO desalination, system design is another area that is undergoing continual research and development. The advancement of system design has led to improvements in energy efficiency, such as introducing a new configuration to improve product quality and reduce the amount of consumed energy simultaneously.

Two-pass SWRO systems have been developed to replace traditional Single pass (Single-stage) systems and increase product water quality, single pass configuration is shown in Figure (2.5). Two-pass RO refers to a desalination process that involves two reverse osmosis (RO) steps. In the first step, seawater is passed through an SWRO membrane at high pressure to separate salt and other impurities from the water. The permeate, or purified water, is then sent to a second step BWRO membranes, where it is further purified to ensure the product quality necessary.

Based on the configurations, the three primary design alternatives for a two-pass RO system are full, partial two-pass, and split partial two-pass [21]. For the best possible product quality, 100% of the permeate flow from the first pass is treated by the second pass BWRO in the whole second pass Figure (2.6). In contrast, in the partial second-pass Figure (2.7), just a portion of the first-pass permeate is treated by the second-pass BWRO, and the permeate from both passes is mixed to provide the desired final product quality and quantity. against fully two-pass designs, partial two-pass systems provide several benefits, such as lower capital and operational costs, higher system recovery, and smaller RO trains. However, it offers more salinity in the product water than a full-two pass [21].

Lastly, Split Partial Second Pass (SPSP) RO Figure (2.8). It is an advanced configuration for reverse osmosis (RO) systems that utilize the detailed knowledge of the RO membrane performance within a pressure vessel. Using front and rear membranes, SPSP RO divided the permeate and sent the front permeate to the finished good where the rear permeate to the second pass with brackish water RO membranes before being blended with the final product while recycling the concentrate from the BWRO to the main feed, It can greatly reduce the size of the two-pass RO plant and reduce capital and operating costs as compared to conventional complete or partial two-pass RO systems [21].

C. Bartels et al. (2010) [25], have made a comparison between partial and split partial second pass (SPSP) designs based on actual collected data from the Larnaca SWRO desalination plant, They discovered that the SPSP design decreased overall RO energy usage by 4.6%, the quantity of 2nd pass membranes required by 21%, and the size of the 2nd pass RO by 23%.

Y. Du et al. (2015) [26], study 3 pass design with SPSP configuration and normal configuration (partial two passes) with three different SWRO membranes type and 1 BWRO membrane, while the water product salinity varies from 50 to 200 mg/L, and the feed salinity and temperature were 35,000 mg/L and 20 °C, respectively. They discovered that the SPSP design saves 1.15–4.30% energy and costs per unit of the product when compared to the normal design, with higher savings at salinities of 200 mg/L and lower savings at 50 mg/L. Also, the SPSP design also favors a membrane with a sizable active surface and good salt rejection.

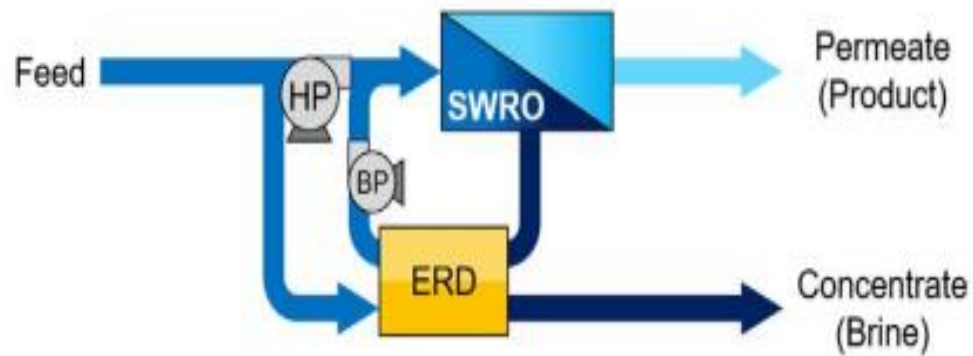


Figure 2.5: Single pass (Single stage) RO configuration [27]

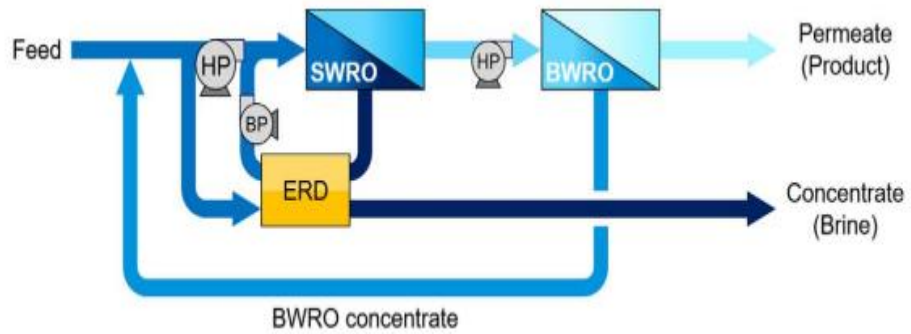


Figure 2.6: Full Two-pass RO configuration [27]

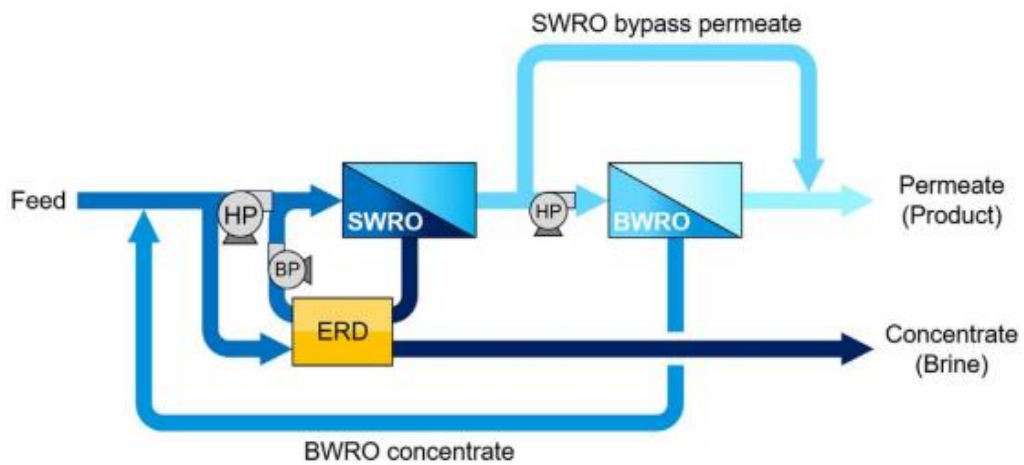


Figure 2.7: Partial Two-pass RO configuration [27]

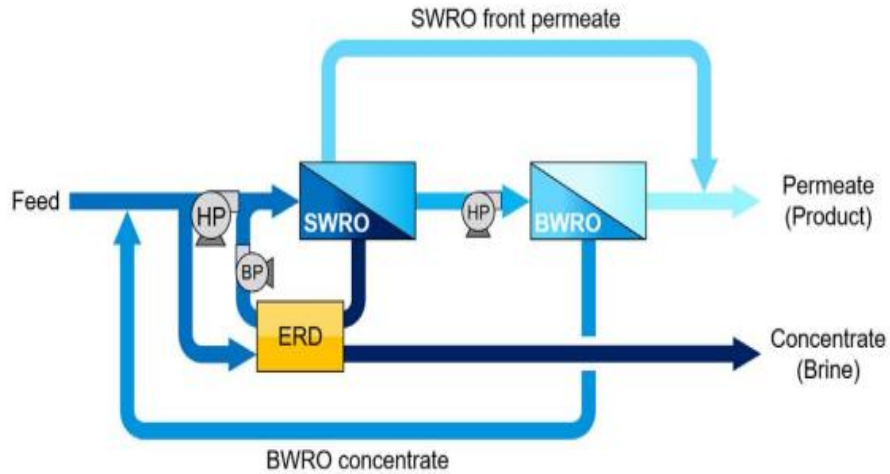


Figure 2.8: Split Partial Second Pass (SPSP) RO configuration

It is not advised to have ROs with more than five stages because, unlike pass designs, two-stage designs treat the concentrate (brine) from the first stage further by SWRO membranes. By extracting more permeate and reducing the SEC of an SWRO plant, this design can improve system recovery as a whole [28]. The product quality is adversely impacted by the concentrate's use as a feed for the second stage RO. High salinity permeate is produced as a result of the feed solution's higher concentration. This indicates that the low-feed salinity or BWRO technique is better suited to the multistage architecture.

Seawater desalination using spiral-wound modules has been studied by Y. Du and L. Xie [29] under varied feed salinities, and they found the one-stage RO system is preferred for feed salinities more than 32,000 mg/L. The two-stage RO system is preferable when the feed salinity is less than 28,000 mg/L. As the required permeate salinity decreases, the cost of the unit product rises. The one-pass setup can produce desalted water of the requisite quality for the looser permeate salinity criterion of 300 mg/L. A two-pass

system is better suited when the lower permeate salinity requirement ranges from 50 to 200 mg/L.

Internally staged design (ISD) has been introduced first time in 2004 [30] as a new internal configuration for the membranes. Unlike a single-pass system, that only employed one membrane, the inter-staged design comprises a series of membranes with different properties to create multiple stages of membrane filtration within a single pressure vessel, as shown in Figure (2.9).

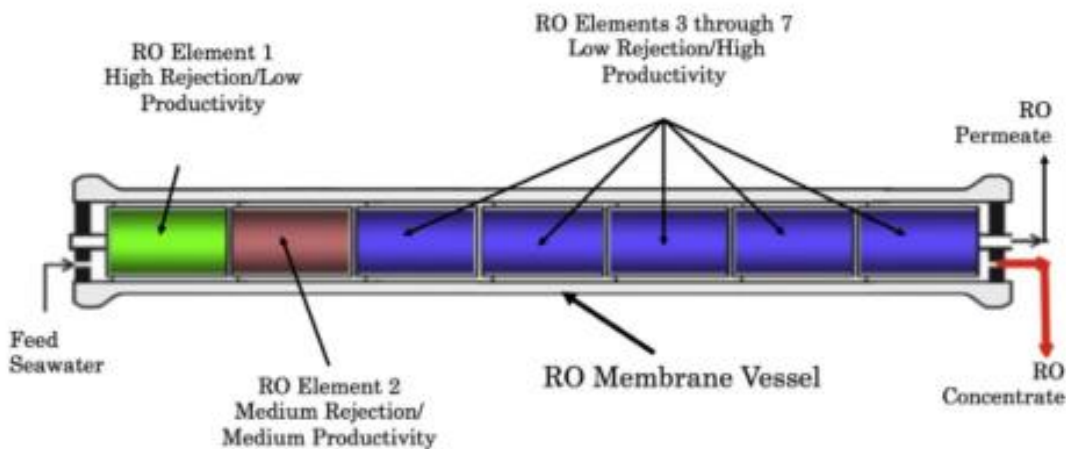


Figure 2.9: Internally staged design RO configuration [19]

B. Peñate, and L. Rodríguez [31], made a comprehensive study about inter-stage design (ISD), these combinations, which combine various RO membrane types in a single PV, are purchased from the three major membrane producers., Toray, Filmtec, and Hydromantic. Using manufacturers' software to assess their representative membranes, two situations have been simulated and contrasted with a typical design using one membrane

only inside PV_{ro} . The first scenario involves maintaining the permeate flow at $87.6 \text{ m}^3/\text{day}$ and the recovery rate at 45% while working at lower pressures (i.e., increasing the flux distribution as illustrated in Figure (2.10). This results in a decrease in the SEC and reduction in feed pressure from 3 to 6 bar [31].

The second scenario uses the same feed flow ($194.6 \text{ m}^3/\text{day}$) and high-pressure feed, and the recovery rate can be increased by 6 to 8% as a result. This situation also makes it possible to save 5 to 8% on capital expenses because the installation utilizes less PVs and membranes [31].

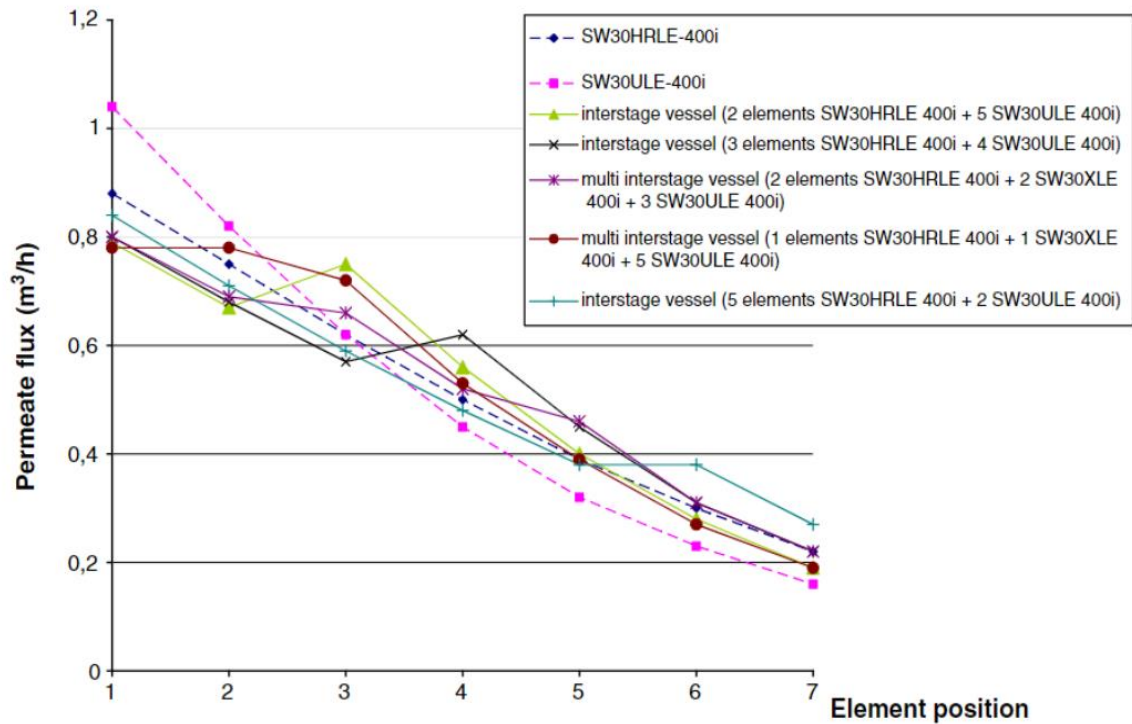


Figure 2.10: Permeate flux distribution with different ISD configurations using Filmtec membrane at case one [31]

Jungbin. K & Seungkwan. H (2018) [32] studies the internally staged design (ISD) for RO desalination systems to investigate the flux distribution and improve energy efficiency and water quality. The authors used mathematical modeling and simulation with the software MATLAB to figure out how well the ISD system worked. A trade-off relationship between SEC and permeate salinity was discovered when 36 ISD combinations using three types of SWRO membranes were evaluated for their performance under various operating conditions. By taking fouling formation into account, they discovered that using a combination of high rejection and moderate membranes led to a low permeate salinity and reduced the flux in the front membranes, while combining moderate and high-flux membranes was appropriate to reduce SEC. However, the high-flux operation can increase the fouling potential which leads to clogging the membrane surface with impurities, reducing the water flow and increasing energy consumption.

Lastly, split partial single-pass (SSP) is an improved single-stage single-pass RO unit recently introduced by Jungbin. K, Seungkwan. H (2018) [27], it enhances the RO performance by improving the permeate quality while keeping the energy consumption lower than the two-pass RO system Figure (2.11). The permeate from the rear elements inside the pressure vessel split from the front elements and mixed with the feed flow which led to diluting of the feed and reducing the osmotic pressure. Comparing SSP RO to traditional single-pass RO, the purer permeate produced was around 15% higher [27].

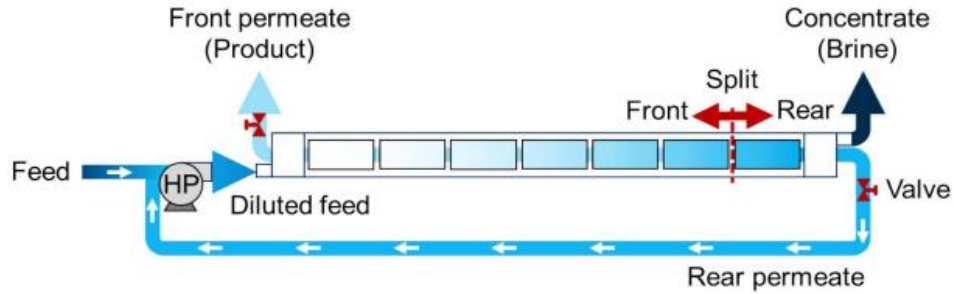


Figure 2.11: Schematic design of Split partial single-pass (SSP) [27]

2.3 Reverse osmosis System Powered by Photovoltaic System as Renewable Energy

The growing need for sustainable and renewable energy sources has driven the application of solar PVs systems to power RO desalination. Solar PVs -powered RO systems have been widely studied in the literature due to their potential to provide energy-efficient and cost-effective water desalination solutions. The use of solar PVs energy as a power source for RO systems can overcome the limitations associated with conventional energy sources, such as fossil fuels and grid electricity.

Saleh et al. 1995 [33] constructed and tested an early PV-RO system demonstration in Riyadh, Saudi Arabia for research purposes. The straightforward architecture of the system comprises without any energy recovery machinery, the system consists of fixed 10 kW PV panels, MPPT, batteries, and a single pass, single stage. The community can effectively use the 15 m³ of clean water produced each day (600 L/h) for 24 hours.

A modest RO pilot unit with a small capacity of 500 L/day was described by Joyce et al. in 2001 [34]. For various feed salinities the tests contrast the working pressure of the membrane with the permeate quality and particular energy usage. However, it may be

inferred that the tiny RO pilot uses less specific energy when the feed pressure and feeding water recovery rise.

Espino et al.'s 2003 [35] investigation into the experimental PVRO system performance for a 10 m³ per day capacity. Actual results from the experiments were used to maximize the performance of the RO plant by coordinating and timing the PVs system. Salt water that has been heated is used to feed the facility in order to consume less energy overall. The plant runs automatically on average for 8 hours during the summer and 7 hours during the winter while being adjusted to the PVs generator's variable energy output.

PVRO plant that is run at variable flow/pressure in equatorial areas was designed by Oliveira et al. in 2005 [36], allowing it to effectively utilize the naturally varying solar resource. The duty ratio of the DC/DC converter was managed by a new feed-forward control algorithm, ensuring the best possible utilization of the power from the nine inadequate PV sources. A complete feed-forward control Simulink model was developed and successfully experimentally validated.

The addition of storage batteries raises the price of the PVRO system, and in hot areas, the battery life cycle is shortened. A further characteristic of tiny PVRO systems is that, because of pressure and flow changes, they do not include ERD. In light of these, Mohamed et al. 2008 [37] created a PV-SWRO system without batteries that are fitted with an ERD. The system, was installed, tested, and contrasted to a battery-based system. It produced 0.35 m³/d in winter (feed water temperature 18 C) and required just 4.6 kWh/m³. Large battery banks (>1500 Ah) may enhance system performance but may be environmentally unfriendly and expensive to operate in distant areas.

The maximum power point of the PV panels was tracked by Douglas et al.'s feedback and feed-forward control methods, which were created, simulated, and put into practice in 2009 [38]. According to reports, utilizing this controller to operate a PVRO system increases daily permeate production by 60% and decreases daily operating time by 30%.

Figure (2.12) from Kelley et al. (2013) [39] illustrates the active thermal management control system they created to boost the PVRO desalination system's efficiency. For a specific amount of solar radiation, a photovoltaic panel generates more power at a lower temperature. For a given amount of power, a RO system produces more clean water at a higher feed water temperature. An active thermal management system uses these complementary features by warming the RO feed water and cooling the solar panel. We give experimental and simulation-based confirmation of this hypothesis. An increase in freshwater of 57% was achieved in experiments using an active thermal management control system and solar concentrators with PV panels.

In a study by Forstmeier et al, 2008 [40], the authors review the use of renewable energy sources to power RO desalination systems. They discuss how solar and wind energy could lower desalination's energy costs and carbon footprint. The authors note that hybrid systems, which combine multiple renewable energy sources, can provide a reliable and sustainable solution to power RO desalination.

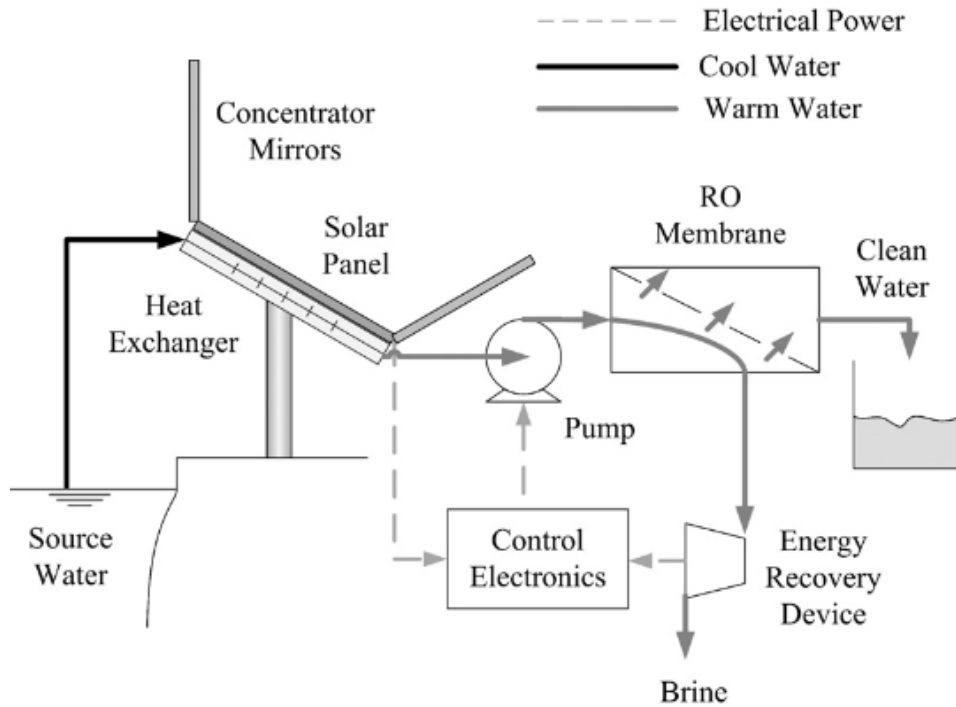


Figure 2.12: Schematic design of a PV/RO system with concentrating mirrors [39]

A solar-powered RO desalination plant was put through a 16-month test by Petterson et al. [41] in Brisbane, Australia. Solar panels with a tracking system and a 1.44 kW rating were used to power the bore pumps. 3.36 million liters of permeate were expected to be produced by the pilot plant throughout the 16-month trial, which ran from November 2008 to February 2010.

Bilton and Dubowsky have created a computer-designed modular solution for PV-RO at various locations [42]. It employs a number of parts, including eight RO membranes, six PV panels with 225 W of power each, seven pumps, and five separate motors. 350 L of freshwater are produced by a PV-RO system in Boston on a lovely summer day by

combining the RO and PV_s units. A 1 m³, 5 m³, and 20 m³ of freshwater can be produced by the systems for \$4.71, \$3.45, and \$3.01 per m³, respectively.

One of the most effective programs for simulating and enhancing the scaling of hybrid renewable energy systems, whether they are grid-connected or independent, is called Hybrid Optimization of Multiple Energy Resources Software (HOMER). The best configuration that minimizes costs while satisfying the constraints given by the designer is taken into account in the HOMER optimization technique [43].

Minimizing the probability of power supply loss (LPSP) and the cost of energy (COE) leads to optimal system sizing. Fthenakis et al. [44] used HOMER software to analyze the techno-economic viability of a PV-RO system with a predicted daily capacity of 190,000 m³ and powered by a 148 MW PV_s system with a backup diesel generator. It is possible to cut annual CO₂ emissions by 832 million tons.

2.4 Research Objectives

The research objectives of this study entail conducting a comprehensive review of literature pertaining to reverse osmosis (RO) systems with a specific emphasis on performance improvement and system design advancements. These advancements have resulted in improved energy efficiency, including the implementation of novel configurations to enhance product quality and reduce energy consumption. Of particular interest is the recent introduction of the Split partial Single Pass (SSP) method, which has

demonstrated superior permeate quality in single-pass RO systems while consuming less energy compared to two-pass RO systems.

However, existing literature has limited evaluations of SSP design under standard seawater conditions and with limited parameters. Therefore, the primary objective of this thesis is to conduct a detailed investigation of SSP design under various conditions and operating parameters, with the aim of improving its performance and integrating it with a photovoltaic system to provide the necessary electrical power. In summary, this research is aimed at advancing the understanding of SSP design and its potential applications in the field of RO systems. Hence, the current work is focused on:

- Examine the Split Partial Single Pass (SSP) operation under various operating parameters including both mild and severe seawater conditions.
- To investigate how the performance of the SSP is impacted by actual density value (as a function of salinity and temperature) versus constant density value.
- To investigate the impact on SSP performance of increasing the number of membranes inside the pressure vessel from 7 to 8.
- Introduce a new configuration design by fusing internal staged design (ISD) with SSP, then assess its effectiveness.
- Calculating the size of a photovoltaic (PV) system to power the upgraded SSP-ISD design.

CHAPTER 3

METHODOLOGY

This chapter deals with assumptions and mathematical modeling of Reverse Osmosis and Photovoltaic systems. A RO system consists of three major parts: membrane module, high-pressure and booster pumps, and energy recovery device (Pressure exchanger). The Photovoltaic system consists of PV modules, inverter, and Battery.

3.1 RO Modeling

Membrane modules are cross-flow filtration types used in this study as module configuration. We are considering a Spiral-Wound membrane that is rolled up membrane leaves around a tube (Permeate tube) and separated by using feed spacers, in order to provide space for water to flow uniformly between the membrane's surface. It consists of several modules, which force the feed water by a high-pressure pump to pass tangentially over the membrane surface to pass some of water and salt while rejecting the majority of salt contents as represented in Figures (3.1, 3.2). The advantage of cross-flow filtration against other types of filtrations is the continuous operation which helps to minimize fouling and scaling on the membrane surface. It keeps the surface of the membrane clean by scouring it. To scour the surface effectively, a minimum flow rate across the membrane surface is required. However, based on the feed water condition, membranes need to be

taken off from the line regularly, so that cleaning accumulated material in the surface can be performed as an option. Backwashing is another option for surface cleaning.



Figure 3.1: Spiral-wound RO module from company Dupont water solution (Filmtec).

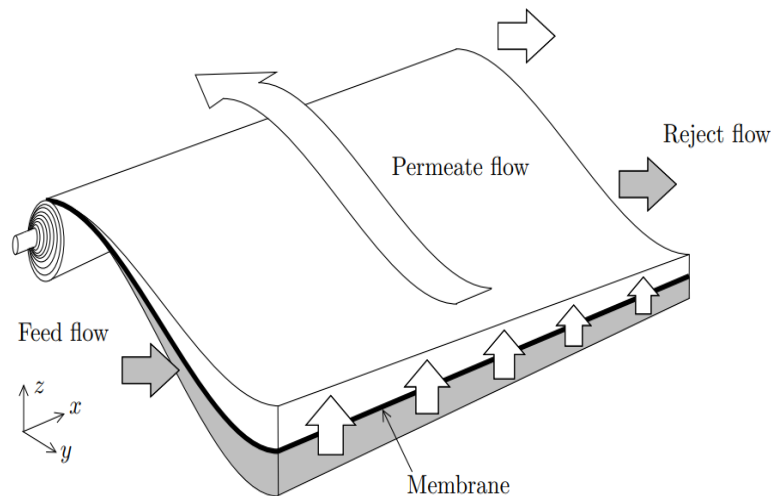


Figure 3.2: Diagram of a spiral-wound RO module.

Many models describe the flux transport of water and solutes through RO membranes, these are based on different assumptions and degree of complexity. The

Solution-Diffusion (non-porous) model is the leading theory that uses physical and chemical properties of the membrane and feed solution to describe the transportation, such as (membrane permeability coefficient for water and solutes, feed concentration ...).

Irreversible thermodynamics is one of the theories that does not use the membrane properties to describe the mechanism of transport, it assumes existing of local equilibrium by dividing the system into small subsystems. also, some models based on porous membranes that assume some of imperfections in the membrane that allow leakage of solution.

3.1.1 Solution-Diffusion (Non-Porous) Model

It was developed by Lonsdale et al. [45] and used in my studies, assuming the membrane is free from imperfection (non-porous) and the solution (Solvent and solutes) dissolve into the membrane surface. Then, it diffuses through the membrane to the permeate side. The transport of solvent and solutes have different rates of diffusion independent of each other as shown in Equation (3.1, 3.2) where the water flux through the membrane is linearly proportional to the water permeability coefficient and the net driving pressure that occurs by the difference of applied pressure versus osmotic pressure. While the salt flux has linear proportionality to salt permeability coefficient and concentration difference between feed and permeate side.

$$J_w = A_w \text{ FF TCF NDP} = A_w \text{ FF TCF} [(P_f - P_p) - (\text{CPF } \pi_f - \pi_b)] \quad (3.1)$$

$$J_s = B_s \text{ TCF} (\text{CPF } C_f - C_p) \quad (3.2)$$

Where:

J_w = Water flux (Solvent), L/m². h.

J_s = Salt flux (solute), mg/m².h

A_w = water permeability coefficient, L/m².h.bar that can be calculated from membrane manufacture data at standard condition.

B_s = Salt permeability coefficient, L/m². h or m/h that can be calculated from membrane manufacture data at standard condition.

FF = Fouling Factor.

TCF = Temperature correction factor.

NDP= Net driving pressure which is applied to the membrane.

P_f, P_p = Feed and Permeate pressure, bar.

π_f, π_p = Feed and permeate osmotic pressure, bar.

CPF= Concentration polarization factor.

C_f, C_p = Feed and permeate concentration (salinity), mg/L.

The water volume flow rate m³/h or m³/day, and salt mass flow rate mg/s can be found by multiplying the water or salt flux by A_m effective membrane area m² as shown in Equations (3.3, 3.4).

$$Q_w = J_w \times A_m \quad (3.3)$$

$$Q_s = J_s \times A_m \quad (3.4)$$

Equations (3.1 and 3.2) are valid at any point on the membrane from the entrance of feed water along to the outlet of concentrate water, but we should consider the continuous increase of osmotic pressure and decrease of applied pressure along the length of a spiral-wound module due to downstream pressure drop and solute accumulation. Therefore, the overall flux value must be determined by integration.

3.1.2 Osmotic Pressure

Osmosis is a natural process that occurs due to the difference of fluid chemical potential on both sides of the semipermeable membrane, which is a function of pressure, temperature, and concentration (salinity) of dissolved solids. This potential difference allows the pure water (solvent) to flow across the membrane, but it's not allowed for the solutes within the solvent to travel through the membrane as freely as water does. which leads to separation.

At equal pressure and temperature, but with an existing concentration gradient between the two solutions separated by a membrane, osmotic flow will occur from the low-concentration side to the high-concentration side until the equilibrium is restored. In order to overcome the osmotic flow, a hydrostatic pressure needs to apply at the higher concentration side to prevent the osmotic flow and it is equal to osmotic pressure. As

illustrated in Figure (3.3) osmotic pressure prevents the water flux from flowing to the permeate side until the feed pressure exceeds the osmotic pressure.

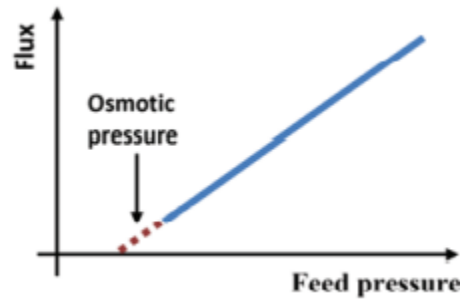


Figure 3.3: Schematic of osmotic pressure prevent water flux [47]

By using the Van't Hoff Equation [27], the osmotic pressure π bar can be expressed by Equation (3.5)

$$\pi = \frac{\gamma \cdot C \cdot R(T + 273) \times 10^{-5}}{M_w} \quad (3.5)$$

Where γ is the solute coefficient (for sodium chloride it is 2), C is the solute concentration mg/L, R is the universal gas constant J/K mol, T is temperature of water °C, and M_w is the molecular weight of solute.

3.1.3 Flow and Mass Balance

The feed flow is divided into two flows in the RO module: the concentrate flow or retentate (brine) and the permeate flow. Figure (3.4) [46] shows the general design of the RO system.

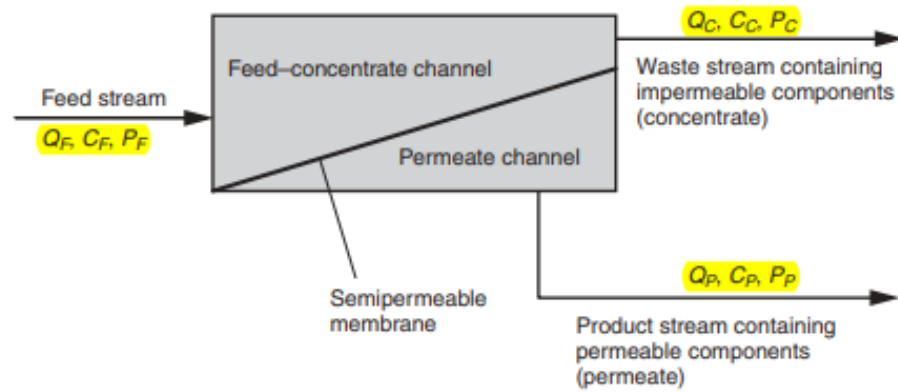


Figure 3.4: Simple schematic of RO module [46]

The flow and mass balance equations using concentration terminology are:

$$Q_f = Q_p + Q_c \quad (3.6)$$

$$Q_f C_f = Q_p C_p + Q_c C_c \quad (3.7)$$

Where Q_f , Q_p , and Q_c are the feed, Permeate, and concentrate flow rate m^3/h or m^3/day , respectively. C_f , C_p , and C_c are feed, Permeate, and concentrate concentration mg/L , respectively.

The recovery ratio RR is defined as the ratio between permeate to feed flow rate:

$$RR = \frac{Q_p}{Q_f} \quad (3.8)$$

Salt rejection is defined as a percentage of feed concentration that is rejected by the membrane and can be calculated by (3.9):

$$Rej = \left(1 - \frac{C_p}{C_f}\right) \times 100\% \quad (3.9)$$

Increasing the rejection percentage meaning better removal of solute from permeate water. Currently, the average salt rejection can reach 98 - 99% for most membrane manufacturers.

The salinity of the permeate water (product) C_p is a ratio of solutes flux to the water flux transport and can express by Equation (3.10):

$$C_p = \frac{J_s}{J_w} \quad (3.10)$$

the lower solutes flux or the higher water flux, is an indication of purer product water.

By substituting recovery ratio and salt rejection Equation (3.8, 3.9) into flow and mass balance Equation (3.6, 3.7), we get the following expression of concentrate salinity:

$$C_c = C_f \left[\frac{1 - (1 - Rej)RR}{1 - RR} \right] \quad (3.11)$$

3.1.4 Concentration Polarization

The phenomena of concentration polarization occurs when the pressure drives the feed sea water to flow through a semipermeable membrane, the solute transport towards the membrane surface is mostly or totally retained, and it accumulates in a thin layer adjacent to the membrane surface. This will generate concentration gradient, which means the solute concentration near the membrane surface is much higher than the bulk feed concentration.

As a consequence, there is a buildup of solute at the membrane surface until the equilibrium between diffusive flux of solute back to the bulk feed and the convective solute flux to the membrane is attained as shown in Figure (3.5).

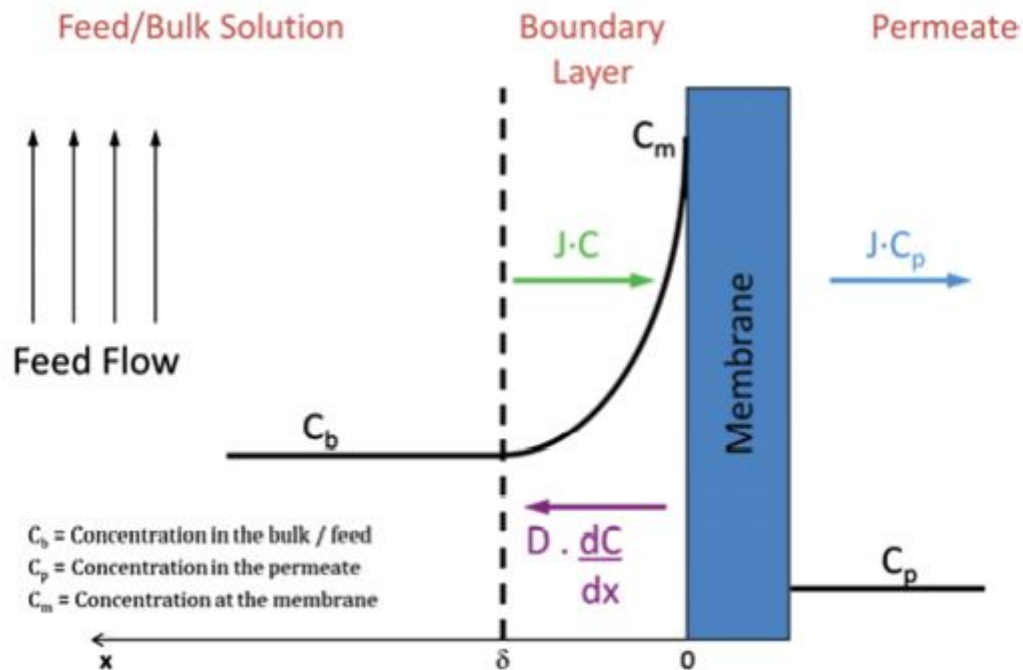


Figure 3.5: Concentration profile under steady state condition [47]

This phenomenon has several negative effects on the reverse osmosis performance. Such as, the case where actual osmotic pressure on the membrane surface becomes higher than bulk feed resulting in a reduction in the net driving pressure. therefore, reducing permeate transport and increasing salt transport through membrane. Concentration Polarization Factor (CPF) can be determined by the ratio of salinity at membrane surface to the bulk feed salinity inside the feed-concentrate channel as shown in Equation (3.12) [27]. Membranes manufacturers specify a value 1.2 to be the maximum Concentration Polarization value allowed [46].

$$CPF = \frac{C_m}{C_b} = \exp\left(\frac{J_w}{k} \times \frac{1}{3.6 \times 10^6}\right) Re_j + 1 - Re_j \quad (3.12)$$

Where C_m , is salinity at membrane surface C_b is salinity of bulk feed inside the feed-concentrate channel and k is mass transfer coefficient m/s that represent the diffusion of solute to the bulk feed Equation (3.13) and D_s salt diffusivity m²/s computed by Formula (3.14) [27], as a function of salinity C mg/s and Temperature °C .

$$k = \frac{D_s}{\delta_b} \quad (3.13)$$

$$D_s = 6.725 \times 10^{-6} \exp\left(1.546 \times 10^{-7} C - \frac{2513}{T + 273}\right) \quad (3.14)$$

Mass transfer coefficient k is usually determined using Sherwood (Sh) correlation which is function of Reynolds (Re), and Schmidt (Sc) numbers. These correlations (3.15, 3.16, 3.17, 3.18) relay on system physical characteristic and flow condition (laminar or turbulent) [27].

$$Sh = 0.16 Re^{0.605} Sc^{0.42} \quad (3.15)$$

$$k = Sh \left(\frac{D_s}{d_H} \right) = \frac{0.16 Re^{0.605} Sc^{0.42} D_s}{d_H} \quad (3.16)$$

$$Sc = \frac{\mu}{\rho D_s} \quad (3.17)$$

$$Re = \frac{\rho v d_H}{\mu} \quad (3.18)$$

Where d_H is the hydraulic diameter m, μ is the viscosity kg/m.s, ρ is the density kg/m³ and v is the cross-flow velocity in feed-concentrate channel m/s.

Viscosity μ kg/m.s depends on the temperature, salinity, and can be expressed by Equation (3.19) [27]:

$$\begin{aligned} \mu = & (1.476 \times 10^{-3} + 2.482 \times 10^{-9} \\ & + 9.329 \times 10^{-15} C^2) \exp(-2.008 \times 10^{-2} T) \end{aligned} \quad (3.19)$$

The geometry of the flow channel determines the hydraulic diameter. In Spiral-wound modules, the feed channel width is much larger than the height ($w \gg h$). Hence, the d_H is twice the channel height as expressed by Equation (3.20), and the cross-flow velocity v m/s is given by Equation (3.21) [27]:

$$d_H = \frac{2wh}{w+h} \approx 2h \quad (3.20)$$

$$v = \frac{1}{86400} \frac{Q_f}{whn} \quad (3.21)$$

Where w is channel width m, h is the channel height m, n is the number of channels.

Researchers often assume a fixed value for the density of water; $\rho = 1000 \text{ kg/m}^3$ as a standard value for fresh water, but because the density of sea water is affected by salinity and temperature of water, Millero and Poisson [48] formula (3.22, 3.23, 3.24a-c) is used in this study to get accurate density value. Especially, the salinity keeps increasing along the feed-concentrate channel and can reach twice the sea water salinity at the concentrate port.

$$\rho = \rho_0 + A_1(C \cdot 10^{-3}) + B_1(C \cdot 10^{-3})^{1.5} + D_1(C \cdot 10^{-3})^2 \quad (3.22)$$

$$\begin{aligned} \rho_0 = & 999.843 + 6.794 \times 10^{-2} T - 9.095 \times 10^{-3} T^2 + 1.002 \times 10^{-4} T^3 \\ & - 1.12 \times 10^{-6} T^4 + 6.536 \times 10^{-9} T^5 \end{aligned} \quad (3.23)$$

$$\begin{aligned} A_1 = & 8.245 \times 10^{-1} - 4.09 \times 10^{-3} T + 7.644 \times 10^{-5} T^2 - 8.247 \times 10^{-7} T^3 \\ & + 5.388 \times 10^{-9} T^4 \end{aligned} \quad (3.24a)$$

$$B_1 = -5.725 \times 10^{-3} + 1.023 \times 10^{-4} T - 1.655 \times 10^{-6} T^2 \quad (3.24b)$$

$$D_1 = 4.831 \times 10^{-4} \quad (3.24c)$$

Where ρ_0 is the density of pure water kg/m^3 , C is water salinity mg/s , A_1 , B_1 and D_1 are coefficients.

3.1.5 Temperature Correction Factor and Pressure Drop

Beside the fouling and scaling, membrane water and salt permeability coefficients (A_w B_s) are influenced by feed temperature as well, it affects the membrane material and water viscosity, which lead to variance in the transport rate. The RO membrane

manufactures experimentally determine the permeability coefficient at typical a value 25 °C, as temperature increases, the permeability rises by 3% per °C [47]. TCF value is normally obtained by each manufacturer separately, and for FilmTec™ TCF is expressed by the following eq (3.25a-b) [32]:

$$\text{TCF} = \exp \left[2640 \left(\frac{1}{298} - \frac{1}{273 + T} \right) \right] \quad T > 25 \text{ } ^\circ\text{C} \quad (3.25a)$$

$$\text{TCF} = \exp \left[3020 \left(\frac{1}{298} - \frac{1}{273 + T} \right) \right] \quad T \leq 25 \text{ } ^\circ\text{C} \quad (3.25b)$$

The pressure drop P_d bar along length Δz m inside the spiral wound module is calculated in Equation (3.26) [27]:

$$P_d = - \frac{\Delta z \ 6.23 \ K}{2 \ d_H} \left(\frac{\rho_i Re_i^{-0.3} v_i^2}{2} + \frac{\rho_{i+1} Re_{i+1}^{-0.3} v_{i+1}^2}{2} \right) \times 10^{-5} \quad (3.26)$$

Where K is friction factor correction parameter and is taken as 2.4 [27].

3.1.6 RO System Performance

Specific Energy Consumption (SEC) kWh/m³ and permeate quality mg/L are the main factors that reflect the performance of RO system. Performance can be improved by reducing the SEC, increase the permeate quality (getting lower permeate salinity) or both

of them. SEC is evaluated by dividing the energy consumption E_w kWh/d on the produced permeate Q_p m³/d, as given in Equations (3.27, 3.28) [27, 32].

$$SEC = \frac{E_w}{Q_{p,sys}} \quad (3.27)$$

$$\begin{aligned} E_w &= \frac{1}{36} \sum \frac{\Delta P_{device} Q_{f,device}}{\eta_{device}} \\ &= \frac{Q_f}{36\eta_{motor}} \left\{ \frac{RR (P_f - P_{inlet})}{\eta_{HPP}} \right. \\ &\quad \left. + \frac{(1 - RR)[(P_f - P_{inlet}) - \eta_{ERD}(P_c - P_{outlet})]}{\eta_{Bp}} \right\} \end{aligned} \quad (3.28)$$

Where η_{motor} , η_{HPP} , η_{Bp} and η_{PX} are the efficiencies of electric motor, the high-pressure pump, the booster pump, the energy recovery device. P_c is the concentrate pressure bar, P_{inlet} and P_{outlet} are pressure of inlet that coming from pre-treatment plant and pressure of outlet saline water that discharge from RO system.

3.1.7 RO System Discretization

The feed water characteristics continuously change along the RO module (such as salinity, osmotic pressure, hydraulic pressure, density, viscosity...). Also, simultaneous solving of the model equations is required to obtain the RO performance. Therefore, to improve the calculation accuracy, the RO module is discretized into 25 segments per each membrane on one direction as shown in Figure (3.6), where the Pressure vessel (PV_{ro}) usually contains 6 to 8 membranes.

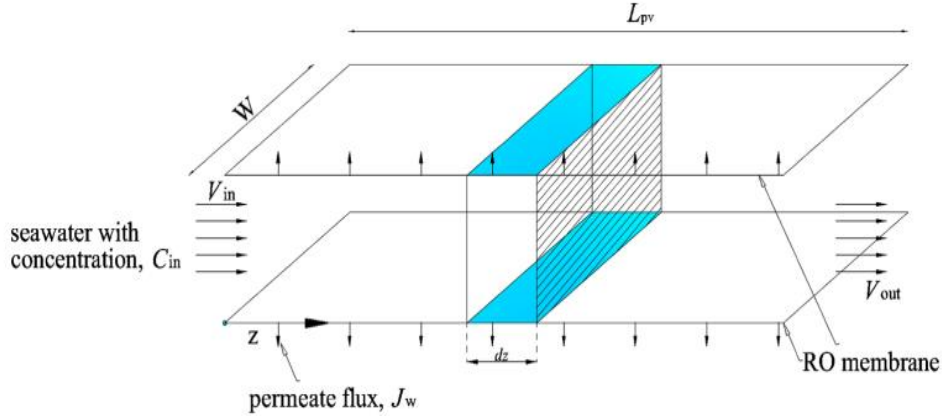


Figure 3.6: One dimension discretize segment on rectangle flow channel [29]

3.1.8 RO System Assumption

The basic assumptions for the RO modeling are as follows:

- The curvature of the channels is neglected, and the feed flows inside a flat channel, because the channel thickness is much lower than the module radius.
- The pressure drop inside the permeate channels is negligible.
- The membrane width is much larger than membrane height
- Flow variation is in one direction.
- Fouling factor is constant with the time and equal 0.85.

3.1.9 Product Cost of Desalted Water for SWRO System

The unit product cost (*UPC*) \$/m³ can be determined using Equation (3.29), which takes into account the total capital cost CC_{total} and total operation cost OC_{total} [27,29]

$$UPC = \frac{1}{365Q_p} \left[CC_{total} \frac{Ir(1+Ir)^y}{(1+Ir)^y - 1} + OC_{total} \right] \quad (3.29)$$

Where Q_p is total produced permeate m³/day, Ir is the interest rate set to be 8%, y is the RO plant lifetime assumed 25 years. An estimation of CC_{total} and OC_{total} can be derived by utilizing simplified cost equations as presented below [27,29]:

$$CC_{total} = 1.411(CC_{SWIP} + CC_{hpp} + CC_{ERD} + CC_m) \quad (3.30)$$

$$CC_{SWIP} = 996(Q_f)^{0.8} \quad (3.31a)$$

$$CC_{hpp} = \frac{52}{24}(\Delta P_f Q_f) \quad (3.31b)$$

$$CC_{ERD} = 3134.7 \left(\frac{Q_c}{24} \right)^{0.58} \quad (3.31c)$$

$$CC_m = \sum C_m n_m n_{PV} + \sum C_{PV} n_{PV} \quad (3.31d)$$

$$OC_{total} = OC_m + OC_e + OC_{insure} + OC_{labor} + OC_{ch} + OC_{main} \quad (3.32)$$

$$OC_m = 0.2 CC_m \quad (3.33a)$$

$$OC_e = 365 C_e f_c E_w \quad (3.33b)$$

$$OC_{insure} = 0.005 CC_{total} \quad (3.33c)$$

$$OC_{labor} = 0.01 \times 365 Q_p f_c \quad (3.33d)$$

$$OC_{ch} = 0.0225 \times 365 Q_f f_c \quad (3.33e)$$

$$OC_{main} = 0.01 \times 365 Q_p f_c \quad (3.33f)$$

Where CC_{SWIP} , CC_{hpp} , CC_{ERD} , and CC_m are the capital cost of the seawater intake and pretreatment (SWIP), the pressure pumps, the energy recovery device, and membranes and pressure vessel, respectively \$. the coefficient 1.411 represent the indirect cost associated with the capital cost, C_m is the membrane price \$. n_m is the number of membrane element inside the pressure vessel, n_{PV} is the number of pressure vessel, and C_{PV} is the price of the pressure vessel \$. Q_f and Q_c are feed and concentrate flow rate for the RO system m³/day, ΔP_f is the pressure difference across the pump Bar.

Also, OC_m , OC_e , OC_{insure} , OC_{labor} , OC_{ch} , OC_{main} are the operation cost for membrane replacement, energy, insurance, annual labor, chemical supply, and maintenance, respectively \$. RO plant load factor f_c are assumed to be 0.9, and C_e is Electricity cost \$/kWh obtained from HOMER software by design the optimum PVs configuration, as shown in section 6.2.2 the value is 0.426 \$/kWh.

3.2 Photovoltaic PVs Modeling

Photovoltaic system (PVs) is used to provide the required energy to the RO system in electrical form, this energy is obtained directly from solar radiation, which is converted inside the PVs into electrical power. The RO electrical load profile is simulated by using HOMER simulation software; one of popular renewable energy software that give the best configuration of PVs system that contains number of PVs panels, number of batteries and size or converter.

In the following section, an elaboration of the mathematical model used to calculate the incident radiation on the PV_s panel and the converted amount to electrical power is presented.

3.2.1 Incident and Absorbed Radiation

By using the Isotropic diffuse sky model, Liu and Jordan [49] reported that total incident radiation on a tilted surface (I_T) is expressed by:

$$I_T = I_b R_b + I_d \left(\frac{1 + \cos \beta}{2} \right) + I \rho_g \left(\frac{1 - \cos \beta}{2} \right) \quad (3.34)$$

Where ρ_g is the reflectance of the ground and is assumed to be 0.2. I_b and I_d W/m² are direct and diffuse radiations and β is the tilt angle for the collector.

R_b is the ratio of direct radiation between the tilted surface and horizontal surface and is expressed by:

$$R_b = \left(\frac{\cos \theta_1}{\sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega} \right) \quad (3.35)$$

Where ϕ [°N] is latitude, ω is the average hour angle, δ is declination angle and θ_1 is the incidence angle.

$$\theta_1 = \cos^{-1}(\cos \delta \cos \omega) \quad (3.36)$$

By knowing the extra-terrestrial hourly radiation (I_{ET}) W/m² we can determine I_b and I_d :

$$I_{ET} = \frac{12 \times 3600}{\pi} G_{SC} \left(1 + 0.033 \cos \frac{360n}{365} \right) \times \left[\frac{\pi(\omega_2 - \omega_1)}{180} \sin \phi \sin \delta + \cos \phi \cos \delta (\sin \omega_2 - \sin \omega_1) \right] \quad (3.37)$$

Where G_{SC} W/m² is the solar constant with a value of 1367 W/m², ω_2 and ω_1 are the hour angles, n is the number of days in a year.

The hourly clearness index, k_t is determine by:

$$k_t = \frac{I}{I_{ET}} \quad (3.38)$$

To determine the diffuse hourly radiation (I_d), Erbs et al. (1982) correlation [49] is used:

$$\frac{I_d}{I} = 1 - 0.9k_t \quad \text{for } k_t \leq 0.22 \quad (3.39a)$$

$$\frac{I_d}{I} = 0.95 - 0.16k_t + 4.39k_t^2 - 16.64k_t^3 + 12.37k_t^4 \quad \text{for } 0.22 \leq k_t \leq 0.8 \quad (3.39b)$$

$$\frac{I_d}{I} = 0.165 \quad \text{for } k_t > 0.8 \quad (3.39c)$$

I_b can be determined by:

$$I_b = I - I_d \quad (3.40)$$

Using Isotropic diffuse sky model by Liu and Jordan [49], solar energy absorbed by a tilted collector, S [W/m²] can be calculated by:

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1 + \cos \beta}{2} \right) + I \rho_g (\tau\alpha)_g \left(\frac{1 - \cos \beta}{2} \right) \quad (3.41)$$

The transmittance-absorptance products ($\tau\alpha$) rely on the optical properties of glazing material (glass) and the incident angle of the radiation. It can be estimated by the following approximation:

$$(\tau\alpha) \cong 1.01\tau\alpha \quad (3.42)$$

The PVs absorptance α remains constant, but the glass transmittance is affected by the angle of radiation, B. Muehl and Beckman (1980) relation [49] for calculating effective incidence angle based on the Isotropic diffuse sky model is used.

$$\theta_g = 90 - 0.58\beta + 0.0027\beta^2 \quad (3.43)$$

$$\theta_d = 59.7 - 0.14\beta + 0.0015\beta^2 \quad (3.44)$$

The relationship between glass transmissivity τ and angle of radiation θ is defined as follows:

$$\tau = \tau_a \tau_r \quad (3.45)$$

$$\tau_a = \tau_a e^{-K_g L_g} \quad (3.46)$$

Where K_g is the extinction coefficient of glass and L_g is the thickness of glass.

3.2.2 Electrical Model for PVs System

A portion of solar energy absorbed $S \text{ W/m}^2$ by solar cell is converted into electrical power and the remainder is converted into heat as thermal energy, an electrical five-

parameter model [50] is used to find the maximum value for voltage (V_{mp}) volt, current (I_{mp}) Ampere, power (P_{mp}) W and efficiency (η_{mp}).

Initially, values are determined for reference conditions, i.e., 25 °C and 1000 W/m², which are known from each PV_S module. Then, the values at reference conditions are substituted in the five-parameter model to determine the output values at cell temperature (T_c) and actual absorbed radiation (S).

The electrical power, P_{mp} and efficiency, η_{mp} will be [49]:

$$P_{mp} = I_{mp}V_{mp} \quad (3.47)$$

$$\eta_{mp} = \frac{P_{mp}}{I_T A_c} \quad (3.48)$$

Where A_c m² is the collector area.

CHAPTER 4

VALIDATION

4.1 Validation Against Literature Studies

4.1.1 Jungbin. K, Seungkwan. H [27]

Jungbin K and Seungkwan H [27] have developed a novel single-pass reverse osmosis (RO) configuration to enhance RO performance by improving the quality of the permeate while maintaining lower energy consumption compared to a two-pass RO system. This configuration, called Split Partial Single-Pass (SSP), involves splitting the permeate from the rear elements of the pressure vessel and mixing it with the feed flow. This dilutes the feed and reduces the osmotic pressure, thereby improving the overall performance of the RO system.

Our model was validated against the SEC and permeate quality (performance) of the study [27]. The SSP configuration comprises 7 identical elements per pressure vessel, and the split ratio ranges from SSP7 (where only the permeate product from the 7th element is mixed with the feed) to SSP 4-7 (where the permeate products from elements 4 through 7 are mixed with the feed). Our model demonstrated good agreement with the experimental data, as shown in Table (4.1) and Figure (4.1), under the operating conditions of feed

salinity 35,000 mg/L, temperature 25 °C, fouling factor 1, SWRO average flux 12.81 LMH, SWRO recovery rate 40%, and BWRO recovery rate 80%.

The SWRO and BWRO membranes used in this study were SW30HRLE-400i and BW30-400, respectively. The water and salt permeability coefficients (A_w and B_s) for SWRO were calculated to be 1.25 L/m² h bar and 5.82×10^{-5} m/h, respectively, while for BWRO, they were 3.29 L/m² h bar and 1.92×10^{-4} m/h, respectively.

Table 4.1: Comparison of permeate salinity and SEC obtained by thesis model against study [27]

	Permeate Salinity [mg/L]			Specific Energy Consumption (SEC) [kWh/m3]		
	Reference [1]	Model	Diff %	Reference [1]	Model	Diff %
Single Pass	225	229	1.80%	2.11	2.12	0.50%
SPSP	122	128	4.90%	2.22	2.22	0.00%
SSP7	190	197	3.70%	2.17	2.2	1.40%
SSP6-7	162	169	4.30%	2.29	2.32	1.30%
SSP5-7	136	141	3.70%	2.51	2.55	1.60%
SSP4-7	111	116	4.50%	2.91	2.97	2.10%

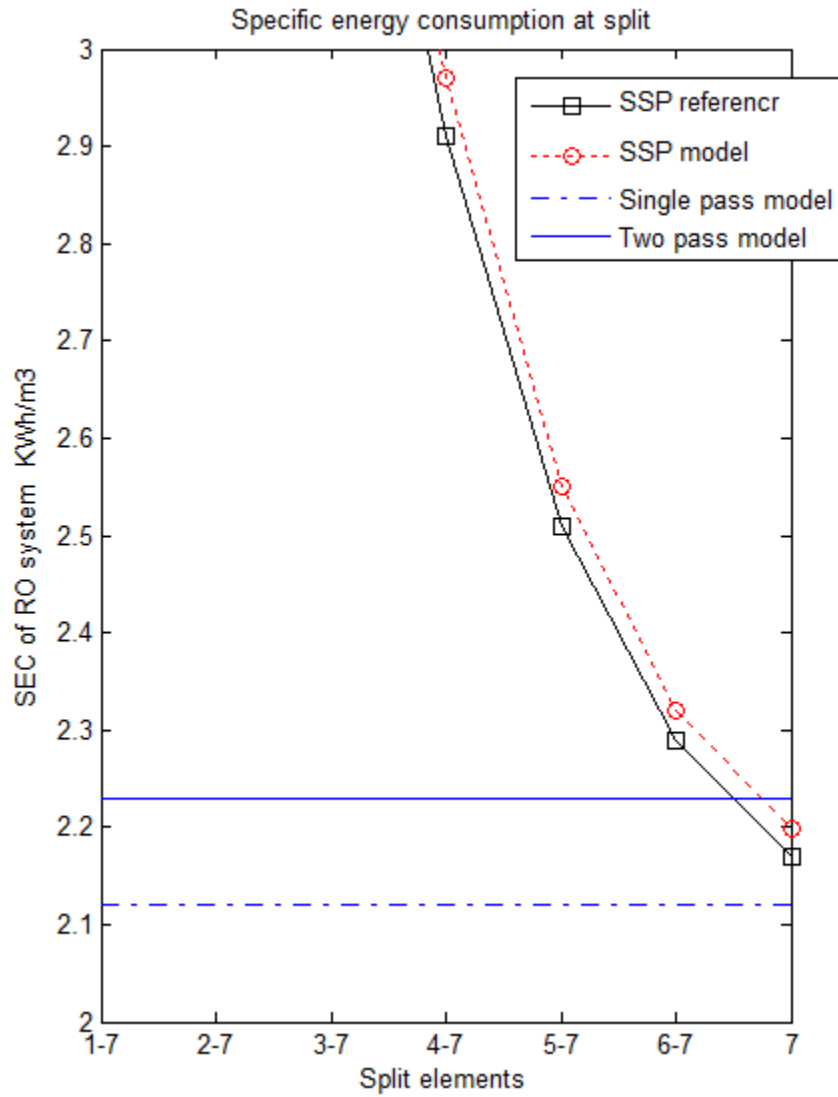


Figure 4.1: Validation of SEC at different split ratios

Furthermore, we have conducted a validation of the permeate quality at various feed salinity levels, ranging from 32,000 to 42,000 mg/L, as illustrated in Figure (4.2). The operating conditions for this validation experiment were a temperature of 25 °C, a fouling factor of 1, an SWRO average flux of 12.81 LMH, and an SWRO recovery rate

of 40%. The results of this validation demonstrate good performance of the system under these conditions.

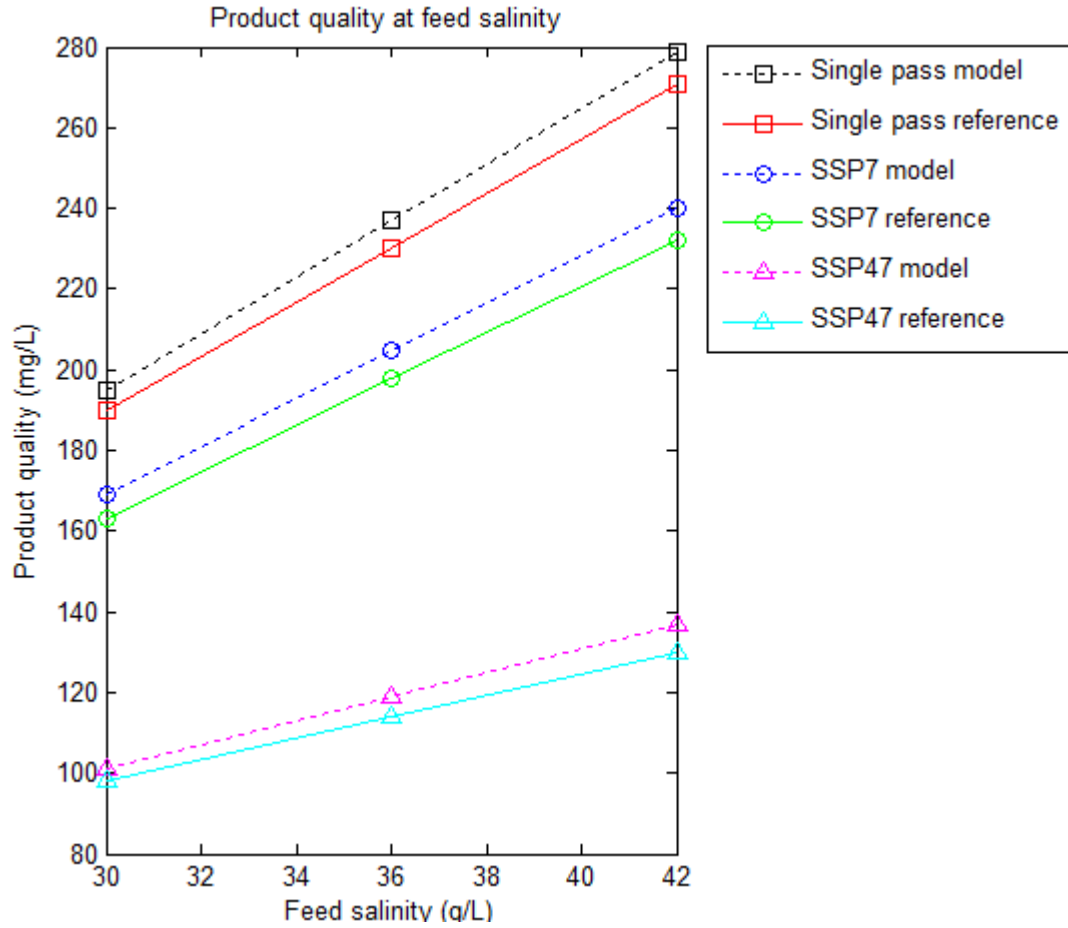


Figure 4.2: Validation of product quality at different feed salinity

4.1.2 Geraldes V, and Nuno E, [51]

In their study, Geraldes V and Nuno E [51] optimized a newly developed numerical model for spiral-wound modules using experimental field data from an SWRO plant in Portugal. The model incorporates the longitudinal variation of pressure, feed flow rate, concentration, and other relevant parameters along the downstream as its main

considerations. The optimized model was utilized to design a single-stage, medium-sized SWRO plant with a daily capacity of 1000 m³. The plant comprises pressure vessels in parallel, each accommodating seven spiral-wound modules in series. The modules used in this plant were FilmTec SW30HR-380 (Dow Chemical Company), and their properties are presented in Table (4.2).

Table 4.2: FilmTec SW30HR-380 properties [53]

Properties	Value
Effective membrane area	35 [m ²]
Effective membrane leaf length	0.88 [m]
Effective membrane leaf width	0.69 [m]
number of membrane leaves	29 [-]
feed cross-section open area	0.0147 [m ²]
Feed spacer Hight	0.737 [mm]
Maximum flow rate	440.64 [m ³ /day]
maximum feed pressure	82 [Bar]

The membrane water permeability A_w and salt permeability B_s are not directly provided by the membrane manufacturers. Instead, they can be estimated based on a

standard operating condition for one module, and adjusted for actual temperature and fouling factor. For this study [51], the obtained values were 0.864 LMH/bar (2.4×10^{-12} m/s.pa) and 7.2×10^{-5} m/h (2×10^{-8} m/s), respectively, at 20°C.

To verify our model, we utilized the above module parameters and conducted three different cases (set points) to produce a permeate flow of 1000 m³/day. We assumed a fouling factor of 1, and input feed water salinity and temperature of 38 [kg/m³] and 20°C, respectively, for all cases. Tables (4.3-4.5) compare the output values obtained from our model with those from the study [51] under steady-state conditions and with the same parameters. The results show good agreement, with a maximum difference of 4%. Moreover, the difference becomes lower at higher recovery rates.

Table 4.3: Case 1, validation at feed pressure 54.5 bar, inlet feed velocity 0.186 m/s, feed salinity 38 kg/m³ (38,000 mg/L), 14 pressure vessels, and temperature 20 °C.

	Permeate flow [m ³ /day]	Recovery rate [%]	Concentrate flow [m ³ /day]	Average flux [L/m ² .h]
Value from [51]	1,000	30	2,307	12.1 (3.36×10^{-6} m/s)
Predicted from model	959	29	2,349	11.6
Error %	4%	3%	2%	4%

Table 4.4: Case 2, validation at feed pressure 63.4 bar, inlet feed velocity 0.178 m/s, feed salinity 38 kg/m³, 11 pressure vessels, and temperature 20 °C.

	Permeate flow [m ³ /day]	Recovery rate [%]	Concentrate flow [m ³ /day]	Average flux [L/m ² .h]
Value from [51]	1,000	40	1487	15.5 (4.31x10 ⁻⁶ m/s)
Predicted from model	980	39.5	1506	15.2
Error %	2%	1%	1%	2%

Table 4.5: Case 3, validation at feed pressure 71 bar, inlet feed velocity 0.192 m/s, feed salinity 38 kg/m³, 9 pressure vessels, and temperature 20 °C.

	Permeate flow [m ³ /day]	Recovery rate [%]	Concentrate flow [m ³ /day]	Average flux [L/m ² .h]	Permeate salinity [mg/L]
Value from [51]	1,000	45.3	1195	18.9 (5.25x10 ⁻⁶ m/s)	233 (0.233 kg/m ³)
Predicted from model	991	45.2	1203	18.7	223.6
Error %	1%	0%	1%	1%	4%

4.1.3 Yawei. D et al [29].

Our model was validated against the unit product cost (UPC) of the study Yawei. D et al [29]. the configuration consists of single pass single stage process flow and the feed

concentration varied from 32 to 38 kg/m³ while the product demand maintained constant 120 m³/h. The parameters for RO Desalination Model are listed in Table (4.6)

Table 4.6: Parameters for the RO Desalination Model [29]

RO plant load factor, fc	0.9
Cost of electricity, Ce [\$ /kWh]	0.08
Pressure vessel cost (estimation) [\$]	1000
Membrane element cost [\$] (estimation) SW30XLE-400	1200
Interest rate %	5
Plant lifetime, year	25

Our model of UPC demonstrated good agreement with the design data, as shown in Table(4.7)

Table 4.7: Comparison of UPC obtained by thesis model against study [29]

concentration [kg/m³]	38	35	32
System feed flow [m ³ /h]	229.4	217.9	210.3
System product flow [m ³ /h]	120	120	120
System overall recovery [%]	52.3	55.1	57.1
Product concentration [kg/m ³]	500	500	490
Membrane type	SW30XLE-400	SW30XLE-400	SW30XLE-400
Number of elements per PV	6	7	7
Number of PV in stage 1	27	24	25
Operation pressure [MPa]	7.49	7.22	6.84
Unit product cost [\$ /m ³] from literature [29]	0.538	0.519	0.502
Unit product cost [\$ /m ³] Predicted from model	0.54	0.516	0.497
Error %	0.4%	-0.6%	-1.0%

4.2 Validation Against Software WAVA

Water Application Value Engine (WAVE) [52] Figure (4.3), is a modeling software program for water treatment plant design that is owned by Dow Chemical Company. It integrates pretreatment, reverse osmosis, and post-treatment into a comprehensive tool. In our study, we utilized this recognized software to validate our model. Two cases with some differences in feed water input values were used, and the results are presented in Table (4.8). The SW30HR LE-400i membrane was used, and the water and salt permeability parameters were calculated based on standard experimental results and found to be 1.27 LMH and 5.77×10^{-5} m/h, respectively.



Figure 4.3: WAVE RO design software from Dow [52]

Table 4.8: Feed water input values for two cases

	Case 1	Case 2
Membrane name (Dow)	SW30HR LE-400i	SW30HR LE-400i
Feed flow rate [m ³ /day]	176.6	176.6
Feed pressure [bar]	55	60
Feed concentration TDS [mg/L]	32,078	40,106
Feed water temperature [°C]	25	35
Fouling factor	0.85	0.85

In our study, one pressure vessel contained 7 membranes that were evaluated under the aforementioned parameters. The permeate quality of the WAVE software was plotted against the predicted model value, as shown in Figure (4.4). Both cases demonstrated good agreement in the figures, indicating the accuracy of our model.

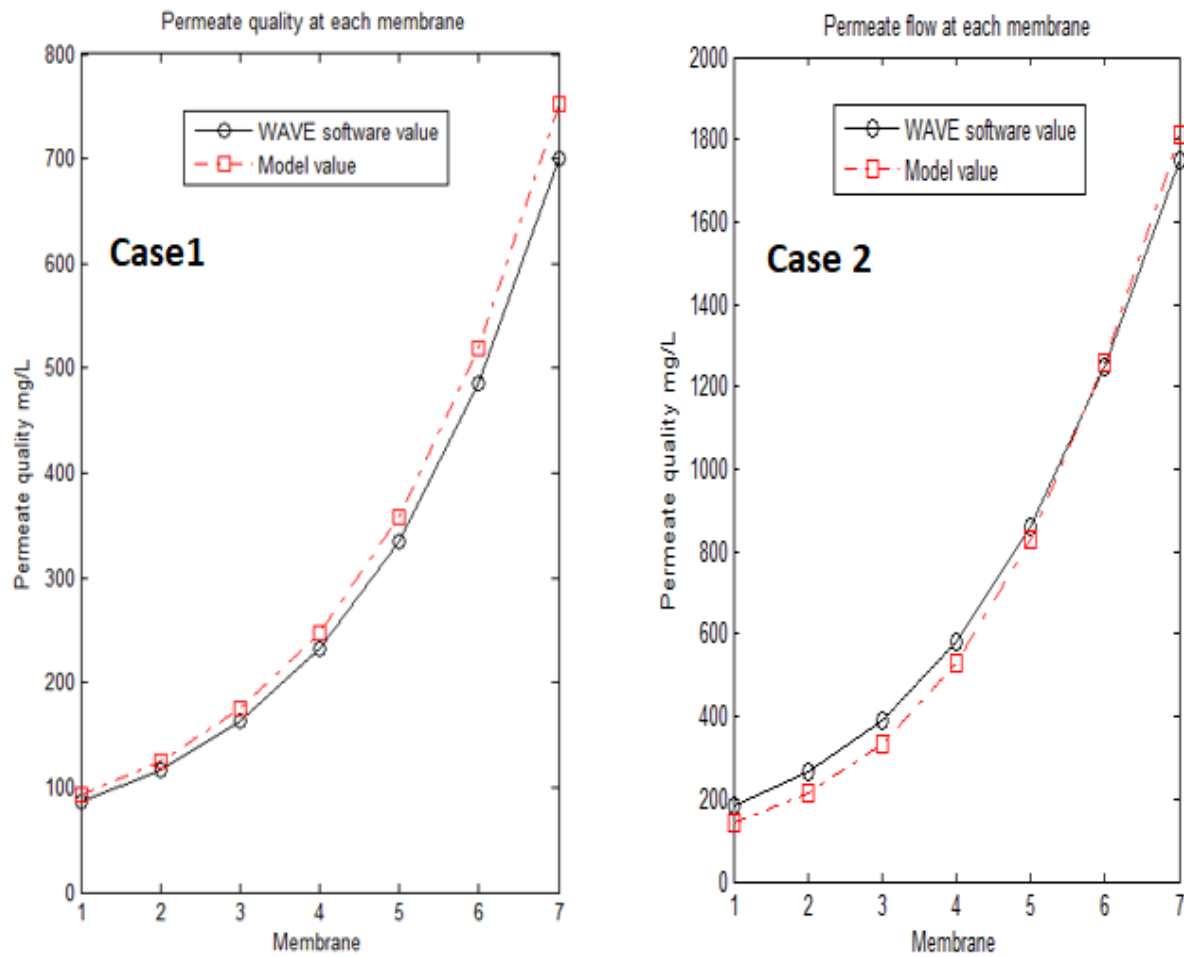


Figure 4.4: Validate Permeate quality (Cp) at each membrane case 1 and 2

Additionally, the permeate flow rate m^3/day was compared between the two cases, and the results are presented in Figure (4.5). The figures demonstrate good agreement between the predicted model values and those obtained from the WAVE software for both cases.

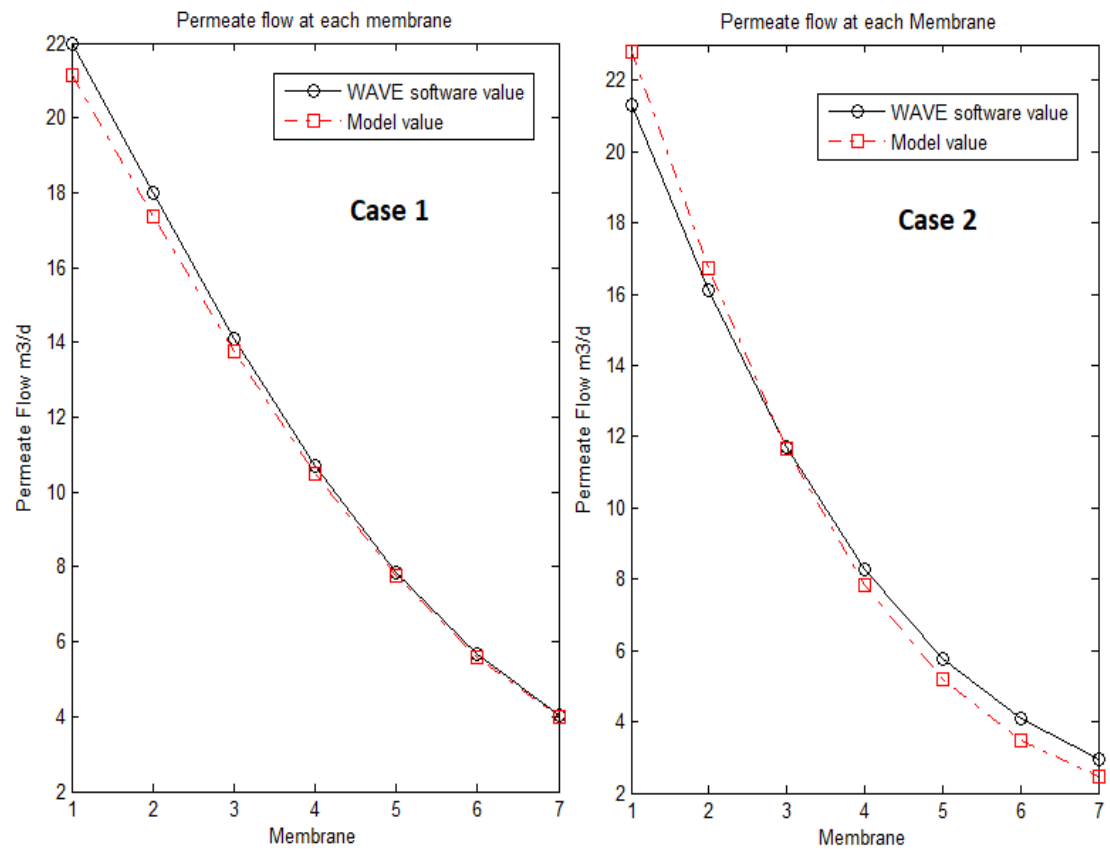


Figure 4.5 : Validate Permeate flow (Q_p) at each membrane case 1 and 2

CHAPTER 5

MATERIAL AND CONFIGURATION

The system comprises two distinct subsystems: Off-grid Photovoltaic and SWRO. The Off-grid Photovoltaic subsystem includes a PV_S module, inverter, a charge controller, and a battery, which provide the necessary electrical power to the SWRO unit. The SWRO unit, as depicted in Figure (5.1), is composed of membrane modules, high-pressure and boost pumps, and an energy recovery device (Pressure exchanger).

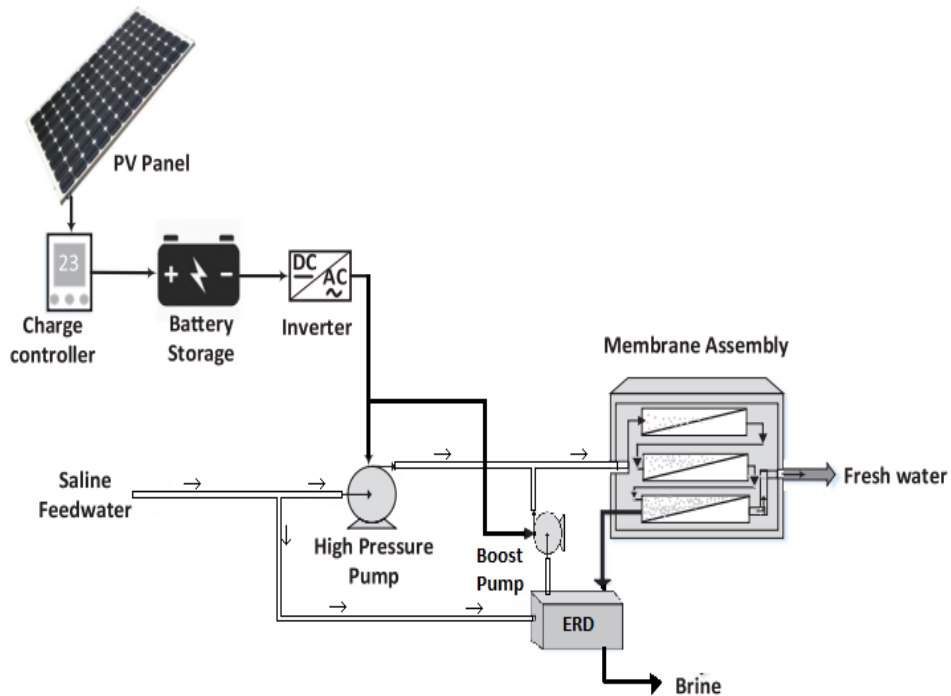


Figure 5.1: A schematic diagram of the PV-SWRO system

5.1 SWRO System Configuration

Split Partial Single-Pass (SSP) is an improved single-stage single-pass RO unit that was recently introduced by Jungbin K and Seungkwan H [27]. By enhancing permeate quality while maintaining lower energy consumption than a two-pass RO system, it improves RO performance. The SSP configuration involves splitting the permeate from the rear elements inside the pressure vessel and mixing it with the feed flow, consequently, the feed is diluted and the osmotic pressure is decreased. The diluted feed is then pressurized by a high-pressure pump (HP) and enters the pressure vessel, which contains several membranes connected in series. The concentrate port then removes the high salinity concentrate, which is sent to the PX (an energy recovery device) to leave the SWRO unit at low pressure while recovering some of the feed's pressure energy. The boost pump (BP) is used to recover the pressure loss after the PX device, as depicted in Figures (5.2, 5.3).

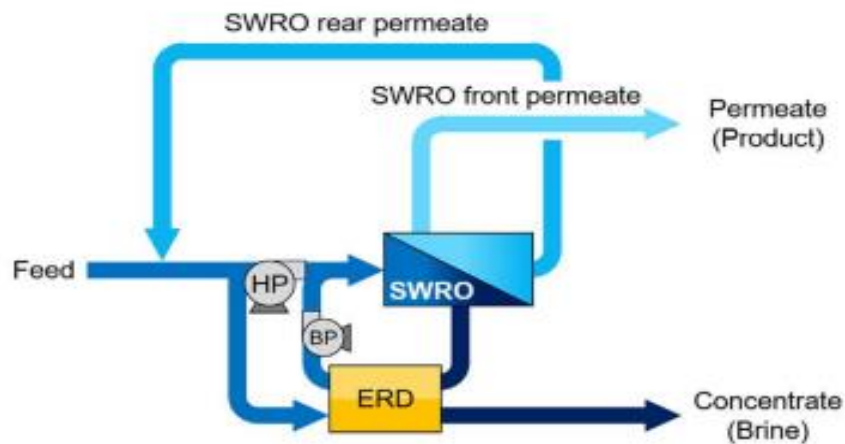


Figure 5.2: Split partial single-pass configuration (SSP) [27]

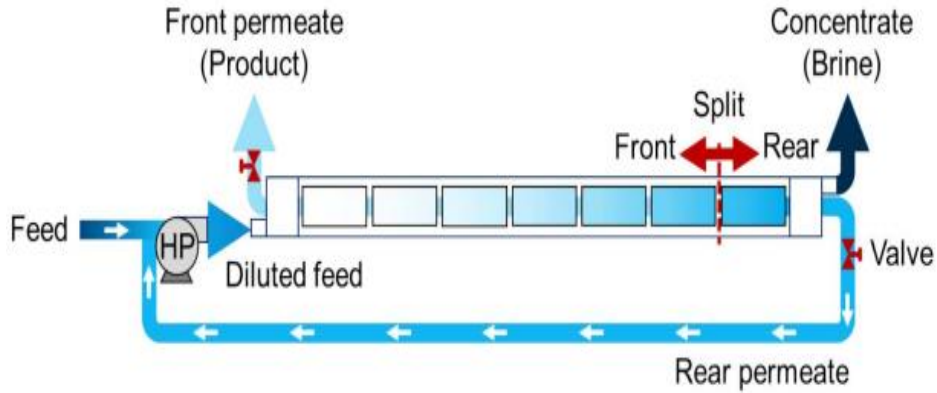


Figure 5.3: Schematic design of single-pass split partial (SSP) [27]

Using MATLAB software, a thorough investigation was conducted to assess and optimize the performance of the most recent Reverse Osmosis (RO) novel, Split Partial Single-Pass (SSP), under various circumstances and designs. This investigation included a study of the impact of high feed salinity of 45,000 mg/L, fouling factor (FF), density kg/m^3 as a function of feed salinity and temperature, and the inner membrane design, which used an internally staged design (ISD) and several membranes inside the pressure vessel (PV_{ro}). As shown in Figures (5. 4 and 5. 5), the performance of SSP was contrasted with that of a single pass (single stage) and an SPSP split partial second pass.

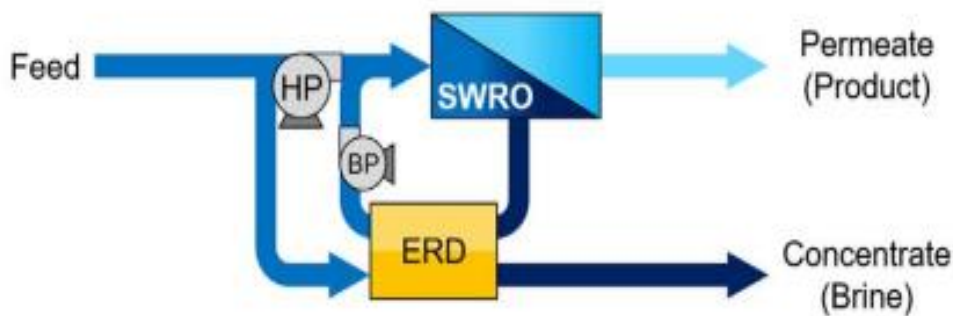


Figure 5.4: Configuration of single pass (single stage) [27]

A Split Partial Second Pass (SPSP) RO configuration was used in this study, where the permeate was split between the 4th and 5th membranes. The front permeate was sent to the final product and the rear permeate was sent to the second pass. Additionally, the concentrate from the brackish water RO was recycled back into the main feed to decrease its salinity.

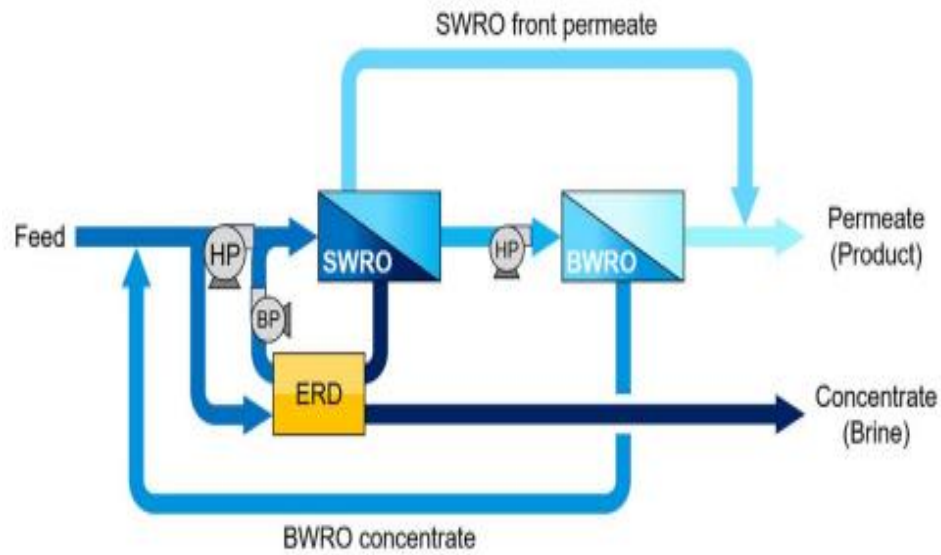


Figure 5.5: Configuration of a Split partial second pass (SPSP) [27]

The Internally Staged Design (ISD) involves using Reverse Osmosis (RO) membranes with different characteristics inside the pressure vessel to achieve uniform flux distribution. This is accomplished by positioning the pressure vessel's front with a high-rejection membrane and its back with an element of low rejection. Three types of FilmTec SWRO membranes from DOW were used in this study and classified as high-rejection (H1), intermediate (H2), and high-flux (H3) based on their calculated water and salt permeability (A_w and B_s). The pressure vessel was positioned with the high-rejection membrane at the front, the intermediate membranes in the middle, and the low-flux

membrane on the back, as depicted in Figure (5.6). Based on the type and number of membranes used inside the pressure vessel, a three-digit number was assigned for identification purposes.

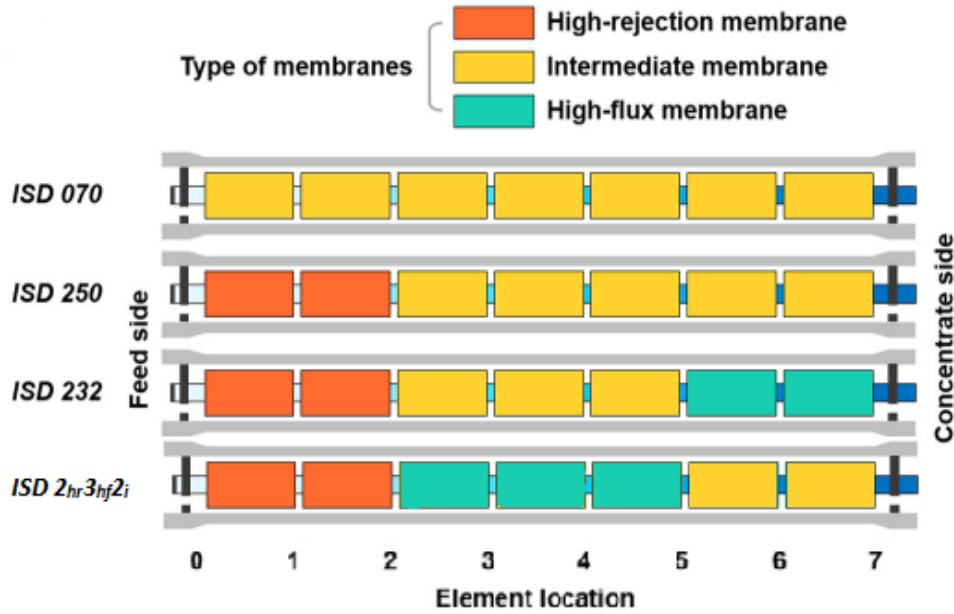


Figure 5.6: ISD membranes combination inside pressure vessel [32]

To identify the specific combination of RO membranes used in the Internally Staged Design (ISD), a three-digit number was assigned based on the number of high-rejection (H1), intermediate (H2), and high-flux (H3) membranes used inside the pressure vessel. For instance, ISD 070 indicates the use of 0 high-rejection (H1), 7 intermediate (H2), and 0 high-flux (H3) membranes, while ISD 232 consists of 2 high-rejection (H1), 3 intermediate (H2), and 0 high-flux (H3) membranes. In some cases, unusual combinations were tested by placing the high-flux membranes before the intermediate ones. For example, in ISD 2_{hr}3_{hf}2_i (an identification for an unusual combination), the arrangement was 2 high-rejection (H1), 3 high-flux (H3), and 2 intermediate (H2) membranes.

Table 5.1: FilmTec Spiral-Wound Reverse Osmosis Membrane Characteristics [27, 53, 29, 62]

	SW30XHR-440i (high-rejection H1)	SW30HRLE-400i (intermediate H2)	SW30XLE-440i (high-flux H3)	BW30-400
Standard water permeability coefficient A_w , [L/m ² .h.bar] ^{b, c}	1.02	1.25	1.54	3.29
Standard salt permeability coefficient B_s , [m/h] ^{b, c}	4.16×10^{-5}	5.82×10^{-5}	6.92×10^{-5}	1.92×10^{-4}
Diameter of the membrane, [m]	0.201	0.201	0.201	0.201
The total length of the membrane, [m]	1.016	1.016	1.016	1.016
Effect length of the membrane, [m]	0.88	0.88	0.88	0.88
Feed spacer thickness, [mil] ^a	28	28	28	28
Active area, [m ²]	41	37	41	37
Maximum operating pressure, [bar]	83	83	83	41
Maximum operating temperature, [°C]	45	45	45	45
Maximum feed Silt density index	SDI 5	SDI 5	SDI 5	SDI 5
Permeate flowrate, [m ³ /d] ^{b, c}	25	28	37.4	40
Salt rejection, (%) ^{b, c}	99.82	99.75	99.8	99.5
Membrane cost, \$ [62]	899	960	1,159	774

a 1 mil = 0.0254 mm.

b The following benchmark conditions of SW membranes: 32, 000 ppm NaCl, 800 psi (5.5 MPa), 77° F (25° C), pH 8, and 8% recovery. **c** The following benchmarks of BW membrane values: 2, 000 ppm NaCl, 225 psi (15.5 bar), 77° F (25° C), pH 8, and 15% recovery.

The characteristic of the Spiral-Wound SWRO and BWRO membranes are given in Table (5.1). Additionally, Table (5. 2) lists the parameters used in the RO calculation.

Table 5.2: Parameters for the RO Desalination Model [27, 29, 46]

Parameter	Value
Universal gases constant, R [J/K mol]	8.314
the molecular weight of the solute, M_w [g/mol]	58.44
high-pressure pump efficiency, η_{HPP} [-]	80%
Boost pump efficiency, η_{BP} [-]	60%
pressure exchanger efficiency, η_{PX} [-]	95%
electric motor efficiency, η_{motor} [-]	98%
friction factor correction parameter, K [-]	2.4
Feed water Silt Density Index (SDI) [-]	5
Fouling factor, FF [-]	0.85
Pressure vessel cost, \$	1,000

5.2 Stand-Alone Photovoltaic System Configuration

The Photovoltaic (PV_s) module is responsible for converting the incident solar irradiation into direct current (DC) electricity. The electricity is then directed to the controller, which supplies the DC electricity to the inverter based on the required power by the SWRO desalination unit. The inverter, in turn, converts the DC electricity to alternating

current (AC) and connects it to the load. Any excess DC electricity is directed to the battery for storage and later use when the produced electricity by the PV_s module is insufficient.

The high-pressure and boost pumps are the primary loads that consume the electrical energy in the system. These loads were simulated using HOMER [54], one of the popular renewable energy software used to evaluate the performance and optimal sizing of Photovoltaic (PV_s) systems.



Figure 5.7: Canadian Solar Maxpower CS6U-340M 340W [55]

The study's PV_s module, CS6U-340M, is constructed of Monocrystalline silicon and has a rated power of 340 W [55]. Table (5.3) lists its specifications.

Table 5.3: Specification of Canadian Solar Maxpower CS6U-340M module [55]

Standard Test Conditions(S. T. C.) for Electrical Performance	
Model	CS6U-340M
Cell Type	Monocrystalline

Dimension	1891 mm x 958 mm
Rated power, [W]	340
Open-circuit voltage, [V]	46.2
Short-circuit current, [A]	9.48
PV module electrical efficiency	17.49 %
Number of cells	72
The voltage at max power, [V]	37.9
Current at max power, [A]	8.97
STC: Irradiance 1000 W/m ² , AM 1.5 spectrum, module temperature 25°C	

Solar radiation and module temperature have a big impact on the PV_s module's output power. To simulate the PV module, the solar irradiation input was obtained from NASA Atmospheric Science Data Center [56]. In this study, the HOMER software was used to simulate the PV_s module using this data.

The study's Battery SSIG 12 255, from Trojan is Lead Acid Battery and has a rated capacity of 255 Ah [57]. Table (5.4) lists its specifications.



Figure 5.8: Trojan SSIG 12 255 Battery [57]

Table 5.4: Specification of Trojan SSIG 12 255 Battery [57]

Model	SSIG 12 255
Cell Type	Lead Acid Battery
Dimension	380 mm x 176 mm x 373 mm
Rated power, [W]	3060
Voltage, [V]	12
Amp capacity, [Ah]	255 @ 100 hr
Round trip efficiency	80 %
Max charge current, [A]	45
Max discharge current, [A]	300
Above value at temperature 25°C	

CHAPTER 6

RESULTS AND DISCUSSION

6.1 Effect of Operating Parameters on SSP Performance

The impact of operating parameters on the performance of the Split Partial Single-Pass (SSP) configuration is investigated to determine their effect on the specific energy consumption (SEC) and permeate salinity (C_p). The feed flow rate and feed pressure are manipulated to maintain a specific RO operating condition. The operating parameters investigated in this study include the average water flux, recovery ratio (RR), feed water density, number of membranes inside the pressure vessel, a combination of SSP with the Internally Staged Design (ISD), and flux distribution within pressure vessel.

6.1.1 Average Water Flux and Recovery Ratio

The typical mean water flux in a seawater reverse osmosis (SWRO) unit falls within the range of 12-17 LMH, while the recovery ratio ranges from 35-50% [13, 58]. In the present investigation, the performance of split mode operation (SSP) is assessed across varying levels of mean water flux and recovery ratio, spanning from 12 to 15 LMH and 35 to 45%, respectively. The comparative analysis is conducted against a conventional single pass (single stage) configuration, as depicted in Figure (6.1). For SSP7, an approach

involving the use of split is implemented before the seventh membrane element (i.e., the final membrane), given that it is the only viable solution when contrasted with a two-pass system (SPSP) [3].

The depiction of the single pass (single stage) configuration can be observed in red, while the SSP7 configuration is denoted in blue within Figure (6.1). The mean water flux values of 12, 13, 14, and 15 LMH are subject to evaluation for both configurations, whereby the recovery ratio (RR) is varied between 35% on the left-hand side and 45% on the right-hand side for each mean water flux value. Notably, an increase in the recovery ratio at constant mean water flux resulted in a reduced feed supply to the reverse osmosis (RO) pressure vessel, while the same amount of permeate is extracted. As a consequence, the feed osmotic pressure within the pressure vessel increases rapidly, thereby producing permeate with elevated salinity due to an increase in salt flux relative to water flux, as per Equation (3.10).

Under constant mean water flux, the permeate salinity for SSP7 is demonstrated to be approximately 15% lower than that of the single-pass configuration, whereas the rate of salinity increase observed for SSP7 in response to RR augmentation is lower than that of the single-pass. For example, at a mean water flux of 14 LMH, the disparity between the highest and lowest salinity values measures 20 mg/L for SSP7 (173 at RR 35% and 193 at RR 45%), and 28 mg/L for the single-pass (198 at RR 35% and 226 at RR 45%).

Evidently, these findings provide SSP7 with a competitive edge, as it can operate at a higher recovery rate while incurring less salinity increase relative to the single-pass configuration.

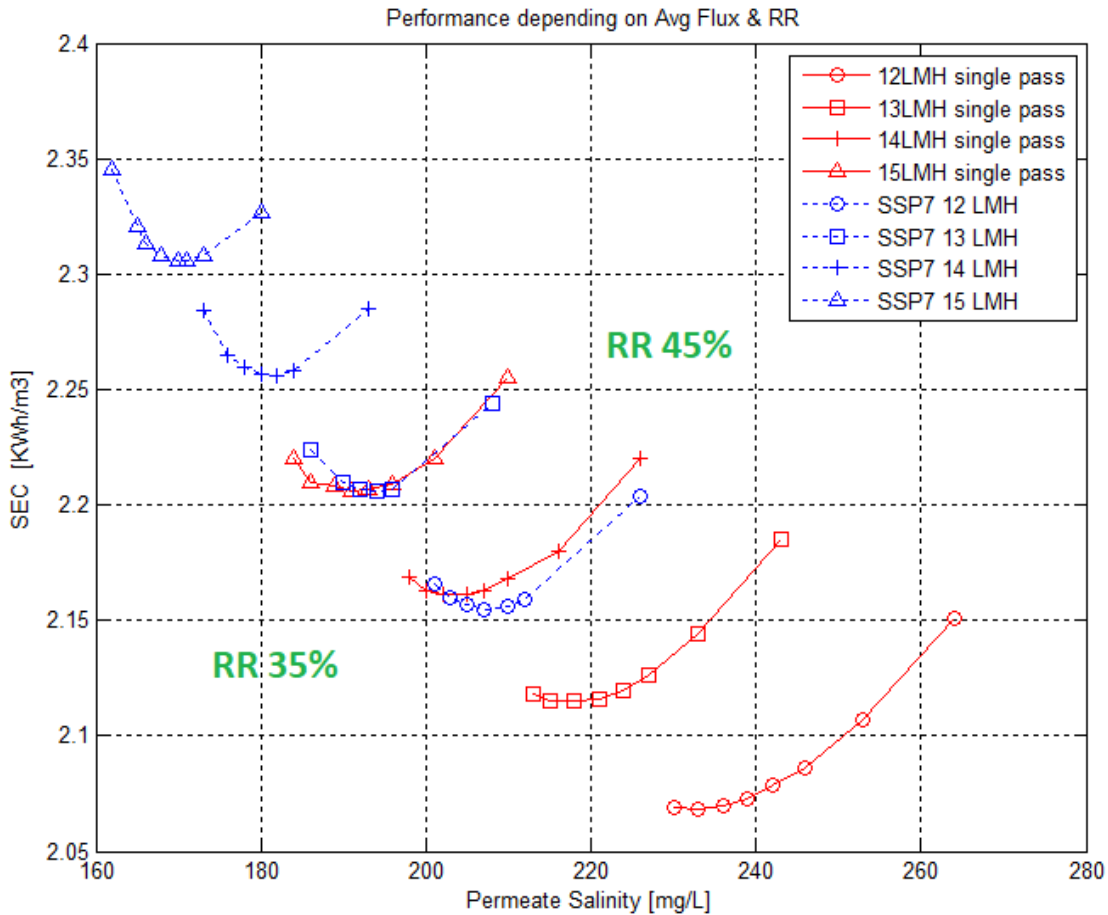


Figure 6.1: SWRO performance for SSP7 and conventional single-pass system depending on average water flux and recovery ratio (RR)

Moreover, the optimal recovery ratio that yields the lowest specific energy consumption (SEC) within a constant mean water flux for SSP7 is higher than that of the single-pass configuration by 2%, owing to feed dilution, as depicted in Figure (6.1).

Specifically, the optimal recovery ratios for SSP7 at 12 and 15 LMH are 38% and 41%, respectively, while the optimal recovery ratios for the single-pass configuration are 36% and 39%, respectively. However, the SEC for the single-pass configuration is approximately 4% lower than that of SSP7 at the optimal recovery ratio. Consequently, SSP7 enables the desalination plant to operate at a high recovery rate to extract a maximized water volume from the pretreatment unit.

The average water flux is a term used to describe the water flux throughout the entire reverse osmosis (RO) system. It can be quantified as the total permeate flow divided by the total membrane area within the pressure vessel. As a result of the osmotic rise within the pressure vessel, there is a variable distribution of water flux to the RO membranes, with the front membrane demonstrating the highest flux and gradually decreasing until it reaches the lowest flux at the last membrane.

As demonstrated in Figure (6.1), augmenting the average water flux results in an enhancement of permeate salinity for both SSP7 and single-pass configurations, albeit with a corresponding increase in specific energy consumption (SEC). Additionally, it is evident that the performance of SSP7 at 12 and 13 LMH is comparable to that of the single-pass configuration at 14 and 15 LMH, respectively. This confers an advantage to SSP7, as it can operate at a lower flux than the single-pass configuration while still achieving the same level of performance. In the long-term operation of SWRO, a higher flux has been shown to increase the propensity for fouling, particularly in the front membranes. Consequently, SSP7 can mitigate fouling and reduce scaling in the rear membranes by diluting the feed salinity.

Table (6.1) displays the power consumption for a single pressure vessel at the optimal recovery ratio, which is associated with the lowest SEC. Notably, SSP7 demonstrates a power consumption rate that is 1.5% lower than that of the single-pass configuration under constant flux conditions. However, when comparing SSP7 at 13 LMH with the single-pass configuration at 15 LMH (with similar performance), SSP7 exhibits a power consumption rate that is 18% lower. This reduction in power consumption rate enables the reduction of the required PV_s system size to operate the SWRO, thereby highlighting the economic benefits associated with the use of SSP7.

Table 6.1: Power consumption for 1 pressure vessel of SSP7 & Single pass (single stage)

	Single Pass		SSP7		Diff %
Flux [LMH]	Optimum RR [%]	Power [Kw]	Optimum RR [%]	Power [Kw]	
12	36	6.46	38	6.37	-1.4
13	37	7.16	39	7.05	-1.5
14	38	7.88	40	7.77	-1.4
15	39	8.62	41	8.48	-1.6

The fixed design parameters used in this section are revealed in Table (6.2).

Table 6.2: Fixed design parameters used for Avg water flux & RR effect on SSP7 & Single pass (single stage) performance

Fixed design parameter	Unit	Value
Type of membrane	-	SW30HRLE-400i
Main Feed Salinity	mg/L	35,000
Number of membranes	Each	7
Temperature	°C	25
FF	-	1

6.1.2 Seawater Density

The majority of research studies have utilized a constant value for seawater density [27, 32, 59, 29], while few have employed seawater density as a function of salinity and temperature [60], as per Equation (3.22). In this section, both approaches are assessed to examine their impact on SSP7 performance, as illustrated in Table (6.3). The disparity in specific energy consumption (SEC) and permeate salinity resulting from the use of both densities (constant value of 1000 kg/m^3 versus function of salinity and temperature) is negligible, even at high salinity and temperature levels. Therefore, it is reasonable to assume a constant density value of 1000 kg/m^3 in SWRO, as it will produce comparable results and be simpler to use. The fixed design parameters employed in this section can be observed in Table (6.4).

Table 6.3: Density effect on SSP7 performance

Feed				SEC [KWh/m ³]		C _p [mg/L]	
Flow rate [m ³ /day]	Pressure [bar]	Temp [°C]	Salinity [mg/L]	Density 1000 [kg/m ³]	Density Fun of Temp & Salinity [kg/m ³]	Density 1000 [kg/m ³]	Density Fun of Temp & Salinity [kg/m ³]
190.52	56.8	25	35,000	2.285	2.285	193	193
191.7	56.15	35	35,000	2.223	2.224	259	259
191.42	70.92	25	45,000	2.82	2.821	252	252
192.28	70.8	35	45,000	2.783	2.784	338	338

Table 6.4: Fixed design parameters used for seawater density effect on SSP7 performance

Fixed design parameter	Unit	Value
Type of membrane	-	SW30HRLE-400i
Avg water Flux	LMH	14
Number of membranes	Each	7
RR	%	45
FF	-	1

6.1.3 Eight Membranes Inside the Pressure Vessel

In the event that the number of membranes within the pressure vessel is increased from 7 to 8, it is pertinent to evaluate the impact of this change on the SSP performance, and whether it would yield improved results. To this end, this section investigates the effect of increasing the number of membranes to 8 on the SSP performance, and compares it with the 7-membrane configuration under two distinct cases, as described below:

a. Constant Permeate Flow Rate (Q_p)

To facilitate a comparison of the impact of increasing the number of membranes, the permeate flow rate (Q_p) has been standardized to 80 m³/day for all SWRO designs under typical operating conditions, which involve a feed salinity of 35,000 mg/L, a recovery ratio of 40%, and a temperature of 25 °C. As the number of split elements employed to dilute the feed increases, the feed pressure required to achieve the targeted permeate flow rate decreases, since the osmotic pressure along the pressure vessel diminishes.

In summary, the SSP design can potentially consume less energy than the single-pass SWRO configuration. However, the loss of rear permeate from the split elements through circulation results in a higher SEC for the SSP design as compared to the single-pass SWRO. Nevertheless, it is imperative to ensure that the SEC of the SSP design does not exceed that of the second-pass design, in order to consider it a feasible solution and make it a viable option for implementation in SWRO plants.

With regard to the design featuring 8 membranes, as depicted in Figure (6.2) and detailed in Table (6.5), the single-pass configuration consumed 2.08 kWh/m^3 , which is lower than the 7-membrane single-pass configuration's consumption of 2.12 kWh/m^3 . This is due to the lower pressure required to achieve the targeted permeate flow rate. However, the permeate salinity of 263 mg/L is worse than that of the 7-membrane single-pass configuration at 229 mg/L . This is because the last added membrane received a high saline concentration, leading to a higher rate of saline transfer in the last membrane relative to the rate of water, thereby increasing the overall permeate salinity.

Furthermore, the second-pass design (SPSP) employing 8 membranes in the SWRO consumed 2.20 kWh/m^3 , which is lower than that of the SPSP with 7 membranes, which consumed 2.22 kWh/m^3 . As for permeate salinity, both designs exhibit almost the same level, at 127 and 128 mg/L , respectively.

SSP8 split element use 2.13 kWh/m^3 which is located between single-pass 2.08 kWh/m^3 and SPSP 2.20 kWh/m^3 , and permeate salinity 231 mg/L has better than 8 membranes single-pass 263 mg/L . But if we compare the performance of SSP8 with 7 membranes single-pass (SEC 2.12 , and C_p 229), it is a little bit higher. So, 7-membranes single-pass unit has better performance than SSP8. Therefore, it's not feasible to consider SSP8 at constant permeate flow rate conditions.

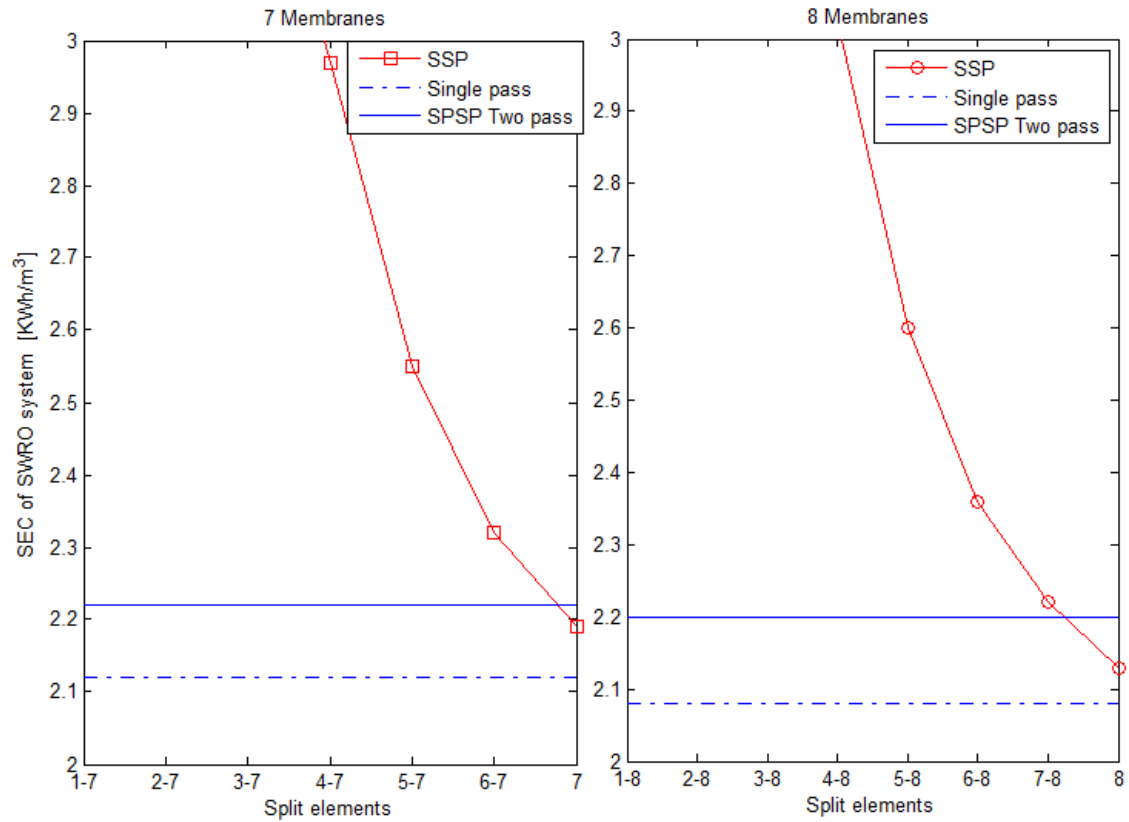


Figure 6.2: SEC for the SSP RO design at the different split for 7 & 8 membranes and at constant permeate flow rate 80 m³/day

Also, the SEC of SSP 7–8 to SSP 4–8 did not fall within the SEC range. Although, they can improve the water quality.

Table 6.5: SEC and permeate salinity value for the SSP RO design at different split for 7 & 8 membranes and at constant permeate flow rate 80 m³/day

Design	SEC [kWh/m ³]	C _p [mg/L]
SPSP- 7 membranes	2.22	128
SPSP- 8 membranes	2.20	127
Single pass- 7 membranes	2.12	229
SSP7	2.19	197
Single pass- 8 membranes	2.08	263
SSP8	2.13	231

b. Constant Avg Water Flux (J_w)

In this case, the average water flux (J_w) is set to be 12.81 LMH for all SWRO designs under the typical operating conditions of a feed salinity of 35,000 mg/L, an RR of 40%, and a temperature of 25 °C, as depicted in Figure (6.3) and detailed in Table (6.6). In this scenario, the 8-membrane single-pass and two-pass configurations consumed 2.15 and 2.29 kWh/m³, respectively, which is higher SEC than the 7 membrane configurations, contrary to the previous case. Additionally, the permeate salinity for the SPSP 8 membrane configuration was 110 mg/L lower than that of the SPSP 7 membrane configuration (at 128

mg/L), while the single-pass 8 and 7 membrane configurations had almost the same permeate salinity at around 230 mg/L.

Out of the split element designs evaluated in this study (SSP4-8), SSP8 is the only feasible solution, as it minimizes the SEC compared to the two-pass (SPSP) design. SSP8 consumes 2.22 kWh/m³ with a permeate salinity of 202 mg/L. However, when comparing the performance of SSP8 with SSP7 (SEC of 2.19 and permeate salinity of 197) under constant average water flux conditions, SSP7 exhibits better performance than SSP8.

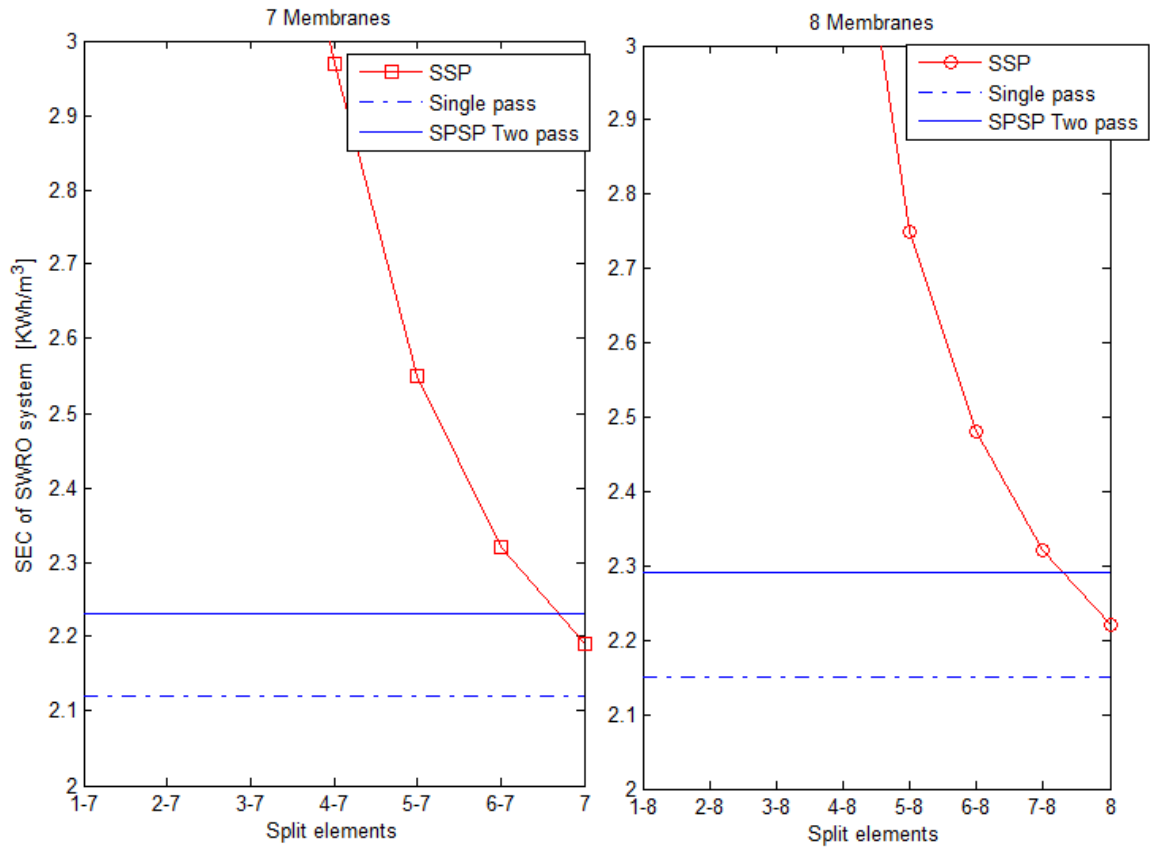


Figure 6.3: SEC for the SSP RO design at the different split for 7 & 8 membranes and at constant Avg water flux rate 12.81 LMH

In summary, based on the previous two case comparison of 7 & 8 membranes, there is no benefit to go with 8 membranes split partial single pass (SSP8).

Table 6.6: SEC and permeate salinity value for the SSP RO design at the different split for 7 & 8 membranes and at constant Avg water flux rate 12.81 LMH

Design	SEC [KWh/m ³]	C _p [mg/L]
SPSP- 7 membranes	2.22	128
SPSP- 8 membranes	2.29	110
Single pass- 7 membranes	2.12	229
SSP7	2.19	197
Single pass- 8 membranes	2.15	230
SSP8	2.22	202

6.1.4 SSP Combined with Internally Staged Design (ISD)

The internally staged design (ISD) involves the adoption of RO membranes with different characteristics inside the pressure vessel to achieve a uniform flux distribution. This is accomplished by placing a high-rejection membrane at the front and a low-rejection membrane at the rear of the pressure vessel. By employing various ISD configurations, it is possible to obtain high-quality product water or low-energy consumption, as well as

reduce fouling potential. In this study, three types of FilmTec SWRO membrane from DOW are utilized and classified into high-rejection (H1), intermediate (H2), and high-flux (H3), based on their calculated water and salt permeability (A_w & B_s). A total of 37 combinations were generated, featuring the three types of SWRO membranes inside a pressure vessel containing seven membranes. Of these, 33 combinations were based on the sequence, while four were based on unusual combinations described in chapter 5. The characteristics of the three types of Spiral-Wound SWRO membranes are provided in Table (5.1).

The SSP design can be easily integrated with the ISD, and this combination is expected to further enhance the SSP performance by reducing SEC or permeate salinity. However, two constraints must be met to consider this enhancement:

- The permeate salinity must be lower than that of the conventional single-pass design.
- The specific energy consumption must be lower than that of the split partial second pass (SPSP) design.

Two seawater conditions are used to conduct the performance test for SSP combined with ISD, standard and harsh seawater conditions.

a. SSP Combined with ISD Under Standard Seawater Condition

Standard seawater conditions typically refer to a salinity of 35,000 mg/L and a temperature of 25 °C. This condition is commonly used to conduct basic performance tests for SWRO membranes. The SSP was tested under different ISD configurations to evaluate its performance in terms of SEC and permeate salinity (C_p), as shown in Table (6.7). The configurations are sorted based on SEC, from the lowest to the highest value at the optimum recovery ratio (where the SEC has the lowest value under the same ISD configuration).

There is an obvious tradeoff relationship between permeate salinity and SEC, where improving water salinity leads to an increase in SEC. This improvement in water salinity can be achieved by increasing the number of high-rejection membranes (H1) inside the pressure vessel. Similarly, reducing SEC leads to an increase in permeate salinity by increasing the number of high Flux membranes (H3) inside the pressure vessel, which lowers the pressure required to produce the required product water and leads to a reduction in SEC.

Table 6.7: SSP performance under different ISD configurations for standard seawater conditions

ISD configuration	Feed flow [m ³ /day]	Pressure [Bar]	Optimum RR% [-]	SEC [KWh/m ³]	C _P [mg/L]	Total area [m ²]	Permeate Flow [m ³ /day]
Single pass 070	208.33	51.06	36	2.07	233	260.4	75.00
007	219.55	49.27	37	2.08	245	287.0	82.66
1 _{hr} 5 _{hf} 1 _i	211.38	50.44	38	2.09	235	283.2	81.56
016	216.30	49.46	37	2.10	239	283.2	81.56
1 _{hr} 4 _{hf} 2 _i	208.34	50.59	38	2.11	228	279.4	80.47
106	219.06	49.62	37	2.11	230	287.0	82.66
025	207.60	50.15	38	2.11	234	279.4	80.47
2 _{hr} 4 _{hf} 1 _i	211.01	50.81	38	2.12	218	283.2	81.56
115	210.23	50.30	38	2.12	225	283.2	81.56
034	204.43	50.30	38	2.13	227	275.6	79.37
205	212.93	50.45	38	2.13	216	287.0	82.66
2 _{hr} 3 _{hf} 2 _i	207.95	50.97	38	2.13	211	279.4	80.47
124	207.12	50.46	38	2.14	218	279.4	80.47
043	201.39	50.44	38	2.14	220	271.8	78.28
214	209.79	50.63	38	2.15	209	283.2	81.56
133	204.00	50.61	38	2.15	211	275.6	79.37
052	198.20	50.59	38	2.16	212	268.0	77.18
070	193.31	51.16	38	2.16	207	260.4	75.00
304	207.08	51.33	39	2.16	202	287.0	82.66

ISD configuration	Feed flow [m ³ /day]	Pressure [Bar]	Optimum RR% [-]	SEC [KWh/m ³]	CP [mg/L]	Total area [m ²]	Permeate Flow [m ³ /day]
223	206.65	50.79	38	2.17	201	279.4	80.47
142	200.86	50.77	38	2.17	203	271.8	78.28
061	190.20	51.26	39	2.17	207	264.2	76.09
160	191.00	51.89	39	2.17	200	264.2	76.09
313	203.98	51.50	39	2.18	194	283.2	81.56
SPSP	184.40	52.43/3.64	40	2.18	138	260.4	75.00
232	198.35	51.48	39	2.18	196	238.4	68.66
151	197.70	50.92	39	2.18	196	268.0	77.18
250	193.57	52.11	39	2.18	190	268.0	77.18
403	206.55	51.69	39	2.19	185	287.0	82.66
322	200.90	51.67	39	2.19	186	279.4	80.47
241	195.27	51.63	39	2.20	188	271.8	78.28
340	196.16	52.33	39	2.20	181	271.8	78.28
430	198.72	52.56	39	2.21	171	275.6	79.37
331	197.78	51.83	39	2.21	178	275.6	79.37
502	205.95	52.07	39	2.22	167	287.0	82.66
520	201.30	52.80	39	2.23	161	279.4	80.47
610	203.85	53.03	39	2.25	151	283.2	81.56
700	206.93	53.40	39	2.25	149	287.0	82.66
601	205.29	52.47	39	2.26	150	287.0	82.66

Furthermore, the combination of SSP with ISD can improve the optimum recovery ratio by 1%, reaching 39% (as in the cases of SPP-ISD 304, 160, 313, and 232), compared to 38% for SSP-ISD 070 and 36% for conventional single-pass. This 1% improvement in the recovery ratio, can increase the permeate production capacity by 720 m³ annually per 1 pressure vessel. The associated design parameters used under standard seawater conditions are presented in Table (6.8).

Table 6.8: Design parameters used with standard seawater conditions to evaluate SSP-ISD performance

Fixed design parameter	Unit	Value
Type of membranes	-	SW30XHR-440i (H1) SW30HRLE-400i (H2) SW30XLE-440i (H3)
Avg water Flux	LMH	12
Main Feed Salinity	mg/L	35,000
Number of membranes	Each	7
Temperature	°C	25
FF	-	1

Out of the 37 combinations, 18 complied with the two constraints, where the permeate salinity was lower than that of the conventional single-pass design and the SEC was lower than that of the SPSP design. Among these combinations, four had notable

results and were plotted against the conventional single-pass, SSP-ISD070, and SPSP designs, as shown in Figure (6.4). These four combinations (SSP-ISD2hr 4hf 1i, SSP-ISD2hr 3hf 2i, SSP-ISD205, and SSP-ISD223) were evaluated under recovery ratios (RRs) ranging from 35% to 45% to thoroughly assess their performance.

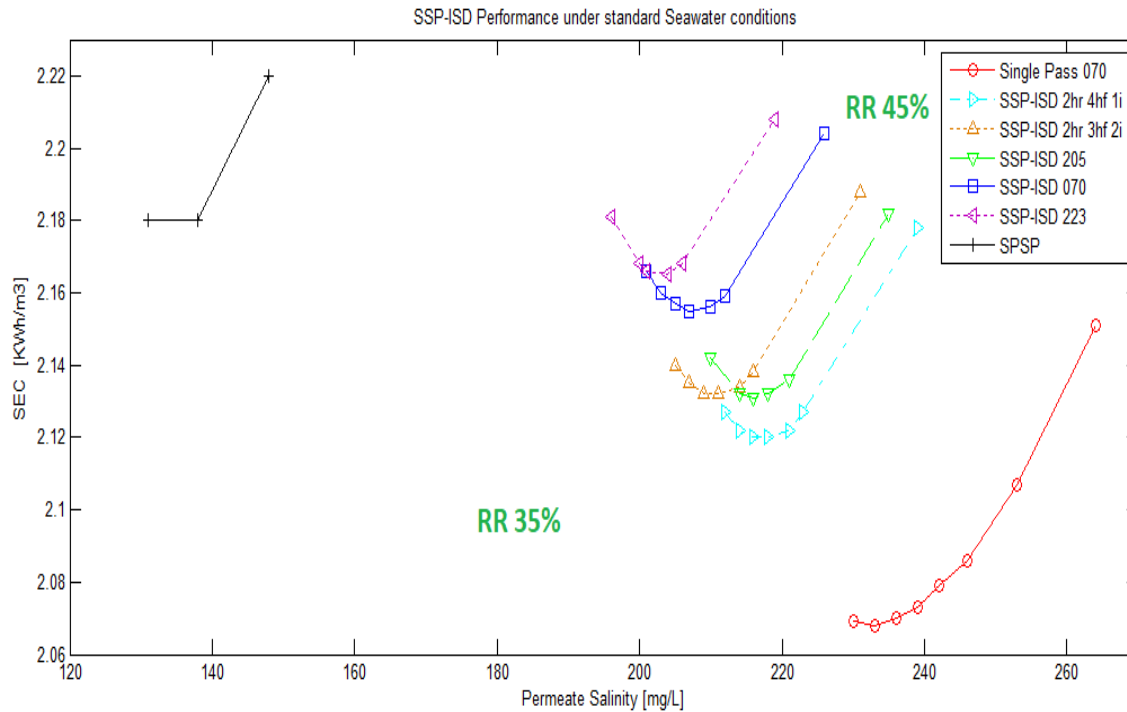


Figure 6.4: SSP-ISD Performance under standard Seawater conditions with 12 average water flux and recovery ratio (RR) ranged from 35% to 45%

At optimum RR, SSP-ISD2_{hr} 4_{hf} 1_i (SEC 2.12 kWh/m³ & C_p 218 mg/L) reduce the SEC by 1.9 % compared to SSP-ISD070 (SEC 2.16 kWh/m³ & C_p 207 mg/L). However, its salinity increased by 5.3 %. Also, both SSP-ISD2_{hr} 3_{hf} 2_i and SSP-ISD205 consumed 2.13 kWh/m³ 1.4% lower than SSP-ISD070, but SSP-ISD2_{hr} 3_{hf} 2_i provided a better salinity 211 mg/L while SSP-ISD205 salinity was 216 mg/L.

SSP-ISD223 provided 201 mg/L water salinity purer than SSP-ISD070 by 3%. However, its SEC is higher by 0.5%.

b. SSP Combined with ISD Under Harsh Seawater Condition

Harsh seawater refers to seawater that has a higher concentration of dissolved salts compared to normal seawater. This can occur naturally in areas of low rainfall and high evaporation, such as in the Red Sea, Arabian Gulf, or in saltwater lakes. High salinity seawater can have negative impacts on marine life and may affect the water quality for human use. In this section, the salinity and temperature of the Arabian Gulf were considered to evaluate the performance (SEC and permeate salinity C_p) of SSP combined with ISD. The average water salinity for the Arabian Gulf was reported as 45,000 mg/L [61], and the summer temperature was 30 °C [29]. The associated design parameters used under harsh seawater conditions are presented in Table (6.9).

Table 6.9: Design parameters used with harsh seawater conditions to evaluate SSP-ISD performance

Fixed design parameter	Unit	Value
Type of membranes	-	SW30XHR-440i (H1) SW30HRLE-400i (H2) SW30XLE-440i (H3)
Avg water Flux	LMH	12
Main Feed Salinity	mg/L	45,000
Number of membranes	Each	7
Temperature	°C	30
FF	-	0.85

Similar to the previous section, the SSP was tested under various ISD configurations under harsh seawater conditions. The configurations were sorted based on SEC, from the lowest to the highest value at the optimum recovery ratio (where the SEC has the lowest value under the same ISD configuration), as shown in Table (6.10). Compared to standard seawater conditions, the SEC for single-pass, SSP-ISD070, and SPSP designs increased by 24%, and the permeate salinity C_p increased by 46%, 46%, and 53%, respectively, under harsh seawater conditions.

Furthermore, it is noteworthy that the optimal recovery rate has undergone a reduction of 2% for all configurations, while the requisite pressure in bar necessary to achieve it has experienced a marked increase of 23%. Analogous to the standard condition, a discernible tradeoff association between the permeate salinity and specific energy consumption (SEC) can be observed.

23 combinations out of 37 complied with the two constraints where the permeate salinity is lower than the conventional single-pass and the SEC is lower than the SPSP, among these combinations 5 of them, which have considerable results are plotted against conventional single-pass, SSP-ISD070, and SPSP as shown in Figure (6.5). these 5 combinations (SSP-ISD2_{hr} 4_{hf} 1_i, SSP-ISD2_{hr} 3_{hf} 2_i, SSP-ISD205, SSP-ISD223, and SSP-ISD313) were plotted under recovery ratio (RR) starting from 35% up to 45% to quite evaluate their performance.

Table 6.10: SSP performance under different ISD configurations for harsh seawater condition

ISD configuration	Feed flow [m ³ /day]	Pressure [Bar]	Optimum RR% [-]	SEC [KWh/m ³]	C _p [mg/L]	Total area [m ²]	Permeate Flow [m ³ /day]
Single pass 070	220.59	62.76	34	2.57	340	260.4	75.00
007	232.65	61.06	35	2.59	358	287.0	82.66
1 _{hr} 5 _{hf} 1 _i	223.66	62.37	36	2.61	342	283.2	81.56
016	229.31	61.24	35	2.61	348	283.2	81.56
1 _{hr} 4 _{hf} 2 _i	220.50	62.51	36	2.62	332	279.4	80.47
106	232.32	61.39	35	2.62	335	287.0	82.66
025	226.07	61.40	35	2.63	338	279.4	80.47
2 _{hr} 4 _{hf} 1 _i	223.36	62.74	36	2.63	318	283.2	81.56
115	222.68	62.20	36	2.63	328	283.2	81.56
034	222.70	61.56	35	2.64	328	275.6	79.37
2 _{hr} 3 _{hf} 2 _i	220.17	62.89	36	2.64	308	279.4	80.47
205	225.56	62.37	36	2.65	315	287.0	82.66
124	219.44	62.36	36	2.65	318	279.4	80.47
043	213.35	62.35	36	2.66	321	271.8	78.28
214	222.28	62.48	36	2.66	307	283.2	81.56
052	210.09	62.49	36	2.67	310	268.0	77.18
070	204.76	63.06	36	2.67	303	260.4	75.00
133	216.19	62.53	36	2.67	307	275.6	79.37
304	225.15	62.71	36	2.68	291	287.0	82.66

ISD configuration	Feed flow [m ³ /day]	Pressure [Bar]	Optimum RR% [-]	SEC [KWh/m ³]	CP [mg/L]	Total area [m ²]	Permeate Flow [m ³ /day]
223	219.12	62.63	36	2.68	293	279.4	80.47
160	202.05	63.94	37	2.68	292	264.2	76.09
142	212.93	62.67	36	2.68	297	271.8	78.28
061	201.34	63.30	37	2.69	302	264.2	76.09
232	210.05	63.46	37	2.69	289	275.6	79.37
313	215.94	63.55	37	2.69	283	283.2	81.56
250	204.80	64.16	37	2.70	277	268.0	77.18
151	204.04	63.48	37	2.70	288	268.0	77.18
403	218.66	63.73	37	2.71	269	287.0	82.66
241	206.87	63.60	37	2.71	277	271.8	78.28
SPSP	184.70	66.10/4.20	40	2.71	211	260.4	75.00
322	212.71	63.71	37	2.71	272	279.4	80.47
340	207.57	64.37	37	2.71	263	271.8	78.28
430	210.30	64.60	37	2.73	249	275.6	79.37
331	209.48	63.87	37	2.73	260	275.6	79.37
502	218.14	64.10	37	2.74	244	287.0	82.66
520	213.05	64.83	37	2.74	235	279.4	80.47
610	215.76	65.07	37	2.76	221	283.2	81.56
700	218.97	65.45	37	2.77	218	287.0	82.66
601	217.54	64.49	37	2.78	219	287.0	82.66

The rate of SEC and C_p increase as RR increase at harsh condition are much higher than the rate of increase at standard condition, thus because of the rapid salinity accumulation along the pressure vessel for harsh condition which increases the feed osmotic pressure. For instance, for SSP-ISD223 the difference between the highest and lowest SEC is 0.1 kWh/m^3 at harsh condition (2.78 at RR 45% and 2.68 at RR36%), in contrast with 0.04 kWh/m^3 at standard condition (2.21 at RR 45% and 2.17 at RR39%),

At optimum RR, SSP-ISD2_{hr} 4_{hf} 1_i (SEC 2.63 kWh/m^3 & C_p 318 mg/L), SSP-ISD2_{hr} 3_{hf} 2_i (SEC 2.64 kWh/m^3 & C_p 308 mg/L), and SSP-ISD205 (SEC 2.65 kWh/m^3 & C_p 315 mg/L) reduce the SEC by 1.5 %, 1.1%, and 0.8%, respectively. However, the salinity C_p has been raised by 5%, 1.7%, and 4% respectively compared to SSP-ISD070 (SEC 2.67 kWh/m^3 & C_p 303 mg/L).

SSP-ISD223 (SEC 2.68 kWh/m^3 & C_p 293 mg/L) and SSP-ISD313 (SEC 2.69 kWh/m^3 & C_p 283 mg/L) provided water salinity purer than SSP-ISD070 by 3.3% and 6.6%, respectively.

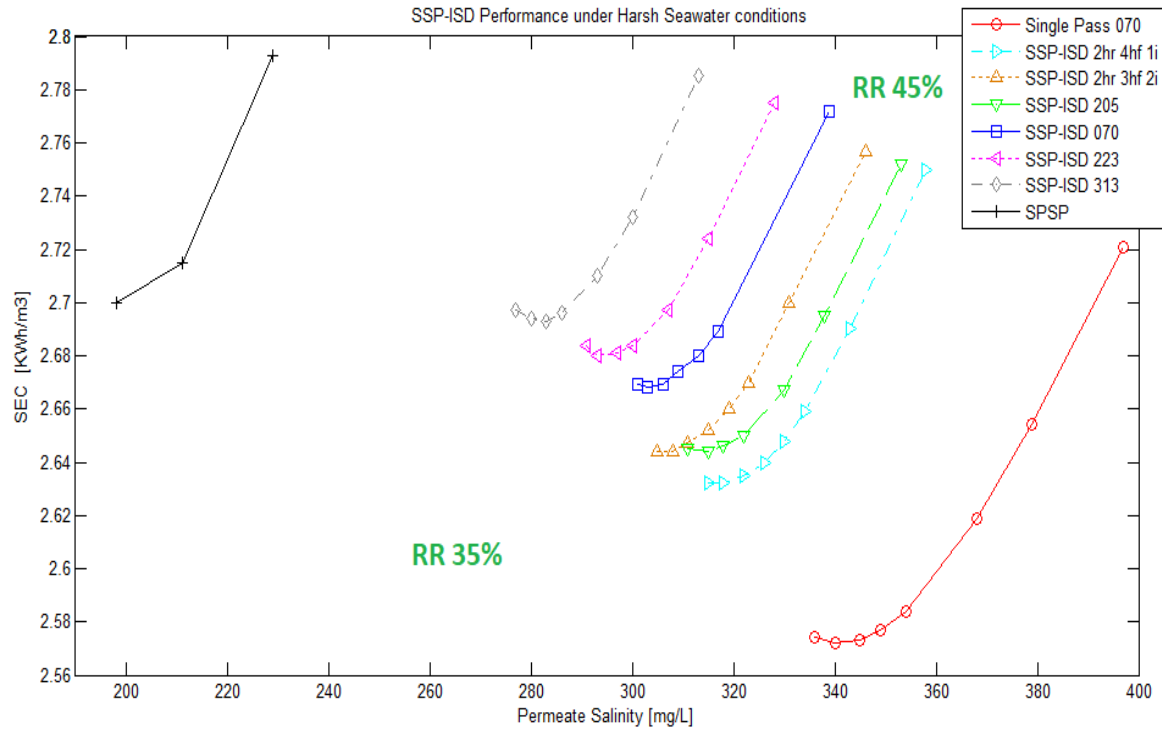


Figure 6.5: SSP-ISD Performance under harsh Seawater conditions with 12 average water flux and recovery ratio (RR) ranged from 35% to 45%

6.1.5 Flux Distribution within Pressure Vessel for SSP-ISD Configuration

In addition to membrane properties, the net-driven pressure (NDP) applied to the membranes within the pressure vessel has a profound impact on the permeate flow rate (flux). Typically, the entire feed seawater is introduced at the anterior end of the pressure vessel, while all the concentrate is released from the posterior end. Consequently, the initial membrane is subjected to a greater NDP value and generates a markedly higher flux than its subsequent counterparts. As the pressure vessel advances, the NDP gradually decreases in a convex quadratic pattern [59], resulting in a decline in flux due to the build-up of

rejected saline from the extraction of water permeate from the vessel, which leads to an increase in osmotic pressure and a reduction in hydraulic pressure.

In actuality, the distribution of flux along the pressure vessel is non-uniform, with approximately 25% of the overall permeate typically being generated by the first membrane, gradually decreasing until it reaches approximately 8% at the final membrane [9]. To prevent fouling and scaling in reverse osmosis (RO) systems, it is beneficial to reduce the flux, particularly from the first two membranes, while simultaneously increasing it at the final membranes. Thus, maintaining a uniform flux distribution is imperative for the efficient operation and long-term performance of an RO system, as well as to utilize the full membrane potential productivity through achieving an even flux distribution.

Under challenging seawater conditions, where the salinity and temperature are high, fouling and scaling tendencies are heightened due to the rapid rise in hydraulic pressure required to overcome the extreme osmotic pressure at the final membrane and maintain a positive net-driven pressure (NDP). This excess hydraulic pressure exacerbates the uneven distribution of flux between the membranes, with the initial membrane being exposed to a much higher permeate flux than the trailing membrane, potentially exceeding the design constraint.

Figure (6.6) depicts the permeate flux (LMH) across seven membranes arranged in varying configurations within a pressure vessel under challenging seawater conditions, with a recovery rate (RR) of 45%. The membrane location indexed as 0 represents the first element in the initial membrane, located just after the feed enters the pressure vessel. Conversely, membrane locations 1 to 7 correspond to the average value for each membrane, comprising 25 elements. Notably, the Single-pass configuration exhibits the

highest flux value of 32.92 LMH at location 0 and an average flux of 28.8 LMH at membrane 1, whereas it possesses the lowest average flux of 2.46 LMH at the final membrane, membrane 7.

By implementing either SSP-ISD070 or SPSP configurations, a uniform flux distribution can be observed, with a slight decrease in flux at the initial membrane (32.66 LMH at location 0 and 28.61 LMH at membrane 1) and a minor increase in flux at the final membrane (2.49 LMH at membrane 7). However, all the aforementioned configurations, including Single-pass, SSP-ISD070, and SPSP, exceed the design constraint of 32.3 LMH [5]. Consequently, fouling may occur, leading to a reduction in water flow and an increase in energy consumption over time.

SSP adopting different ISD configuration could relieved the flux distribution and make it more balanced as shown in Figure (6.6), SSP-ISD_{2hr 3hf 2i}, SSP-ISD205, and SSP-ISD313 success to relieve the permeate flux in the front membrane where they produce 27.33, 27.05, and 27.48 LMH, respectively at membrane location 0, less than SSP-ISD070 by approximately 17% . also, the Average flux at membrane 1 & 2 are less by approximately 15% and 9.6%, respectively. Furthermore, at membrane 3 and subsequent membranes the flux for SSP-ISD205 increase by 26%, 18.6%, 11.4%, 6%, and 3.2% respectively than SSP-ISD070. While SSP-ISD313 start increasing the flux at membrane 4 and subsequent membranes by 24%, 39.3%, 28.5%, and 19.3%, respectively. these flux enhancement at the rear membranes help to mitigate the scaling effect and improve the overall performance.

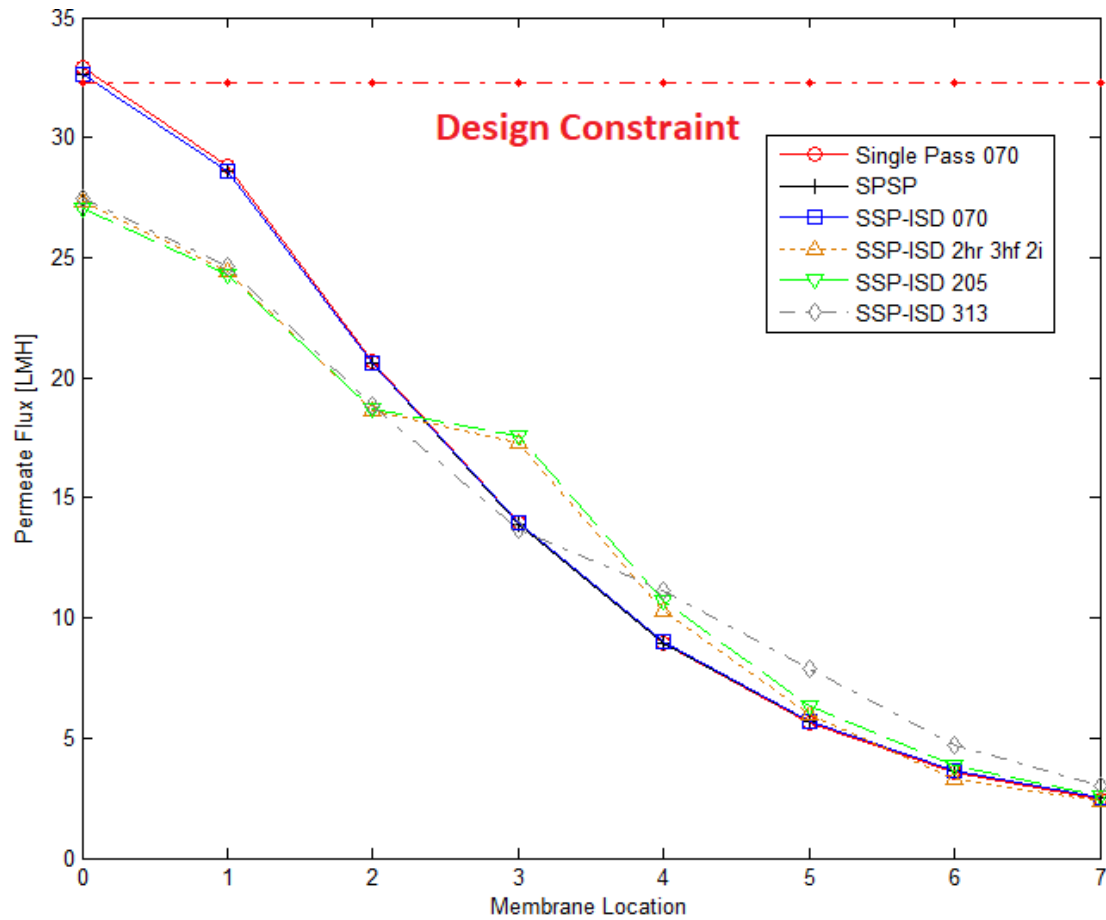


Figure 6.6: Flux distribution within Pressure Vessel under harsh Seawater conditions with 12 LMH total average water flux and 45% recovery ratio (RR)

6.2 Sizing the PV_s system to Powered SWRO

HOMER simulation software [was used by a stand-alone PV_s system made up of photovoltaic panels that has been designed to produce the best electrical power, a battery bank to store the excess electrical energy and then use it later, and a converter to convert the DC voltage generated by the PV panels into AC voltage to serve the AC load. This system is located in Dhahran city (Latitude: 26 17', Longitude: 50 09'), Saudi Arabia. The monthly average solar radiation on the horizontal plane and monthly mean ambient

temperature data for Dhahran City are shown in Figures (6.7–6.8), respectively. These data were obtained from NASA's prediction of the worldwide energy resource database [59]. The yearly mean solar irradiance is evaluated to be 5.6 kWh/m²/day, while the annual average ambient temperature is estimated to be 26.73°C.

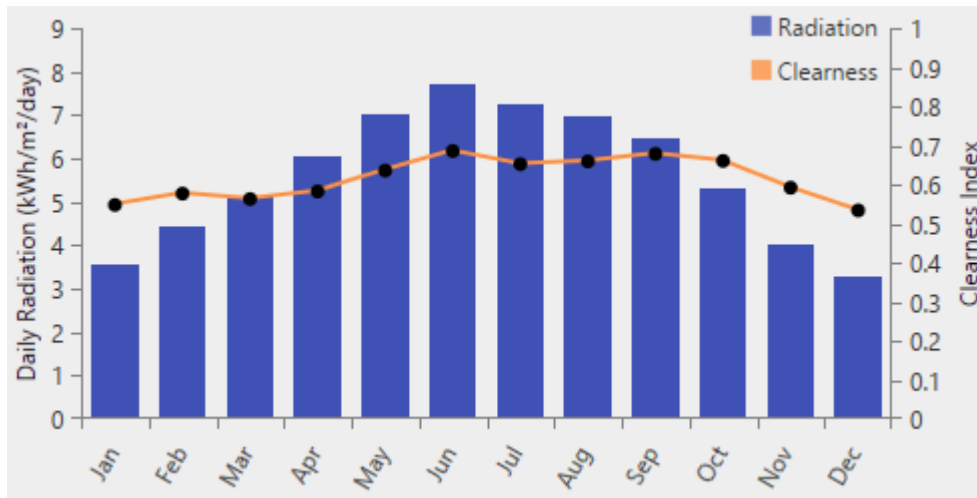


Figure 6.7: Monthly average solar radiation and clearness index on the horizontal plane for Dhahran City

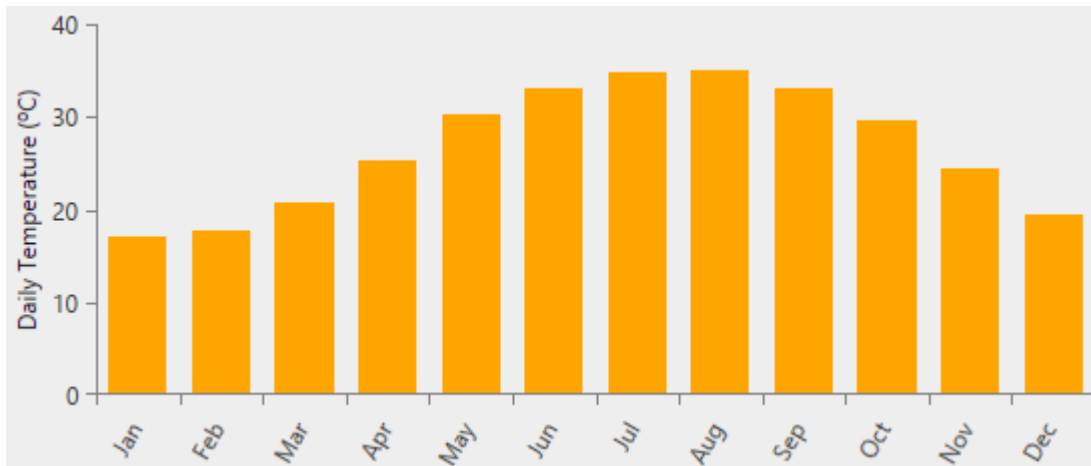


Figure 6.8: Monthly mean ambient temperature data for Dhahran City

The PV_s panels are not using a tracking system and are fixed at a tilted angle of 26 degrees from the ground facing to the south.

6.2.1 Electrical Load Demand

This investigation involves the selection of a seawater reverse osmosis (SWRO) plant with a daily production capacity of 10,000 m³/day, operating under harsh seawater conditions, to be powered by a photovoltaic (PV_s) system. The electrical load of the SWRO unit is contingent on the design configuration of the reverse osmosis (RO) system, which determines the specific energy consumption. The final requisite power is then calculated.

Nine configurations, namely SSP-ISD 2_{hr} 4_{hf} 1_i, SSP-ISD 205, SSP-ISD 2_{hr} 3_{hf} 2_i, SSP-ISD 223, SSP-ISD 313, SSP-ISD 070, SSP-ISD 700, SSP-ISD 601, and SSP-ISD 610 utilizing three different characteristic membranes, are employed to determine the required electrical load under 24 h of SWRO system operation per day.

Table (6.11) presents the calculation worksheet for determining the requisite power in kilowatts (kW) necessary to operate nine seawater reverse osmosis (SWRO) configurations. The load profile remains constant throughout the operation hour, with a maximum power shortage of 1% during the year (3.7 days/year). The specific energy consumption (SEC) values utilized in the calculations were obtained from Section (6.1.4.2).

A schematic diagram is presented to illustrate the setup of the seawater reverse osmosis (SWRO) plant powered by a photovoltaic (PV_s) system.

After the presentation of the schematic diagrams, the simulation and optimization outcomes are provided for each SWRO design configuration.

Table 6.11: Electric load worksheet calculation for 10,000 m³ daily purified water

SWRO Design Configuration	SEC [kWh/m ³]	Total daily energy demand [kWh]	Total Annual Energy demand [kWh]	Power [kW]
SSP-ISD 2 _{hr} 4 _{hf} 1 _i	2.63	26,300	9,599,500	1,095.8
SSP-ISD 205	2.65	26,500	9,672,500	1,104.2
SSP-ISD 2 _{hr} 3 _{hf} 2 _i	2.64	26,400	9,636,000	1,100.0
SSP-ISD 223	2.68	26,800	9,782,000	1,116.7
SSP-ISD 313	2.69	26,900	9,818,500	1,120.8
SSP-ISD 070	2.67	26,700	9,745,500	1,112.5
SSP-ISD 700	2.77	27,700	10,110,500	1,154.2
SSP-ISD 601	2.78	27,800	10,147,000	1,158.3
SSP-ISD 610	2.76	27,600	10,074,000	1,150.0

6.2.2 Simulation and Optimization Result

The load requirement is fulfilled through the use of photovoltaic (PV_s) panels and batteries, with a 1% power shortage allowance for the nine SSP-ISD designs. The schematic diagrams for the SSP-ISD 2_{hr} 4_{hf} 1_i and SSP-ISD 070 systems are depicted in Figures (6.9a, 6.9b), respectively. It is worth noting that the peak load value for SSP-ISD 2_{hr} 4_{hf} 1_i (1095.8

kW) is 1.5% lower than that of SSP-ISD 070 (1112.5 kW). Hourly base simulations are carried out considering many configurations to meet the load demand of all designs, among these configurations, the optimum one that has a lower size of PV_s panels and batteries and has the minimum cost of energy is selected as shown in Table (6.12) .

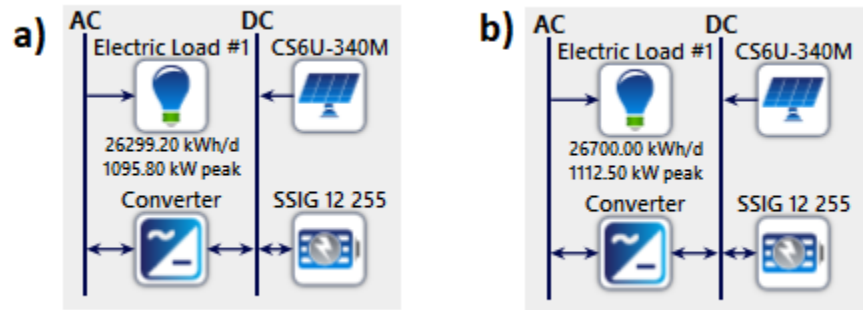


Figure 6.9: Schematic diagram for, a) SSP-ISD 2_{hr} 4_{hf} 1_i b) SSP-ISD 070

The best design that has the lowest cost value \$, PVs capacity kW, and # of batteries is SSP-ISD 2_{hr} 4_{hf} 1_i design that consists of PV_s with 8,942 kW of power, battery capacity of 69,627 kWh (22,533 batteries), and 2,761 kW of converter, while the net present cost (NPC) \$52.429 million, and the levelized cost of energy (LCOE) is 0.426 \$/kWh, as depicted in Figure (6.10). As shown in Figure (6.11), the SSP-ISD 601 design has a PV_s with a power of 9,452 kW, a battery capacity of 73,594 kWh (23,817 batteries), and a converter with a power of 2,919 kW. while the net present cost (NPC) \$55.419 million, and the levelized cost of energy (LCOE) is 0.426 \$/kWh

Table 6.12: Optimum configurations of PV_s panels, converter, and batteries for the nine SSP-ISD designs for Dhahran

SWRO Design Configuration	PV Capacity [kW] CS6U-340M	# of Battery SSIG-12-255	Converter Capacity [kW]	Net present cost (NPC) [\$]	LCOE [\$/kWh]	Annual Energy consumption [kWh/Year]
SSP-ISD 2 _{hr} 4 _{hf} 1 _i	8,942	22,533	2,761	52.429 M	0.426	9.522 M
SSP-ISD 205	9,010	22,704	2,783	52.830 M	0.426	9.595 M
SSP-ISD 2 _{hr} 3 _{hf} 2 _i	8,976	22,617	2,773	52.630 M	0.426	9.558 M
SSP-ISD 223	9,113	22,962	2,815	53.429 M	0.426	9.704 M
SSP-ISD 313	9,146	23,047	2,825	53.626 M	0.426	9.739 M
SSP-ISD 070	9,079	22,875	2,803	53.228 M	0.426	9.667 M
SSP-ISD 700	9,419	23,733	2,909	55.223 M	0.426	10.029 M
SSP-ISD 601	9,452	23,817	2,919	55.419 M	0.426	10.065 M
SSP-ISD 610	9,385	23,646	2,899	55.022 M	0.426	9.993 M

Architecture						Cost			
  	CS6U-340M (kW)	SSIG 12 255	Converter (kW)	Dispatch		NPC (\$)	COE (\$)	Operating cost (\$/yr)	Initial capital (\$)
  	8,942	22,533	2,761	CC		\$52.4M	\$0.426	\$1.45M	\$33.7M

Figure 6.10: Optimization result for SSP-ISD 2_{hr} 4_{hf} 1_i design

Architecture						Cost			
  	CS6U-340M (kW)	SSIG 12 255	Converter (kW)	Dispatch		NPC (\$)	COE (\$)	Operating cost (\$/yr)	Initial capital (\$)
  	9,452	23,817	2,919	CC		\$55.4M	\$0.426	\$1.53M	\$35.6M

Figure 6.11: Optimization result for SSP-ISD 601 design

Thus, it can be inferred that the utilization of the SSP-ISD 2_{hr} 4_{hf} 1_i design can result in a reduction of 5.4% in the required size of the PV_s panels and batteries, specifically 510 kW

less PV_s capacity and 1,284 fewer batteries, also, \$3 million cost saving in the NPC. Figure (6.12) presents the monthly total electrical production by PV_s panels for the SSP-ISD 2_{hr} 4_{hf} 1_i design, with an annual output of 15.64 GWh.

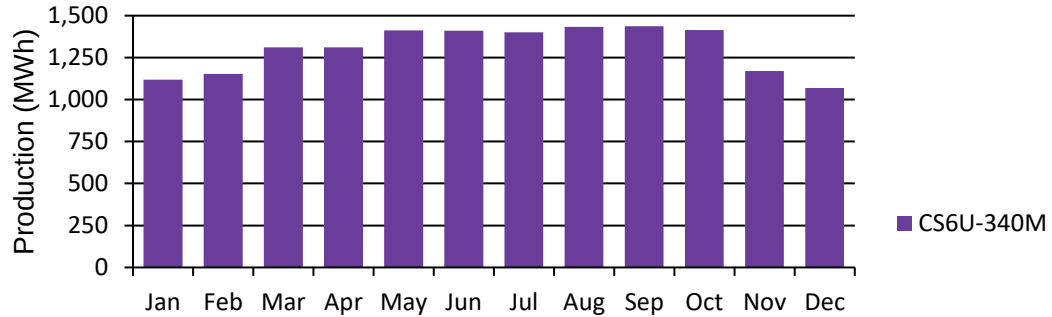


Figure 6.12: Monthly total electrical production by PV panels for SSP-ISD 2_{hr} 4_{hf} 1_i design

6.3. Unit Product Cost of desalted water for SSP-ISD configuration

The unit product cost (UPC) was investigated for two different product capacities, 10,000 and 100,000 m³/day, for the selected combinations of SSP-ISD as shown in Table (6.13). Among the SSP-ISD combinations, the UPC for SSP-ISD 2_{hr} 4_{hf} 1_i has the lowest value at 1.476 \$/m³ for 10,000 m³/day with 5.387 M\$ total annual cost for combined SWRO and PVs systems. Also, under 100,000 m³/day products capacity, the UPC for SSP-ISD 2_{hr} 4_{hf} 1_i has the lowest value at 1.421 \$/m³ with 51.866 M\$ total annual cost for combined SWRO and PVs systems. \$2,700,000 is the annual saving amount by using SSP-ISD 2_{hr} 4_{hf} 1_i configuration instead of SSP-ISD 601 at 100,000 m³/day production capacity.

Table 6.13: Unit product cost of desalted water for SSP-ISD configuration for Dhahran

Design configuration	Unit Product Cost [\$/m ³]		Total annual cost for SWRO and PVs systems [\$]	
	Q _p 10,000 [m ³ /day]	Q _p 100,000 [m ³ /day]	Q _p 10,000 [m ³ /day]	Q _p 100,000 [m ³ /day]
SSP-ISD 2 _{hr} 4 _{hf} 1 _i	1.476	1.421	5.387 M	51.866 M
SSP-ISD 205	1.487	1.432	5.427 M	52.268 M
SSP-ISD 2 _{hr} 3 _{hf} 2 _i	1.480	1.425	5.402 M	52.012 M
SSP-ISD 070*	1.495	1.440	5.456 M	52.560 M
SSP-ISD 223	1.501	1.445	5.478 M	52.742 M
SSP-ISD 313	1.494	1.440	5.453 M	52.560 M
SSP-ISD 700	1.543	1.488	5.631 M	54.312 M
SSP-ISD 601	1.55	1.495	5.657 M	54.567 M
SSP-ISD 610	1.538	1.483	5.613 M	54.129 M

*Base case

The unit product cost breakdown for SSP-ISD 2hr 4hf 1i shown in Figure (6.13), the Energy cost account for the majority of the UPC, comprising 68 % of the total. Meanwhile, capital cost make up 22%, and the remaining 10% is attributed to O&M cost.

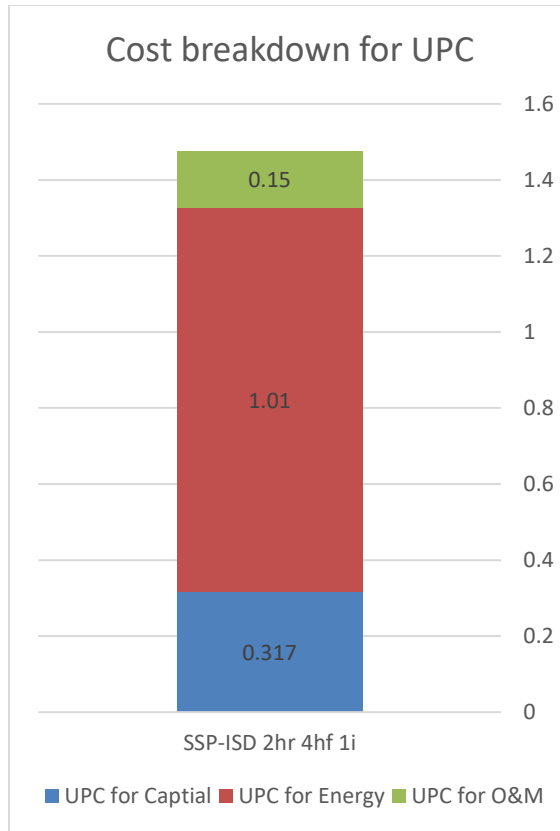


Figure 6.13: Cost breakdown for the UPC

CHAPTER 7

CONCLUSION

This study delved into the performance evaluation of the innovative Split Partial Single-Pass (SSP) seawater reverse osmosis (SWRO) design utilizing MATLAB software under diverse operating parameters and harsh seawater conditions, which have yet to be examined. Additionally, a novel configuration combining SSP with internal staged design (ISD) was tested and yielded significant improvement. Finally, the SWRO system was powered by a stand-alone photovoltaic (PV_s) system. The key conclusions drawn from this study are as follows:

- The permeate salinity for SSP7 is demonstrated to be approximately 13% lower than that of the conventional single-pass configuration under the same condition.
- The rate of salinity increase observed for SSP design in response to RR augmentation is lower than that of the single-pass by 28%.
- The findings of this study indicate that, under constant average water flux, the optimal recovery ratio for the Split Partial Single-Pass (SSP) design, which yields the lowest specific energy consumption (SEC), is 2% higher than that of the conventional single-pass method.
- It is reasonable to presume a constant density value of 1000 kg/m³ in SWRO, as it provides results comparable to density as a function of salinity and temperature.

- Furthermore, increasing the number of membranes from 7 to 8 inside the pressure vessel does not result in a significant improvement to the SSP system.
- Combining SSP with ISD under standard seawater conditions can improve the optimum recovery ratio by 1%, and provide purer water salinity by 3% (using SSP-ISD223), or reduce the SEC by 2% (using SSP-ISD2_{hr} 4_{hf} 1_i).
- Harsh seawater condition reduces the optimal recovery rate by 2%, and increase the requisite pressure in the bar by 23% compared with standard seawater condition for SSP design.
- Combining SSP with ISD under Harsh seawater conditions can improve the optimum recovery ratio by 1%, and provide purer water salinity by 6.6% (using SSP-ISD313), or reduce the SEC by 1.5 % (using SSP-ISD2_{hr} 4_{hf} 1_i).
- The implementation of the Split Partial Single-Pass (SSP) design with different internal staged design (ISD) configurations has been found to effectively alleviate the permeate flux on the front membrane by approximately 17% and increase it on the rear membrane by 18%. As a result, the flux distribution becomes more balanced, which helps to mitigate fouling on the front membranes and scaling on the tail membranes.
- A stand-alone solar photovoltaic (PV_s) system is utilized to power the Split Partial Single-Pass (SSP) design with a product capacity of 10,000 m³. Under 24-hour daily operation, the system requires a PV_s array with a power rating of 8,942 kW and batteries with a capacity of 69,627 kWh.
- Adopting SSP-ISD 2_{hr} 4_{hf} 1_i can reduce the size of solar PV_s systems by 5.4 %

- \$2,700,000 is the annual saving amount by using SSP-ISD 2_{hr} 4_{hf} 1_i configuration instead of SSP-ISD 601, and \$700,000 as compared to standard SSP-ISD 070 design at 100,000 m³/day production capacity.
- Energy cost account for the majority of the UPC, comprising 68 % of the total (1.48 \$/m³). Meanwhile, capital cost make up 22%, and the remaining 10% is attributed to O&M cost.

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