



**T.R.
ONDOKUZ MAYIS UNIVERSITY
INSTITUTE OF GRADUATE STUDIES
DEPARTMENT OF ENVIRONMENTAL ENGINEERING**

**MEMBRANE WATER TREATMENT PLANT DESIGN AND
SIMULATION, AND EVALUATION OF RENEWABLE
ENERGY SOURCE FOR THE ENERGY CONSUMPTION OF
THE PLANT**

Master's Thesis

Hayatullah AHMADZAI

Supervisor

Prof. Dr. Feryal AKBAL

SAMSUN
2022

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ACCEPTANCE AND APPROVAL OF THE THESIS

The study entitled “**MEMBRANE WATER TREATMENT PLANT DESIGN AND SIMULATION, AND EVALUATION OF RENEWABLE ENERGY SOURCE FOR THE ENERGY CONSUMPTION OF PLANT**” was prepared by **Hayatullah AHMADZAI** and supervised by **Prof. Dr. Feryal AKBAL** was found successful and unanimously accepted by committee members as a Master’s thesis of the Department of Environmental Engineering, following the examination on the date 11/08/ 2022.

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APPROVAL
11/ 08/ 2022
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Hayatullah AHMADZAI

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ÖZET

MEMBRAN SU ARITMA TESİSİ TASARIMI VE SİMÜLASYONU VE TESİSİN ENERJİ TÜKETİMİ İÇİN YENİLENEBİLİR ENERJİ KAYNAĞININ DEĞERLENDİRİLMESİ

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Artan dünya nüfusu ve insanların yaşam tarzındaki değişiklikler nedeniyle temiz suya olan talep artmakta ve su temin sistemi üzerinde baskı oluşturmaktadır. Medeniyet ve sanayileşme temiz su kaynaklarını etkilemiş ve temiz su talebini artırmıştır. Alternatif tatlı su kaynakları tuzdan arındırma ve atık su arıtmadır. İnsan ve endüstriyel faaliyetler nedeniyle farklı kirleticiler temiz su kaynaklarına ulaşabilmektedir. Bu nedenle, su arıtma gereklidir. Bu çalışma, suyu içme amaçlı hale getirmek için acı su arıtımı için üçüncül su arıtma teknolojisini ilerletmeyi amaçlamaktadır. Gelişmiş su arıtma teknolojileri arasında ters ozmozlu su tuzdan arındırma, içme suyu arıtma amaçları için ünlü ve uygun bir su arıtma teknolojisidir. Bu çalışma Kırıkkale şehri için RO arıtma tesisi tasarlamıştır. RO tesisi için en verimli ve ekonomik yerleşimi bulmak için WAVE simülasyon yazılımıyla farklı senaryoları harekete geçirdi. RO su arıtma tesisleri, suyu membran yüzeylerinden geçirmek için yüksek enerjiye ihtiyaç duyar. Bu nedenle, yüksek enerji tüketimini azaltmak için bir çözüm bulmak önemlidir. Bu çalışma, enerji tüketimini azaltmanın bir yolunu bulmaya ve RO tesisi için Enerji geri kazanım cihazlarını (ERD) tasarlamaya ve değerlendirmeye çalıştı. Sonuç, turbo şarjlı ERD cihazlarının takılmasının enerji tüketimini %30'a kadar azalttığını gösteriyor. Bu çalışmanın sonunda RO santralleri için yenilenebilir enerji kaynakları (güneş enerjisi) kullanılarak tasarlanmış ve değerlendirilmiştir. Fotovoltaik enerji üretim sistemi değerlendirildi ve PV sisteminin sera gazı (GHG) azaltımını bulmak için RETscreen yazılımı kullanılarak geleneksel sistem (kömür, doğal gaz ve petrol) tarafından enerji üretimi ile karşılaştırıldı. Sonuçlar, PV enerji üretim sisteminin uygulanmasının atmosfere 12750 tCO₂ eşdeğerinden daha fazla emisyon azaltımını azalttığını göstermektedir.

Anahtar Sözcükler: Acı su, Ters ozmoz, WAVE, Enerji azaltımı, Güneş enerjisi, RETscreen

ABSTRACT

MEMBRANE WATER TREATMENT PLANT DESIGN AND SIMULATION, AND EVALUATION OF RENEWABLE ENERGY SOURCE FOR THE ENERGY CONSUMPTION OF PLANT

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Master, June /2022
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Due to the increasing population of the world and changes in the lifestyle of the people, the demand for clean water is increased and applies pressure on the water supply system. Civilization and industrialization affected clean water sources and increased the demand for clean water. Alternative sources of freshwater are desalination and wastewater treatment. Because of human and industrial activities, different pollutants may reach clean water sources. Therefore, water treatment is necessary.

The present study seeks to advance tertiary water treatment technology for brackish water treatment to render the water for drinking purposes. Among advanced water treatment technologies, reverse osmosis water desalination is a famous and suitable water treatment technology for drinking water treatment purposes. The present study designed the RO treatment plant for Kirikkale city. It stimulated different scenarios with WAVE simulation software to find the most efficient and economical layout for the RO plant.

RO water treatment plants need high energy to pass water through membrane surfaces. Therefore, finding a solution to reduce high energy consumption is essential. The present study tried to find a way for energy consumption reduction and design and evaluate the Energy recovery devices (ERD) for the RO plant. The result shows that installing turbocharger ERD devices decreases energy consumption by up to 30%.

At the end of this study, it was designed and evaluated using renewable energy sources (solar energy) for RO plants. The photovoltaic energy production system was evaluated and compared to energy production by the conventional system (coal, natural gas, and oil) using RETscreen software to find the PV system's greenhouse gas (GHG) reduction. The results show that implementing the PV energy production system reduces more than 12750 tCO₂ equivalent emission reduction to the atmosphere.

Keywords: Brackish water, Reverse osmosis, WAVE, Energy reduction, Solar energy, RETscreen

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SYMBOLS AND ABBREVIATIONS

ERD	: Electric recovery devices
EEA	: European environmental agency
WHO	: World health organization
RO	: Reverse osmosis
TDS	: Total dissolved solids
WAVE	: Water application value engine software
PV	: Photovoltaic
MF	: Microfiltration
UF	: Ultrafiltration
CA	: Cellulose acetate
PA	: Polyimide
BOD	: Biochemical oxygen demand
COD	: Chemical oxygen demand
NF	: Nanofiltration
SDI	: Silt density index
TOC	: Total organic compounds
CP	: Concentration polarization
°c	: Centigrade
ASTM	: American society for testing of materials
RCC	: Reinforcement concrete
ESS	: Element specification sheet
PDS	: Product data sheet
Javg	: Average design flux
NE	: Number of elements
Qp	: Permeate flow rate
NEPV	: Number of elements in single pressure vessel
NV	: Number of pressure vessels
Qf	: Feed flow of plant
R	: Recovery of plant

Cc	: Concentrate concentration
Cf	: Feed concentration
CFC	: Average feed concentrate concentration
Qc	: Concentrate flow
SR	: Salt rejection
LMH	: Litter per m ² *hour
Ae	: Element surface area
ΔP	: Pressure loss
Kw	: Membrane permeability coefficient for water
NDP	: Net driving pressure
Pf	: Feed pressure
Pp	: Permeate pressure
Ks	: Membraen permeability coefficient for salt
Cl	: Chlorine
SO4	: Sulfate
As	: Arsenic
Y	: Staging ratio
Π	: Osmotic pressure
Δπ	: Difference of osmotic pressure in membrane vessel
Δpe	: Head loss per element
Pp	: Permeate pressure
Δπavg	: Average osmotic pressure
Qc	: Concentrate flow
CFV	: Cross flow velocity
E	: Energy
Np	: The efficiency of pump
TMP	: Trans membrane pressure
Fw	: Trans membrane water flux
BW	: Backwash
CEB	: Chemically enhanced washing
CIP	: Clean in place
IX	: Ion exchange

SWRO	: Sea water reverse osmosis system
Hcl	: Hydrochloric acid
Naocl	: Sodiumhypochloride
CAPEX	: Capital expenditure
BWRO	: Brackish water reverse osmosis system
HTC	: Hydraulic centrifuger turbocharger
PX	: Pressure exchanger
TC	: Turbocharger
HPTC	: High pressure turbocharger
LPTC	: Low pressure turbocharger
K	: Conversion constant for turbocharger
Wp	: Pump absorbed power
GHG	: Greenhouse gases
IRENA	: International renewable energy agency
DNI	: Direct normal irradiation
GHI	: Global horizontal irradiation
PVOUT	: Photovoltaic power output
DC	: Direct current
NASA	: National Aeronautics and Space Administration

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1. INTRODUCTION

The essential requirement for human health is clean water (Jagani, 2018). Due to the increasing population of the world and changes in the lifestyle of the people, the demand for clean water is increased and applying pressure on the water supply system. The enormous volume of the planet's water is located in the seas and oceans and constitutes around 1350 million m³. Near two third of the earth is water, and according to the European environmental agency (EEA), 97 % of the world's water is salty water (Amin et al., 2020). This is salt water, with average mineralization of 35.0 g/l, making it unsuitable for drinking and agricultural needs (Goncharuk, 2014). Only 3% of earth water is sweet and drinkable. The primary sources of fresh water are in the North and south poles and also in the mountains in the form of glaciers. This resource constitutes 30–50 million m³. However, this source of fresh water is almost unobtainable for human use (Goncharuk, 2014). The earth's rivers and lakes contain about 0.4 million m³ of fresh water that is accessible to humankind. Thus, our planet has only 3 % of fresh water of its total amount, with its bulk in the Arctic and Antarctic pack ice. The fresh water resources accessible to humans constitute only 0.06 %, or 0.8 million m³ (Goncharuk, 2014). this is relatively less amount of freshwater than the world population demands. At present, more than 40 countries of the world experience an absolute water deficiency (e.g., the Near East, Africa, Indochina, and Australia) (Goncharuk, 2014). A fifth of Europe and America's population drink contaminated water, which does not meet international standards. According to World Health Organization (WHO) official data, around 80 % of human diseases around the globe are related to the consumption of low-quality drinking water (WHO, 2004). Physical water scarcity arises from a lack of access to fresh water resources. It can result from historically dry weather conditions or human activity such as excessive water withdrawal for agricultural, industrial, or domestic purposes (de Marsily 2007; WWAP 2012; Jagani, 2018).

The demand for freshwater has increased with urbanization and industrialization, leading to more significant water pollution. Alternative freshwater sources are desalination and wastewater treatment (Walsh et al., 2015; Jagani, 2018). Globally,

approximately 80 % of wastewater is discharged untreated into the environment, contributing to worldwide water pollution (Connor et al., 2017; Jagani, 2018). The increasing number of contaminants entering the water supplies further challenges water authorities worldwide (Umar, 2014). According to WHO, surface water low than 500mg/l of total dissolved solids(TDS) is acceptable for drinking purposes; to ensure surface and groundwater for drinking purposes, it is necessary to remove all hazardous contaminants from water. Different types of water treatment processes are applied for the treatment of the surface, groundwater, and sea water treatment, such as conventional or advanced water treatment processes. Simple or conventional water treatment processes cannot remove several types of pollutants located in the water body. It's a need to search for non-conventional sources and advanced treatment methods to treat the surface and groundwater for drinking purposes. One of the most dynamic processes to achieve this goal is the membrane desalination process.

The main standard membrane desalination processes include electro dialysis and reverse osmosis (RO) (Gökçek, 2018). RO process is based on the separation method and driven by the pressure that large molecules of contaminants cannot pass through the membrane surface by diffusion. Only the water molecule can pass through it (Gökçek, 2018). Desalination processes need a high amount of energy for the operation of the system, and one of the main disadvantages of the RO process is high energy consumption.

The production of energy from conventional sources (coal, oil, and natural gas) are the leading cause of air pollution and climate change. It is essential to produce energy from renewable sources for a sustainable future. Using renewable energy sources such as green energy (wind, solar and hydraulic) for the energy supply for the RO system will help reduce the use of fossil fuels and greenhouse gas emissions.

The present study focused on the RO water treatment process design from surface water for Kirikkale city of Türkiye. Moreover, practically focus on designing and simulating the RO water treatment system using WAVE software. Furthermore, the present study evaluated the reduction methods for the RO energy consumption, tried to find a solution for the energy reduction of the RO system, and designed the electricity recovery devices for the RO system, which reduced the energy consumption by up to 30

% for the designed Ro system. In addition, the present study tried to integrate the combination of renewable energy sources and RO desalination process and design and evaluate the photovoltaic solar energy production system for RO plant and simulate the proposed PV system based on the climate change and CO₂ emission reduction by RETscreen software.

1.1. Significance and Objectives

The water contains several contaminants, notably high salinity, hardness minerals, hydrocarbons, surfactants and other chemicals used in the production process, and sometimes heavy metals. On the other hand, the lack of fresh water in different countries for drinking water purposes leads to advanced water treatment technologies. In this case, conventional water treatment systems find it hard to remove all toxic parameters and micro pollutants. As a result, it's a need to introduce an advanced process for drinking water treatment purposes. Different membrane processes have been developed to remove dissolved solids, organic compounds, and suspended solids. Membrane technology is well-known for water treatment which is achieved by pressure-driven processes, namely: microfiltration, ultrafiltration, Nano filtration, and reverse osmosis (Hausman, 2011 and Jagani, 2018).

This thesis aims to design and simulate a tertiary treatment plant for drinking water purposes for Kirikkale city, such as combining ultrafiltration and reverse osmosis processes that use a green energy source or ERD system. Nowadays, technological development in membranes and process simulation, such software as WAVE (water application value engine) from DOW company that produces membrane elements, IPSEpro (GRZ, AUT), MATLAB (MA, USA), IMSDesign (CA, USA) facilitate solution planning for water supply, and have been demonstrated to use are efficient in calculating and optimizing cost energy yield and permeate recovery (Albiladi, 2019). Furthermore, different software is available in the market for the design and simulation of green energy systems, such as RETscreen from the government of Canada, HOMER, PVsys, and so on. As a result, this study's primary purpose is to use this kind of software in drinking water treatment and the green energy sector to investigate and facilitate advanced water

treatment ways and find sustainable and clean energy sources for the supply of energy for the RO system.

1.2. Study Perspective:

This study was achieved in the following steps;

➤ Data collection: take the data of source raw water from a treatment plant in Turkiye and collect the information of the treatment plant site water characteristic and study area.

➤ Discussion and process evaluation: this section discusses the suitable process according to water parameters and briefly explains the membrane process, applications, structures, materials, pretreatment for the RO system, and problems.

➤ Process design: this section cleared all steps of suitable design for the mentioned water quality and demands and discussed the existing design of the plant and layout.

➤ Alternative design and simulation: This section explains the alternative process for treatment plants using WAVE software and clarifies the new membranes materials and layouts for RO application to find the most effective and economical layout for the RO system based on the water quality and recovery.

➤ Design ERD devices; to reduce energy consumption, it designed the ERD devices for the proposed RO system and calculated the energy reduction percentage.

➤ Comparison of the result: This section compared the designed RO system based on the influent and effluent parameters of water, energy consumption, and the number of pressure vessels in the system and compared these to the site's existing plant.

➤ Design green energy system for RO plant; this section designed and simulated the PV system for the metrological data of the RO plant site and compared the proposed green energy system to conventional energy production sources.

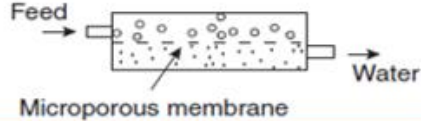
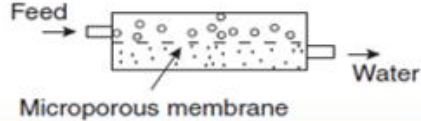
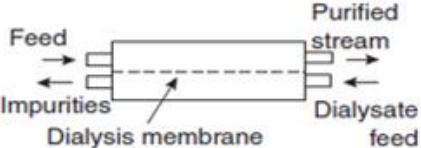
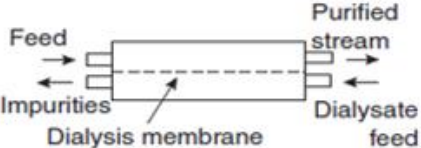
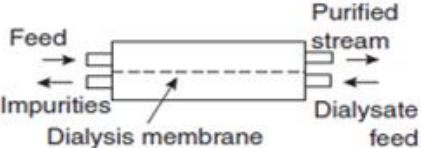
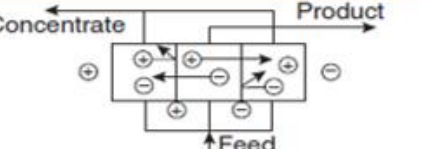
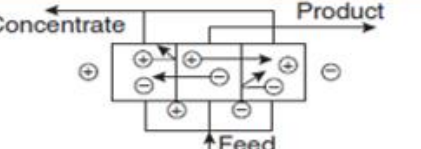
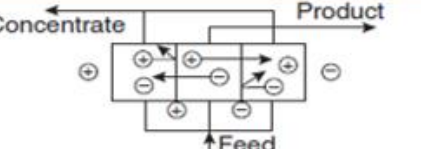
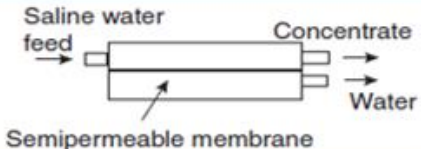
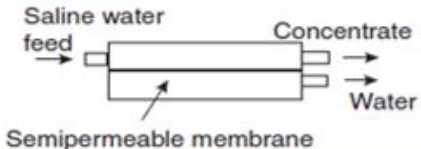
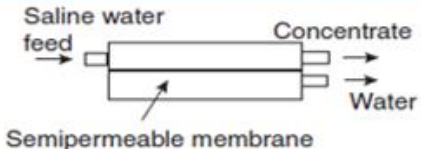
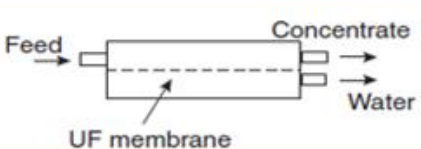
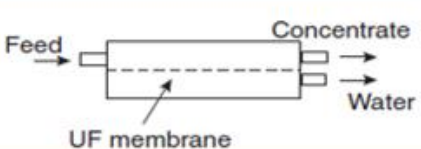
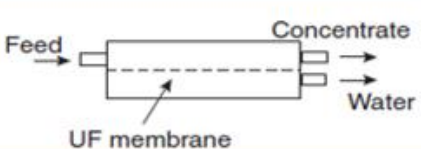
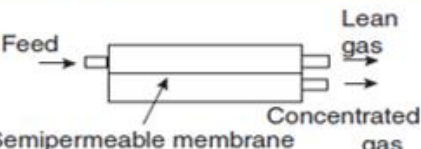
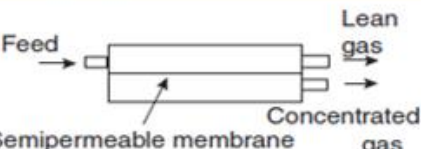
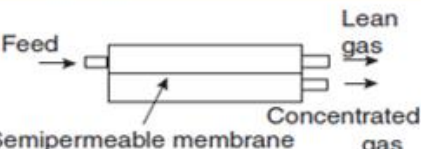
➤ Conclusion and recommendations; at the end of this study, it concluded and recommended different points for the future study.

2. THEORY AND LITERATURE REVIEW

2.1. Introduction to Membrane Processes and Technologies

The American Heritage Dictionary 13 defines a membrane as “A thin sheet of natural or synthetic material that is permeable to substances in solution” (Mareth, 2010). A membrane is defined as a permselective barrier between two homogeneous phases. Schematic diagrams of membrane-separation processes are shown in Table 2.1.

Table 2.1 Schematic diagram of different membrane processes (Singh, 2014)

Process	Separation concept	Materials passed	Driving force
Micro-filtration	 <p>Feed →  → Water</p> <p>Microporous membrane</p>	Water and dissolved species	Pressure difference, typically 10 psi
Dialysis	 <p>Feed →  → Purified stream</p> <p>Impurities ←  ← Dialysate feed</p> <p>Dialysis membrane</p>	Ions and low-molecular-weight organics (urea, etc.)	Concentration difference
Electro-dialysis	 <p>Concentrate ←  → Product</p> <p>Feed ↑ </p>	Ions	Voltage, typically 1–2 V/cell pair
Reverse osmosis	 <p>Saline water feed →  → Concentrate</p> <p>Water → </p> <p>Semipermeable membrane</p>	Water	Pressure difference, typically 100–800 psi
Ultra-filtration	 <p>Feed →  → Concentrate</p> <p>Water → </p> <p>UF membrane</p>	Water and salts	Pressure difference, typically 10–100 psi
Gas separation	 <p>Feed →  → Lean gas</p> <p>Concentrated gas → </p> <p>Semipermeable membrane</p>	Gases and vapours	Pressure difference, 1–100 atm

Virtually all membrane processes are pressure driven, do not involve a phase change, and consume much less energy than alternate separation processes. Since 1960, membrane technology has transformed from laboratory development to industrial applications. More than 95 % of applications are for liquid separations. Membranes are used for desalination of seawater and brackish water, potable water production and for, treating industrial effluents, and water reclamation and reuse. Membrane desalination technology is the primary water treatment process for sea and brackish water treatment. It can obtain potable water from 35000 mg/l of sea water TDS and less than 5000 mg/l of brackish water TDS (Bodzek et al., 2011). Membrane processes have been widely adopted over the last 30 years despite inherent limitations such as fouling, thermal and chemical resistance, and maximum achievable purity. The brackish water desalination process was the first RO system application in 1960 (Van der Bruggen et al., 2002 and Bodzek et al., 2011). The main success of membrane processes is that they can separate particles, dissolved ions, viruses, and bacteria from water. Figure 2.1 shows the separation of different pollutants by the membrane process.

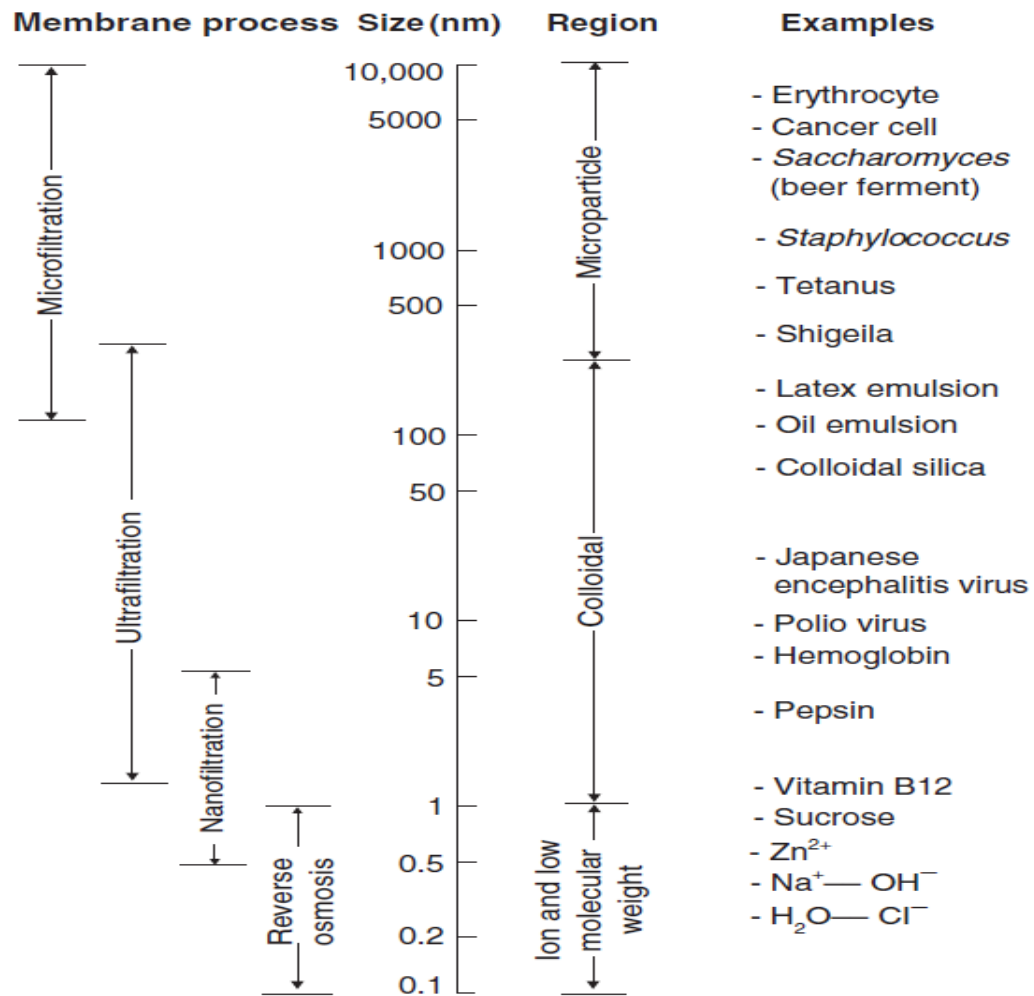


Figure 2.1. Separation of different pollutants by membrane processes source (Singh, 2014)

Figure 2.1 shows the different contaminants that can retain by membrane technology and the size region for the membrane process. The application of membrane technology in the water treatment process can be summarized as follows;

- Reverse osmosis process: RO can retain monovalent Ions of dissolve particles and viruses and can retain organic and inorganic micro pollutants.
- Nano filtration NF: can retain colloidal, low molecule organic compounds and divalent ions.
- Ultrafiltration UF: can retain suspended solids and micro-organic pollutants.
- Microfiltration MF: can retain the turbidity of the water.

Modern membrane technologies are used widely for sea water desalination and brackish water treatment.

2.1.1. Advantages and disadvantages of membrane technology

The Advantages of employing membrane filtration technologies compared to conventional filtration are more minor space requirements, reduced labor requirements, better process automation, and more effective pathogen removal (especially protozoan and bacteria) (Sharma, 2020). Some disadvantages of the membrane process include infrastructure and maintenance costs, limited life of membrane modules, and resulting fouling and scaling (Asano et al.,2007 and Sharma, 2020). In addition, the membrane process needs high energy than conventional water treatment processes.

2.1.2. Historical development

The first recorded study of membrane phenomena appears to have been by the French Abbe Nollet in 1748. He placed the spirit of wine in a vessel, the mouth closed with an animal bladder and immersed in water. Because it was more permeable to water than wine, the bladder swelled and sometimes burst, demonstrating semi permeability for the first time. Dutrechet introduced the term “osmosis” in the 1820s to characterize the spontaneous flow of liquid across a permeable barrier. Fick prepared the first synthetic membrane in 1855, made from nitrocellulose. In 1861 Graham reported the first dialysis experiments with synthetic membranes. He also demonstrated that rubber films exhibited different permeability to different gases. During the next 30 years, Traube and Pfeffer prepared artificial membranes, and their work with osmotic phenomena led to the well-known van't Hoff osmotic pressure relationship (Jagani, 2018). Bechold coined the term “ultrafiltration” in 1906, and Michaels pioneered modern ultrafiltration (UF) in the 1960s. Many of these membranes could be used as very fine particles or molecular filters. The microporous filters developed by Zigmondy and others around 1910 were asymmetric, with a finely porous skin on the feed side and an open structure on the permeate side. The tightest of the UF membranes were made from cellophane or regenerated cellulose. Membrane filters were first commercialized in 1927 by the Sartorius Company in Germany using the Zigmondy process. Reverse osmosis (RO) was first observed and

studied in the 1920s. However, it remained unnoticed until Reid and his co-workers rediscovered it 30 years later. Kolff demonstrated the first practical phenomenon of hemodialysis in the 1940s. Membrane milestones are given in Table 2.2.

Table 2.2. Membrane milestones (Singh, 2014)

Event	Scientist	Year
Osmosis	Abbe Nollet	1748
Law of diffusion	Fick	1855
Dialysis, gas permeation	Graham	1861-1866
Osmotic pressure	Traube, Pfeffer, Van't Hoff	1860-1887
Microporous membranes	Zsigmondy	1907-1918
Distribution law	Donnan	1911
Membrane potential	Teorell, Meyer, Sievers	The 1930s
Hemodialysis	Kolff	1944
Skinned membrane	Sourirajan and Loeb	1959
Membrane transport model	Kedem, Katchalsky, Lonsdale, Merten, Pusch, Sourirajan	1960-1970
The spiral wound membrane element	Westmoreland, Bary	1965-1970
Hollow fiber RO membrane	Mahon, Hoehn, and Milford	1965-1970
Thin film composite membrane	Cadotte and Rozelle	1972

The following will be discussed some of the membrane processes.

2.2. Reverse Osmosis Process

RO is a process for removing solutes such as dissolved ions from a solution using a semipermeable membrane under hydraulic pressure (see Figure 2.2 and Table 2.1) (Singh, 2014). When a semipermeable membrane is used as a barrier to separate water from a concentrated solution of ions, the water moves through the membrane to the concentrated solution due to osmosis to even out the water concentration or equilibrate. Water continues to flow until sufficient osmotic pressure builds up on the concentrated solution side to prevent further water flow up the concentration gradient (Singh, 2014).

The flow is reversed when greater than the osmotic pressure is applied as illustrated in Figure 2.2. The process is called “reverse osmosis” and results in a concentrated salt solution on the feed side of the membrane and a near pure solution on the other side of the membrane; in effect, water gets squeezed out and flows out through the membrane under pressure (Singh, 2014).

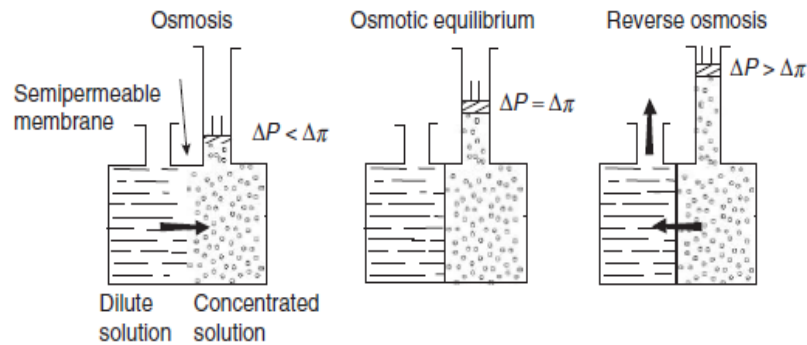


Figure 2.2. Shows the osmotic phenomena at osmotic equilibrium. The hydrostatic pressure precisely counterbalances the osmotic pressure (D_p) across the membrane (DP) applied to the concentrated solution. Source (Singh, 2014).

This technology is used to remove a large majority of contaminants from water by pushing the water under pressure through a semi-permeable membrane (Usman, 2017). The osmosis process happens without needing energy assistance, while the reverse osmosis process needs energy for the more saline solution (Usman, 2017). A reverse osmosis membrane is a semi-permeable membrane that allows the water molecules to pass through it and reject other molecules or ions such as salt, bacteria, viruses, and organics.

The most basic RO desalination system includes the pre-treatment module, high-pressure pumps, the RO membrane module, and the post-treatment module, arranged as shown in Figure 2.3 (Que et al., 2021 and Subedi, 2021).

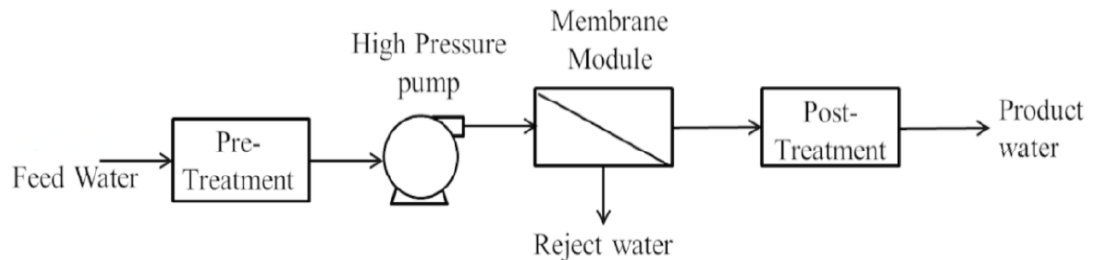


Figure 2.3. Schematic diagram of a general reverse osmosis water treatment plant (Subedi, 2021)

Pretreatment removes suspended solids, reduces the fouling potential to the RO system, and can help increase the life of using the RO system. In the present study, we will use the ultrafiltration (UF) pretreatment process that will be discussed in the design part. A high-pressure pump will be used in reverse osmosis to increase the pressure on the concentrated side to force the water molecules to cross the membrane. The reject stream will leave almost all dissolved solids in the system; if the concentration of the raw water increases, the pressure required for the process will be increased (Usman, 2017). high-pressure pumps need high energy consumption. Sometimes the post-treatment process will be used depending on the treated water application and use purposes. To reduce the energy cost for a RO water treatment system, energy recovery devices (ERD) are used in the concentrate water site to produce pressure and convert it to feed flow to decrease the energy cost of the RO system pumps. The advancement of membrane technology and energy recovery devices (ERDs) over the last 50 years has brought down the energy intensity of RO desalination systems (Que et al., 2021 and Subedi, 2021). Figure 2.4 shows the RO system schematic diagram with the ERD system.

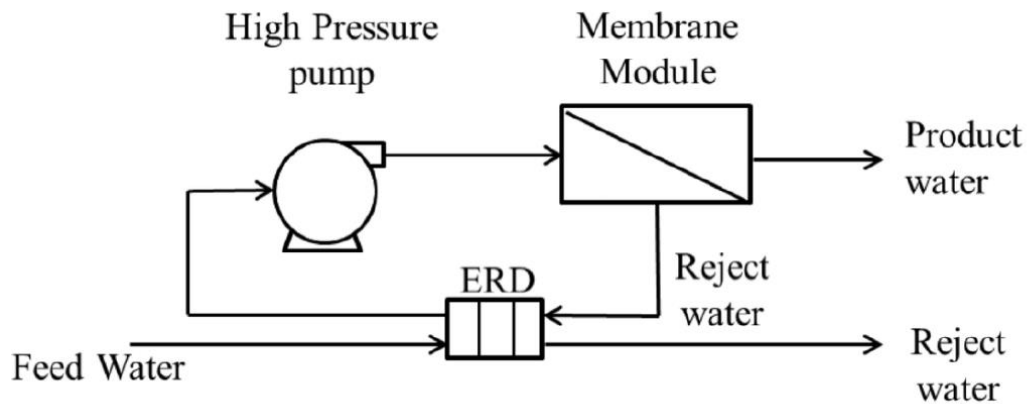


Figure 2.4 Schematic diagram of RO system with feed pump, RO membrane, and ERD recovery device (Subedi, 2021)

RO systems can be designed in different configurations to improve water quality and reduce energy consumption and cost.

a) In a single-stage single-pass RO system filtering water for one time, it is an economic system. In a single stage, multiple passes filter water more than once, improving water quality, but this system is more expensive than a single pass. Furthermore, in this system, the feed pressure reduces for the second pass and needs the booster pump to increase the feed pressure (Figure 2.5).

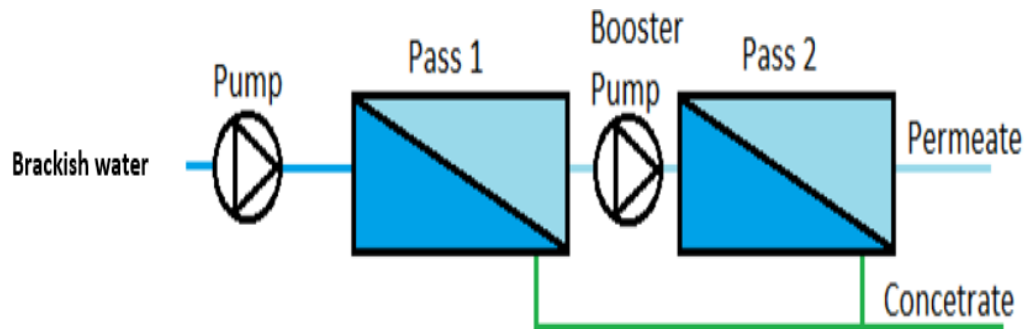


Figure 2.5. Schematic diagram of two-pass RO system

b) To improve the water recovery, the double-stage RO system has been used as the concentrate water for the first stage becoming the feed water for the second stage. Figure 2.6 shows double stage RO system

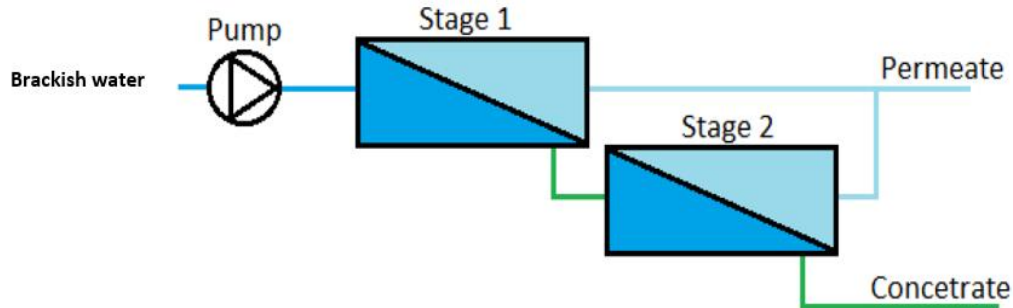


Figure 2.6. schematic diagram of two stages RO system

2.2.1. Reverse osmosis membranes and materials

there are two significant types of RO membrane Cellulose Acetate (CA) and Polyamide (PA). A significant breakthrough in the RO membrane history was the asymmetric semipermeable cellulose acetate membrane developed by Sidney Loeb and Srinivasa Sourirajan at UCLA in the late 1950s (Sidney and Srinivasa, 1964; Cohen and Glater, 2010). In 1972, John Cadotte of North Star Research developed the first interfacial polyamide membrane that had better salt rejection and water flux at lower operating pressures than the cellulose acetate membranes. The CA membrane is a semi-permeable thin film of a polymeric material with Thousands of angstroms thick polymeric porous material. The lifetime of the membranes varies between 3 to 5 years depending on the inlet water quality and the pretreatment system efficiency (Arthanareeswaran et al., 2004 and; Usman, 2017). The CA membranes are made from diacetate and triacetate cellulose. The separation process mechanism is to remove the solvent material by evaporation. The structure of CA membranes with a surface layer of 0.1 to 0.2 micron is responsible for the salt removal. The membrane film is very porous with high solution permeability. The temperature variations are responsible for controlling the amount of water flux and salt rejection (Arthanareeswaran et al., 2004 and Usman, 2017).

The PA membrane has two layers; one is a porous support layer, while the other is a semi-permeable layer. The PA membrane is a higher water flux and lower salt pass than the CA membrane. In addition, the PA membrane is stable with a broader pH range than the CA membrane. However, the CA membrane is less degraded by exposure to free chlorine than the PA membrane when the feed water has high fouling, such as surface

water supplies. Hence, the CA membrane is more applicable than the PA membrane because the surface of the CA membrane is more stable to free chlorine (Zhou et al., 2009 and Usman, 2017).

The selection of membrane material depends on raw water quality, required permeate quality, and membrane costs. Furthermore, some factors must be considered when selecting membrane materials, such as performance, cost, ease of fabrication, and resistance to environmental factors such as pH, temperature, and pressure.

For the selection of membrane modules or shapes, there are some aspects to assure these;

- a. Excellent and constant flow over the membranes without dead-water zone
- b. Low pressure losses
- c. High packing density
- d. Low-cost production
- e. Easy cleaning
- f. Easy replacement of the membranes
- g. Low disposition for clogging

2.2.2. RO membrane configuration

Following are the main shapes of RO membrane between manufacturing sites.

- 1- Flat sheet configuration.
- 2- Spiral wound configuration.
- 3- Hollow fiber configuration.

According to shapes, membrane Manufacturers do several designs for cross-flow membrane devices. Some basic configurations for constructing membrane modules include hollow fiber, spiral wound, tubular, plate and frame, and capillary (Scott, 1998).

1) A flat sheet is the basic membrane configuration where pressure is applied to move water across a sheet of semi-permeable dense membrane. However, sheet membranes are usually used in the research stages to develop and test new membranes. Figure 2.7 shows a schematic form of a flat membrane.

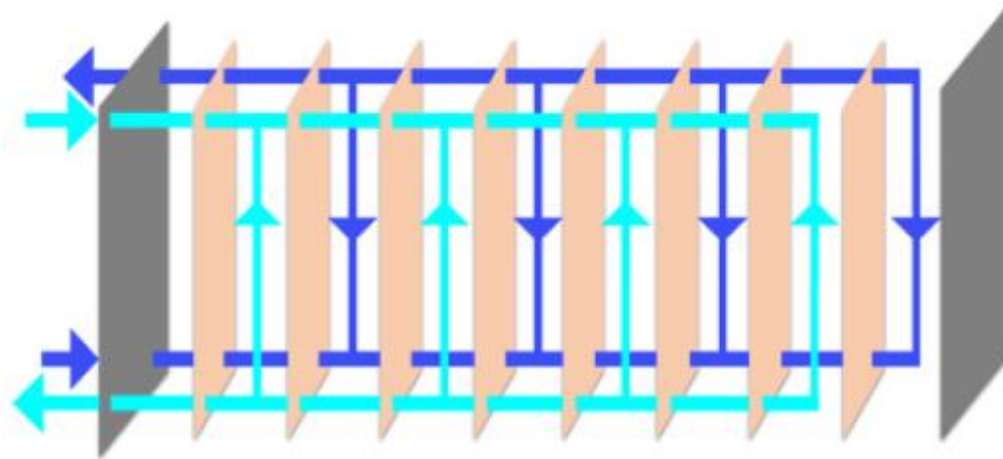


Figure 2.7. schematic form of a flat membrane (Albiladi, 2019)

2) The spiral wound is the most common form of packing RO membranes (Bartels et al., 2008) because it maintains a good balance among packing density, resistance to fouling, ease of cleaning, water flux, and fabrication cost (Schwingee et al., 2004). spiral wound RO membrane separation is used in various industrial applications, including portable water production from brackish groundwater and ocean water (Elimelech and Phillip, 2011). municipal and industrial wastewater treatment (Bodalo-Santoyo et al., 2003; Dialynas and Diamadopoulos, 2009), whey and lactose concentration (Balannec et al., 2005), and boiler feed water pretreatment (Cuda et al., 2006). Figure 2.8 shows the detailed geometry shape of spiral wound Ro membrane

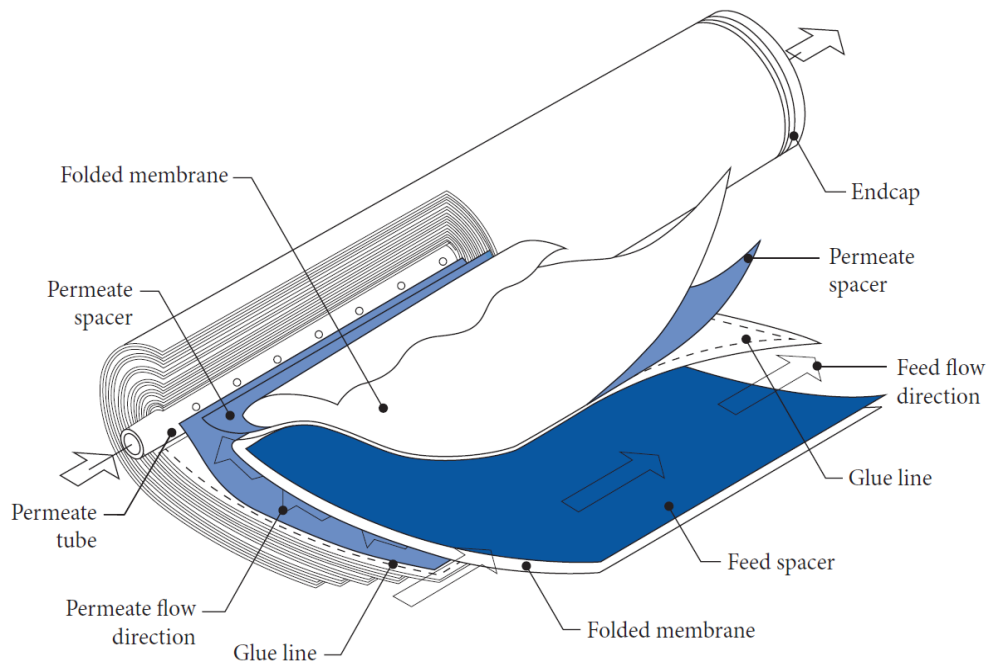


Figure 2.8. A spiral wound RO module (Johnson and Busch, 2010).

In the following table, there are some characteristics, values, capacity, advantages, and disadvantages of tubular and flat membranes;

Table 2.3. values, capacity, advantages, and disadvantages of tubular and flat membranes

Characteristics values, advantages, and disadvantages of tubular membranes						
Model type	Packing density(m ² /m ³)	Separation layer arrangement /diameter	Concentration polarization fouling	Operating mode	Advantages	Disadvantages
Tube	10-25	Inside/12.5-25	Very good	Cross flow	1- Hardly susceptible to blockage 2- Low-pressure low operation controlled by covering layer is possible	Low component density
Capillary	400-1000	Outside-inside/0.5-5	good	Cross flow/dead-end	1- High component density 2-Cheap production backwashing is Possible on the permeate side	Low-pressure resistance
Hollow fiber	2000-15000	Outside-inside/0.8-1	poor	Dead-end	1- Extremely high component density 2- Favorable specific membrane cost 3- High-pressure resistance	Susceptible to blockage pressure loss
Plate	50-200		Good	Cross flow	1- Membrane can be changed separately 2- Hardly susceptible to blockage	Low component density Many seals
Spiral wound	500-1000		Moderate	Cross flow/dead-end	1- Cheap production, few seals 2- High component density	Long flow path on the permeate side Mechanical cleaning is not possible Risk of blockage
Chusion	400		poor	Cross flow/dead-end	1- Little pressure loses on the permeate side 2- Hardly susceptible to fouling	Low component density Many seals

Hollow fiber is the latest configuration used in reverse osmosis desalination. It has the maximum area-to-volume ratio (packing density) among all the modules (Albiladi, 2019). hollow fiber modules consist of tiny membrane tubes with an inner diameter of 42 - 77 mm. These tiny tubes are cross-wound around a perforated central tube and contained in a pressure vessel. Thus, each pressure vessel contains millions of hollow fibers, which is why the packing density is the highest in hollow fiber modules compared to the plate and frame and spiral wound modules (Albiladi, 2019). Figure 2.9 shows the model of hollow fiber models.

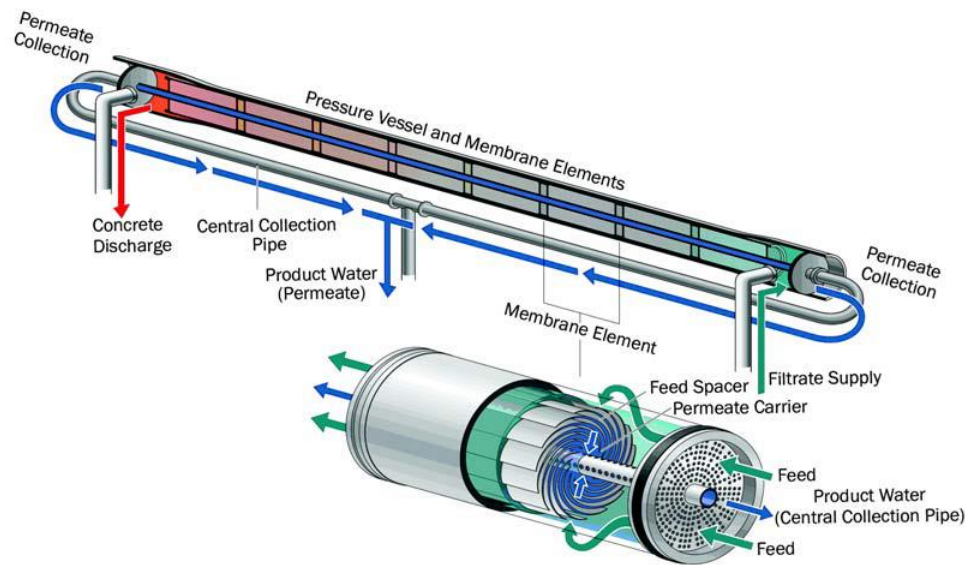


Figure 2.9. Hallow fiber model with eight elements (AWWA, 2007)

The most common diameters of an RO membrane element are 2.5 in. (61 mm), 4 in. (99 mm), and 8 in. (201 mm). The typical length is 40 in. (1016 mm), although 14 in. (356 mm) and 21 in. (533 mm) are available for small and compact systems. Some larger diameter RO elements (e.g., 16 in. and 18 in.) have emerged in the market which have the benefits of cost-saving and ease of operation. Several (typically, six to eight) spiral wound

RO elements are connected in a series and enclosed in a The fiberglass-reinforced plastic pressure vessel as shown in Figure 2.10.

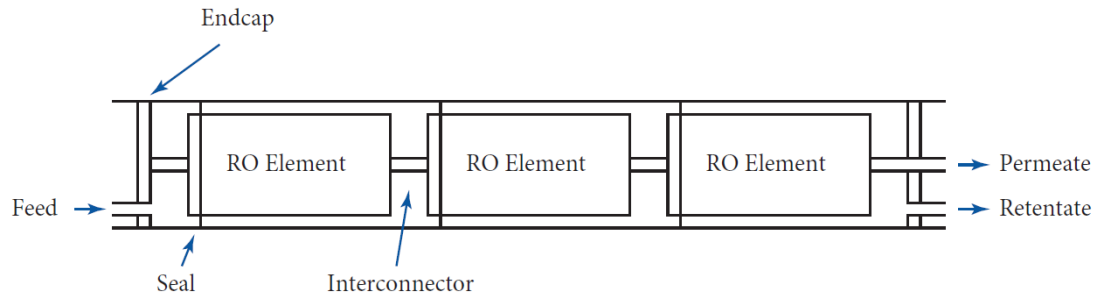


Figure 2.10. A single pressure vessel with elements

2.3. Membrane Problems

due to the concentration of the water constituents taking place at the raw water side of the membrane, the following effects may occur on the membrane surface as well as on the components of the membrane elements or the membrane models. This phenomenon has adverse effects on the performance of the membrane installation. These effects contain Fouling, scaling, bio fouling, and concentration polarization. Following it will briefly discuss some of the membrane problems.

2.3.1. Membrane fouling

the fouling of the pressure-driven membrane is generally referred to as the accumulation, deposition, or adsorption of the foulants onto the surface of the membrane or within the membrane pores, or it can be said as external and internal fouling (Voutchkov, 2017). Fouling can cause the basic membrane function to deteriorate over the filtration time, permeate flow, solute removal efficiency, and pressure drop across the membrane. Membrane fouling is the major obstacle to the widespread use of membrane technology. Membrane fouling occurs when suspended solids, microbes, or organic material deposit on the membrane surface and form layers of undesired material that can plug the membrane. Control of membrane fouling is essential for the successful long-term performances of plants (Peinemann and Nunes, 2010). Membrane manufacturers have put much emphasis on the silt density index (SDI) measurement to evaluate the water fouling

potential of membranes, particularly NF/RO systems (Peinemann and Nunes, 2010). Three major factors influence membrane fouling.

1- Membrane material properties such as hydrophobicity, roughness, and electrical charge.

2- Feed solution characteristics such as the nature and concentration of the foulants.

3- High-pressure operations can exacerbate operating conditions such as fouling.

The membrane process can occur in three kinds of fouling: biofouling, particulate or colloidal fouling, and organic fouling.

A- Biofouling is related to the microorganisms living in the feed water and attached to the surface of the membrane. Several studies indicate that the biofilm formed by microorganisms on the RO membrane surface negatively impacts the decline in water productivity and salt removal rate. Bacteria are the main contributor to biofouling in the RO membrane (Voutchkov, 2017). Figure 2.11 shows the occurrence of biofouling in the RO membrane.



Figure 2.11. Occurrence of bio fouling by microorganism in RO membrane (

<https://www.wur.nl/en/show/Isolation-and-characterization-of-microorganism-involved-in-membrane-biofouling-1.htm>)

B- Particulate fouling occurs when suspended solids or colloidal materials clog the holes of a membrane or adhere to its surface, as particles accumulate on the membrane

and form a cake layer that obstructs water from flowing through the membrane pores. Particulate fouling causes pressure differential measurement and increased energy consumption. Particulate fouling is caused by the presence of non-biological and inorganic particles such as the presence of salt and clay in water, especially in the surface water source. For the measurement of relative particulate fouling risk in surface water treatment, it measures the silt density index (SDI) of the feed stream. Particulate fouling can prevent by applying the coagulation process and filtration as a pretreatment. Figure 2.12 shows the sample of particulate fouling in the RO membrane.



Figure 2.12. Shows the sample of particulate fouling due to suspended solids (Voutchkov, 2017).

C- Organic fouling is the combination of position, reaction, and interactions of high molecular weight organic compounds such as natural organic matters with the membrane surface. These organic matters consist of humic substances, polysaccharides, proteins, lipids, nucleic acids, amino acids, organic acids, and cell components (Cho et al., 1999 and Jeong et al., 2016). Currently, only suitable pretreatment may limit biofouling (Peinemann and Nunes, 2010). Organic fouling is the main problem for wastewater treatment in RO systems because the high concentration of total organic compounds (TOC) is much higher (10-20ppm) than surface water treatment which is (2-5ppm).

According to the removal of fouling, there are two types of fouling in the RO system.

1- reversible fouling

2- irreversible fouling

reversible fouling can be removed by backwashing of the membrane or by lowering the driving pressure on the surface of the membrane. When the fouling from a strong matrix layer on the surface of the membrane with the solute during a continuous filtration process, the reversible fouling becomes irreversible and cannot be cleaned by physical cleaning. To prevent all types of fouling in the membrane, it is necessary to install an excellent pretreatment to decrease the fouling in the membrane. A suitable pretreatment allows a much longer membrane life at lower cleaning costs. Disinfection of water is used to destroy bacteria. However, RO membranes are sensitive to oxidizers, so they must be removed before entering the membranes (Peinemann and Nunes, 2010).

2.3.2. Scaling

scaling can be formed as a coating by inorganic precipitation or crystallizations. It occurs in the RO membrane when the dissolved solid solubility limit exceeds concentration on the membrane surface (Singh, 2014). Different salts can form scale in membrane processes, such as CaCO_2 , CaSO_4 , SiO_2 , BaSO_4 , SrSO_4 , etc. The most common scale in the RO membrane is the calcium carbonate scale which forms quickly. The fouling and scaling of feed water are measured by the Langelier saturation index and Stiff and Davis stability index, which will be discussed in the chemical adjustment part of the study. For the reducing the scaling problem in the membrane, we can reduce the water recovery factor to operate below solubility limits, decrease pH by adding acids to regulate the calcium carbonate speciation, add inhibitors or anti scalants that delay the induction time of precipitation or use ion exchange for the elimination of undesirable ions.

2.3.3. Membrane cleaning

Membrane cleaning is a critical stage that should be minimized, if possible. Membrane technology is essential for periodic cleaning in the water and wastewater treatment process (Sadhvani and Veza, 2001; Yang et al., 2013; Jiang et al., 2017). Cleaning fouled membranes depends on the type of fouling. To keep RO membrane

performance, regular cleaning of membranes is required (Singh, 2014). A simple wash along the membrane or opposite the flow direction is the easiest type. Low pH is used when salts are precipitated. High pH is effective when silica is precipitated and includes organic matter or bacteria. There are two main types of cleaning for membranes.

- 1- physical cleaning
- 2- chemical cleaning
- 3- biological cleaning
- 4- enzyme cleaning

in chemical cleaning, detergents or other cleaners can disperse foulants from the surface of the membrane and keep back the performance of the membrane element (Singh, 2014). the efficiency of chemical cleaning increases by increasing water temperature, and the chemical reaction rate doubles by increasing by 10 °C of water temperature (Singh, 2014).

The selection of chemicals for chemical cleaning is related to the fouling type, foulant resistance, chemical properties, and the price of chemicals (Jiang et al., 2017). for the removal of membrane scaling, different acids such as hydrochloric acid, nitric acid, and sulfuric acid are used most in the membrane cleaning process (Jiang et al., 2017). for the removal of organic and biofouling, the alkaline solution such as sodium hydroxide is most efficient (Jiang et al., 2017). the most commonly used chemical for cleaning RO systems is ethylene diamine tetra acetic acid (Jiang et al., 2017). high flow velocity, backwashing, and air sparging are the physical cleaning types. Applying these types of cleaning processes can remove the particles from the surface of the membrane.

2.3.4. Concentration polarization

concentration polarization (CP) is a natural consequence of the selectivity of a membrane. This leads to an accumulation of particles, solutes, or salts in a mass transfer boundary layer adjacent to the membrane surface (Salinas-Rodríguez et al., 2021). as the salt or particles will reject by the membrane surface and water pass through it, the retained salt can accumulate the membrane surface while the concentration of salts will be an increase (Salinas-Rodríguez et al., 2021). the concentration of this retained salt will generate a diffusive flow to the bulk of feed. CP and fouling affect the membrane life and

permeate flux (Sablani et al., 2001). CP increases resistance to solvent flow which is responsible for the water flux decline observed in many membrane filtration processes (Sablani et al., 2001). CP is strongly related to the osmotic pressure rise, which increases resistance to permeation such as jell formation and fouling sustainability, which also may change the membrane separation properties due to surface charge variations. CP cannot be avoided in the membrane process but can be minimized by various methods such as mixing the bulk feed solution with the solution near the membrane surface and velocity adjustment (Jiang et al., 2017). Furthermore, by decreasing of flux, increasing the feed flow, and increasing the concentrate flow by decreasing the plant recovery. For the measurement of CP in the membrane, experimental and modeling studies have been done (Sablani et al., 2001). The recommended value of CP is given below 1.2 for most membrane element manufacturers (Salinas-Rodríguez et al., 2021).

2.3.5. Silt density index (SDI)

SDI was introduced to characterize the fouling potential of feed water for RO system (Salinas-Rodríguez et al., 2021). It is a kind of raw water test that measures the target contaminants such as suspended and colloidal matters in raw water, which are the primary fouling materials in water (Salinas-Rodríguez et al., 2021). At present, $SDI < 5$ is selected for pretreatment of the RO system, and $SDI < 3$ is the suitable water for RO feed flow (Salinas-Rodríguez et al., 2021). The SDI test must be done according to the American Society for Testing and Materials (ASTM) and can be done for 5 and 15 minutes.

2.4. Pretreatment for RO System

Pretreatment is the primary and key process in RO water treatment or desalination system. The most crucial component in a RO system is the pretreatment system. Pretreatment system performance greatly impacts the RO system efficiency and the life of RO membranes. The primary objective of pretreatment is to make the feed water compatible with the membrane. Pretreatment for the RO system can remove suspended solids (e.g., silt, algae), oil, and grease to make RO feed water quality and prevent rapid fouling in the RO system. (Goh et al., 2018; Anis et al., 2019 and Brover et al., 2022).

Several pretreatment technologies can be applied before the reverse osmosis (RO) system, containing physical and chemical processes such as coagulation, flocculation, dissolved air flotation, and filtration (Brover et al., 2022). These pretreatment processes depend on the potential of fouling of raw water sources. Applying pretreatment in the RO water treatment system can minimize the fouling and scaling of the RO membrane, reduce membrane degradation and reduce the cost of the system. For selecting an appropriate pretreatment system, it is essential to analyze different chemical and physical parameters of raw water such as; pH, suspended and dissolved solids, total hardness, dissolved oxygen, conductivity, specific solute concentration, COD, BOD, etc.

Among these technologies, UF has widely spread over the last decade (Brover et al., 2022). UF filtration treatment process is a kind of physical separation process that can separate compounds from the water body through semi-permeable membranes (Lilane et al., 2020). UF technology has some advantages over the other processes, such as a smaller footprint, increased water quality for RO system, and high resistance to seawater quality variations (Brover et al., 2022). UF filters are more effective for removing suspended organics, silt, and pathogens. Micro- and ultrafiltration remove substances from the water phase by a sieving mechanism (Lilane et al., 2020). Figure 2.13 shows the UF system, which can remove different microorganisms.

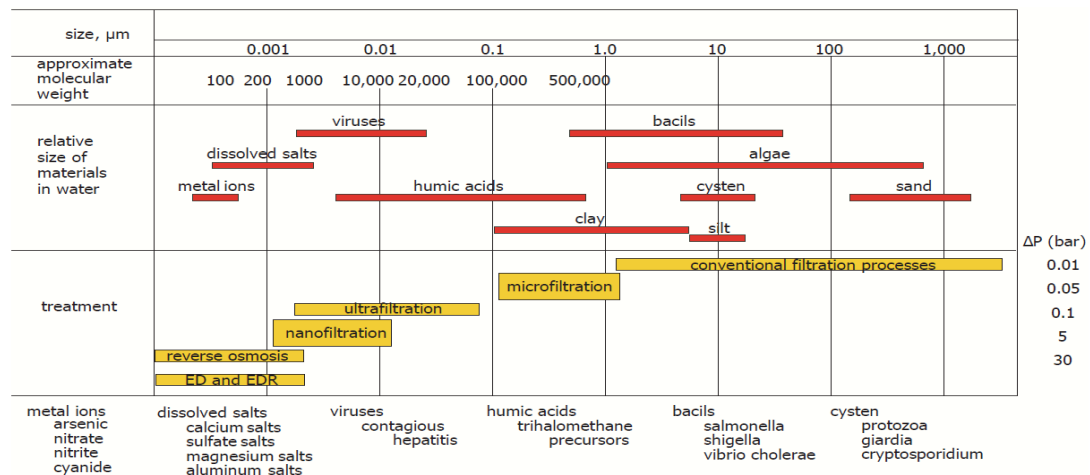


Figure 2.13. Microorganisms which retain by the UF system (Lilane et al., 2020)

Different studies indicated that the most common RO pretreatments are ultrafiltration, coagulation-flocculation, and micro filtration, as seen in Figure 2.14 (Jiang et al., 2017).

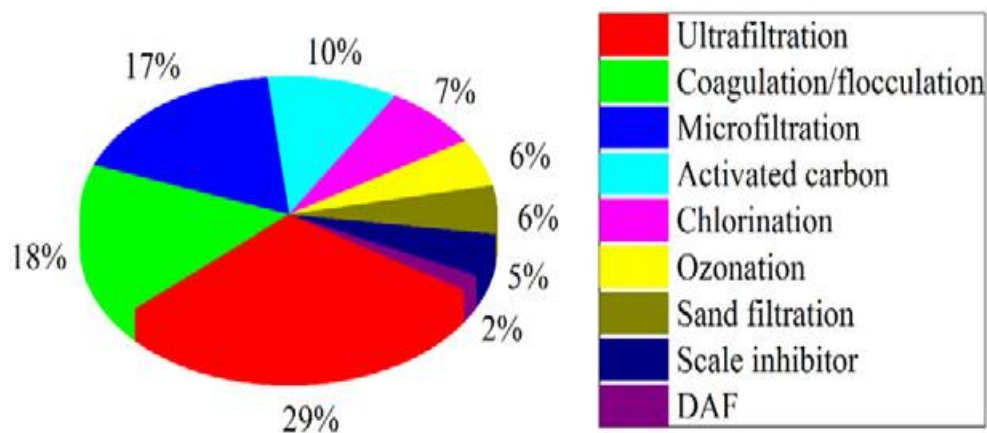


Figure 2.14. Common studied RO pretreatment technologies in the past ten years (Jiang et al., 2017)

In fact, the UF and MF systems as RO pretreatment are gaining as most popular in recent years. Ultrafiltration (UF) technology has become widespread over the last decade (Tabatabai, 2014 and Brover et al., 2022). To provide definite barriers to the suspended particles and colloids, microporous UF pretreatment filtration is widely used worldwide.

2.4.1. Ultrafiltration membrane

Ultrafiltration (UF) is between MF and NF membrane according to the degree of separation, as seen in Figure 2.1 (Singh, 2014). Ultrafiltration uses a finely porous membrane to separate water and micro solutes from macromolecules and colloids (Baker, 2012). The average pore diameter of the UF membrane is in the 10–1000 Å range (Baker, 2012). Bechhold prepared the first synthetic UF membrane from collodion (nitro cellulose) (Baker, 2012). UF is a new process mainly used for municipal water treatment and different industrial processes such as concentrating milk, protein, and cells; recovering process materials such as paint, colloidal metals, and dyes; and recovering oily wastewater. A UF membrane would retain colloidal silica, protein, humic substances, and viruses, but dissolved salts, sugar, and mid-sized organic molecules would not. In recent years the application of UF in drinking water expanded because of changes in water

quality and related regulations. UF membrane comes in all configurations as (Spiral Wound, Tubular, Compound Tubular, Flat Sheet) except for fine hollow fiber.

If the feed water suspended solids content is low, spiral wound modules are best since they have the highest area/volume ratio of all UF-type configurations. Nevertheless, if the feed water does contain a high concentration of suspended solids, one of the tubular configurations will be easier to maintain. UF is the most competitive pre-treatment, especially for high fouling feed water sources such as surface water, wastewater, or open-intake seawater. (I.G. Wenten, Khoiruddin et al., 2016). (UF) starts to be recognized as the best pre-treatment before RO because it removes, in only one physical filtration stage, all the suspended solids and biological materials of the seawater (O. Lorain et al. 2007). Figure 2.15 shows the general shape of the UF filter.



Figure 2.15. Integra Flux™ Ultrafiltration Modules from DuPont manufacturer (DuPont, 2020).

One of the main obstacles to using the UF system is the formation of membrane fouling. Membrane fouling cause to reduce in the permeate flux, increases the need for cleaning, and reduces the lifetime of the membrane.

To keep all the operating condition for UF as a pretreatment its essential to clean the UF filters by physical or chemical cleaning. Following it will discuss Backwash (BW), chemical enhanced backwash (CEB) and clean in place (CIP) for UF system as a pretreatment.

2.4.1.1.Backwash (BW) of UF membranes

during the water filter process in the UF system, the solids filtered from source water accumulate on the side of the membrane. These solids are removed by periodically backwashing membranes daily (Voutchkov, 2017). for backwashing, it can be used filtered or concentrate water. Backwash in the UF system recovers the performance of UF membranes. Backwash in the UF system consists of a pump, permeate water collecting tank, and a valve for the dosing system. The backwash is usually triggered by a timer and occurs every 20-120 min for approximately 30-60 seconds or after each water filtration (Cromphout et al., 2011). Backwash could also be initiated when the TMP reaches a certain maximum threshold, beyond which the membrane system cannot perform at the target flux and filtered water quality (Voutchkov, 2017). the backwash is continuously applied from the top drain to the bottom drain of the membrane and forward flush (Dow, 2011). before the backwash step air scour step is applied as air is introduced for 20 to 30 seconds to membranes and then opened the bottom drain to remove dislodged particulates (Dow, 2011). Figure 2.16 shows that the air scours step is applied to the UF system.

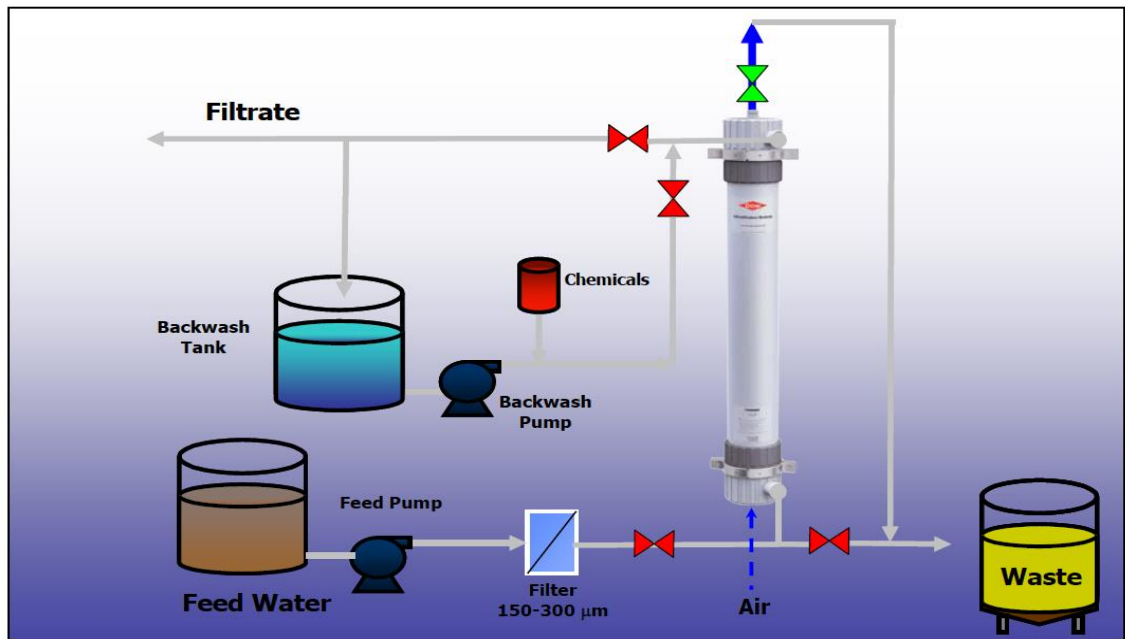


Figure 2.16. Air scour process in UF backwash (DOW, 2011)

if it is unavailable, the air scours step directly the backwash process is applied to the UF system. Figure 2.17 indicate the backwash step for the UF system.

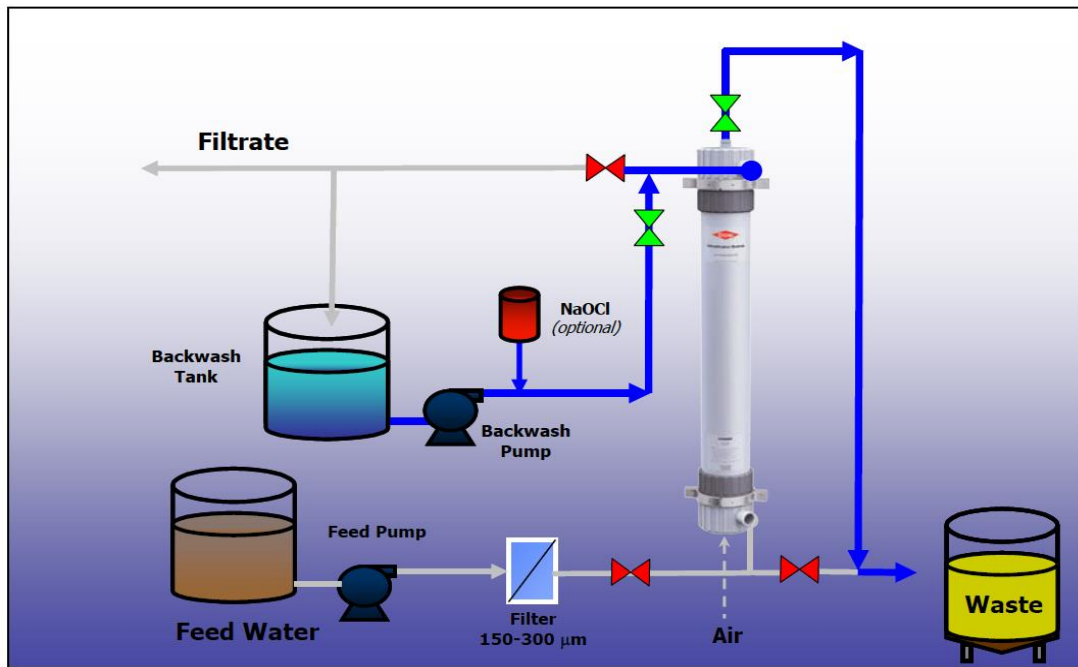


Figure 2.17. Backwash step operation (DOW, 2011)

Figure 2.17 shows the first backwash step, in which the permeate water flow is reversed from the inside of the fiber to outside the drain to the top of the membrane. The first BW step is applied to remove contaminants in the area of greatest concentration. The second BW is applied to remove the contaminants from the bottom of the membrane element housing, as can be seen in Figure 2.18.

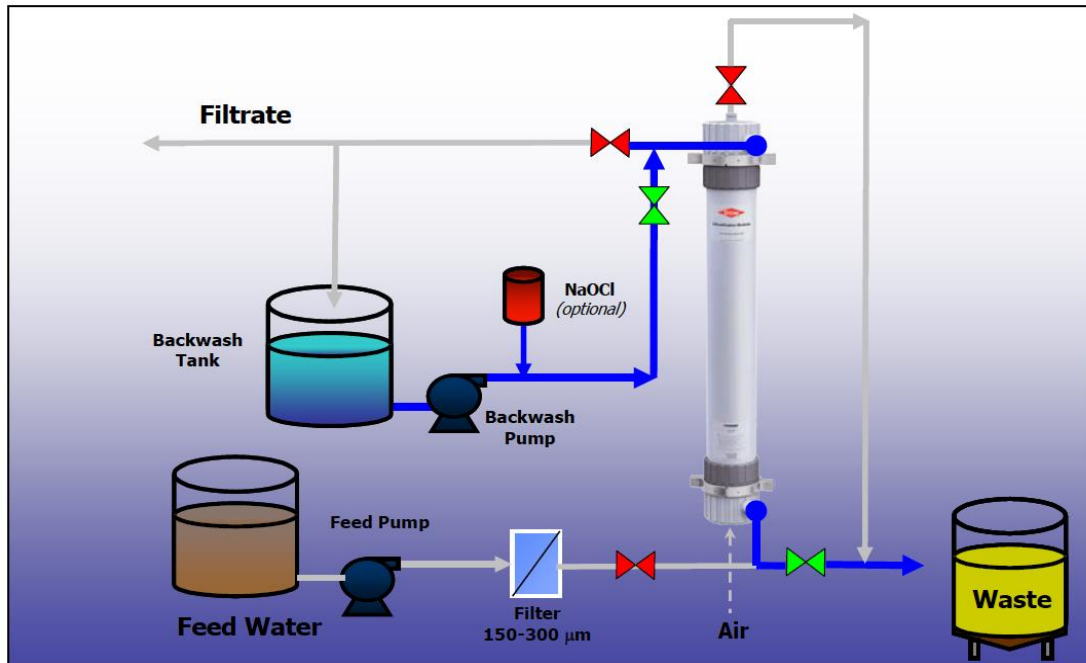


Figure 2.18. Backwash for the second time (DOW, 2011)

As seen in Figure 2.18, the permeate flow is applied from the top drain to the inside of the membrane housing to remove heavier materials and contaminants from the bottom drains. After the backwash step is complete, the forward flush is applied to remove any remaining contaminants and air trapped outside the fibers, and the model is returned to operating mode back.

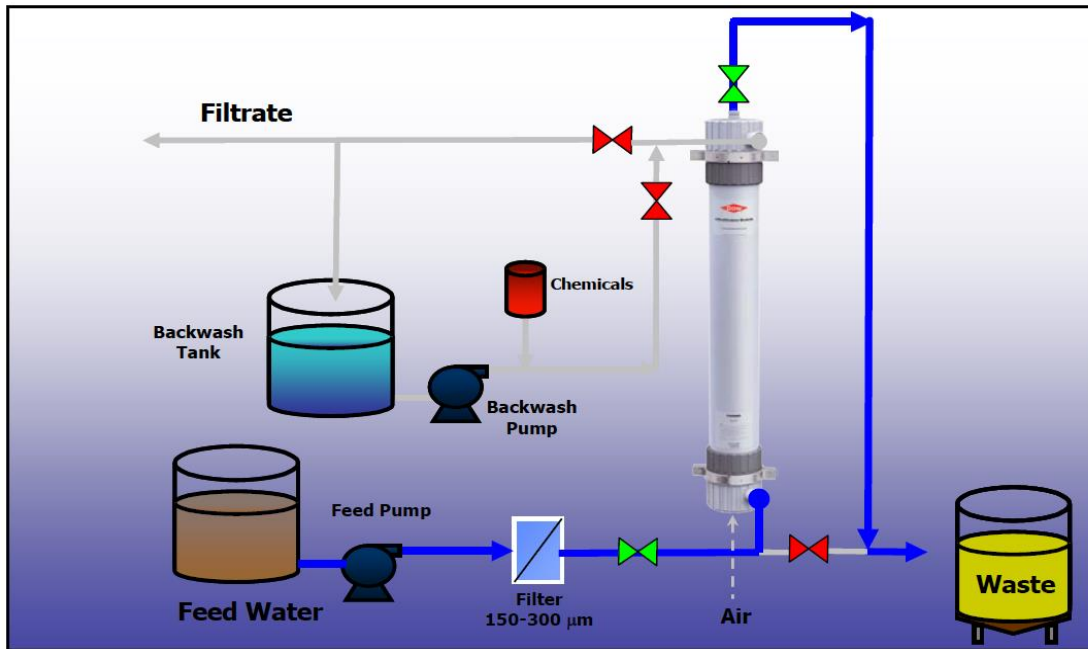


Figure 2.19 Normal operation (Dow, 2011)

In the backwash step applying the chemicals are optional (Dow, 2011). The time of the BW step is adjusted based on the amount of solids in feed water and their fouling potential (Voutchkov, 2017).

2.4.1.2. Chemically enhanced backwash (CEB) for UF system

If forward, air or backwash is not enough to clean UF membranes, CEB must apply to the UF system. Time for CEB is related to feed water quality. On high water quality, CEB may not be needed. CEB is applied using UF filtrate or adding some acid or oxidant to clean the surface of UF membranes more effectively. During CEB time, the membrane elements are shocking for several minutes in acid or some other chemicals ((acids, alkali, or sodium bisulfite) and then are backwashed (Voutchkov, 2017). The chemical dosage and types are related to contaminants in source water and the types of membrane materials. The step for CEB is the same as BW, except chemicals are added in CEB and soak in membranes from 5 to 20 minutes to react the chemicals to contaminants attached to the surface of membranes and fibers (Dow, 2011).

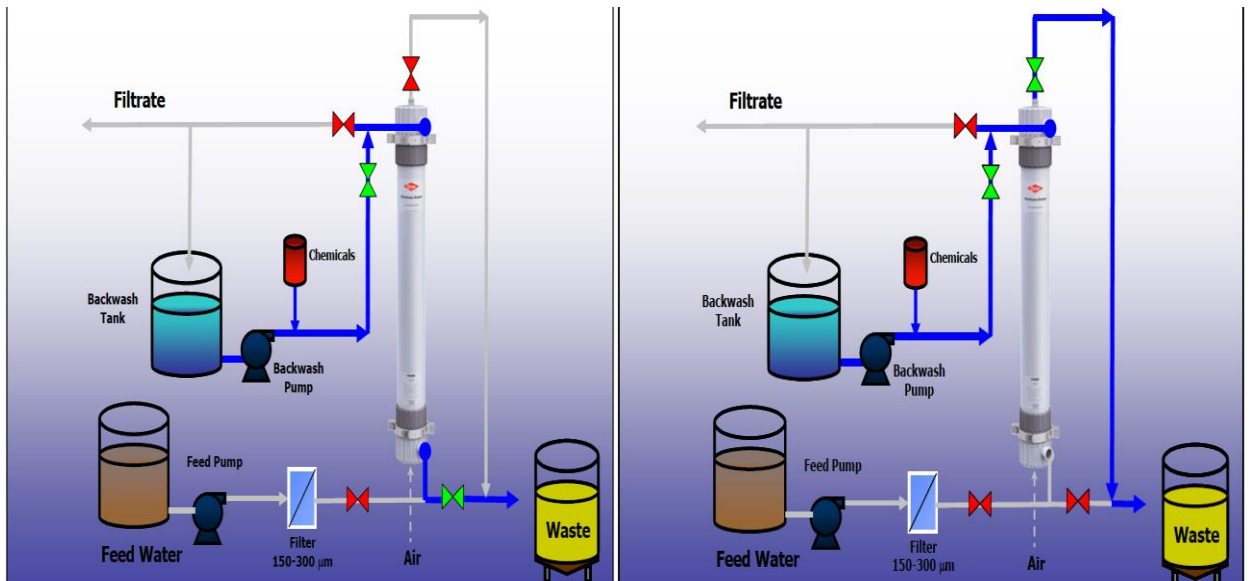


Figure 2.20. Shows the CEB step for the UF system (Dow, 2011)

After that, the forward flush is applied to remove contaminants and chemicals from membrane housing and then applied operating mode to the UF system.

2.4.1.3. Clean in place (CIP) of the UF system

Backwash and CEB cannot completely eliminate membrane fouling and contaminants from the UF membrane surface; therefore, clean in place (CIP) must apply to UF membranes (Voutchkov, 2017). CIP for membranes is needed from 1 to 3 months by using a low pH solution of an acid (citric or sulfuric acid) followed by a high pH solution of sodium hydroxide or sodium hypochlorite. The process is the same as backwash and includes air scour, draining, backwash through the top drain, and backwash through the bottom drain are performed with chemicals and performed 3 to 8 times to remove all contaminants from fiber and surface of UF membranes (Dow, 2011). the CIP solution can be heated up to 40 °C to improve its effectiveness at removing contaminants from the membrane. Figure 2.21 shows the CIP step for the UF system.

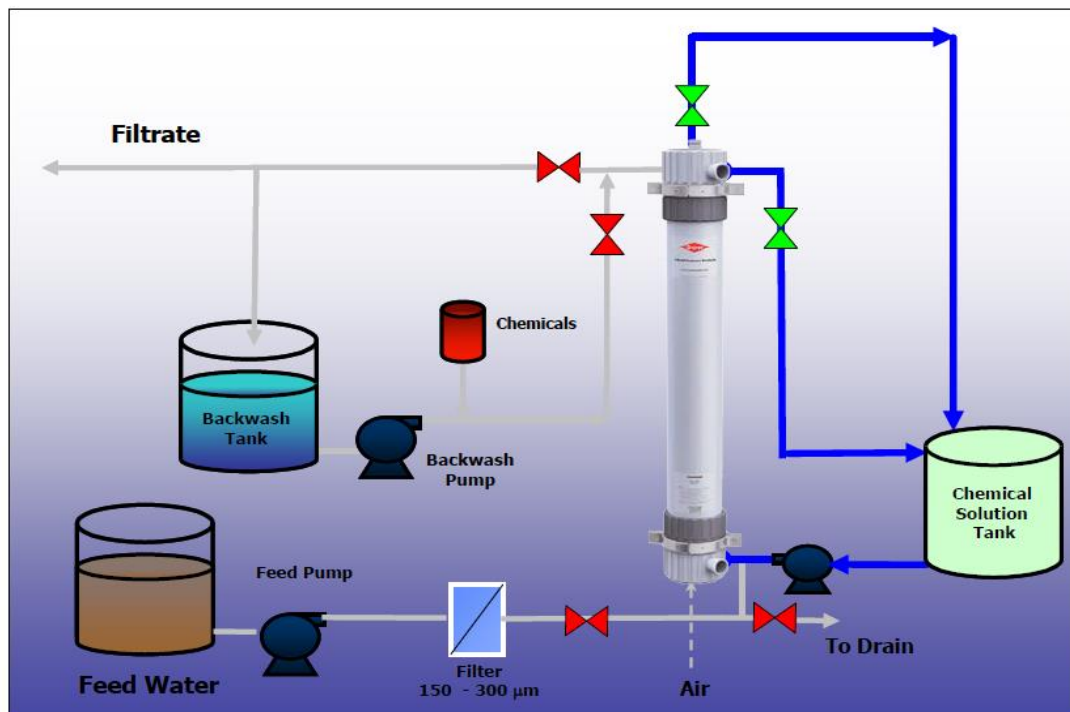


Figure 2.21. CIP step for UF cleaning (Dow, 2011)

The duration of soak and recycling of the chemicals is 60 minutes or longer, related to the degree of the fouling which occurred. When the recycling is completed, an air scour is performed, and the module is drained to remove concentrated chemicals. The two steps of backwash and a forward flush are performed to remove any remaining contaminants outside the fibers, after a CIP and at the start of the operating step.

2.5. Energy Recovery (ER) for RO System

RO system for seawater desalination and brackish water treatment is one of the most popular water treatment systems among the other technologies (Fritzmann et al., 2007 and Altaee, 2012). This technology has different advantages over the other technologies, such as it has high efficiency and can remove 95 to 99% of TDS from water, is simple equipment, and need simple maintenance, but the big issue for RO technology its high energy demand. This system needs more energy due to the flush of a high concentration of feed water through the membrane element space and the function of other feed water parameters (feed flow, feed pressure, and water temperature) (Wei and McGovern, 2017;

Alsarayreh et al., 2020). To reduce an RO system's total energy cost, it is recommended to use energy recovery devices (ERD). ERD is one of the well-known and most used devices in seawater desalination systems (SWDS) because of its high concentrate pressure and high concentrate concentration of SWDS (Drak and Adato, 2014). ERD can also be used in the BWRO system but is always based on the life cycle cost estimation of the plant. Different ERDs are available in the market for sea and brackish water desalination RO systems, such as Francis Turbine, Pelton Wheel, Hydraulic centrifuge Turbochargers (HTC), Hydraulic Pressure Booster (HPB). Pressure exchanger (PX), iSave, Salino. DWEER, Saltec, Osmorec, and Isobaric (Wang et al., 2022). among these devices, two types of ERD are mostly used in the BWRO system.;

- 1- Centrifugal turbocharger (TC)
- 2- Isobaric ERD

A Centrifugal turbocharger contains a turbine and a pump with a single-stage rotor and is specifically designed for an RO system (Wang et al., 2022). The application of TC is like the concentrate flow flows to the turbine part of the TC and the rotor of the turbine extracts the hydraulic energy of the concentrate flow and converts to the mechanical energy (Drak and Adato, 2014; Farooque et al., 2004). the pump changes the mechanical energy back to hydraulic energy to feed stream by raising the feed pressure of the feed water thus the CT is energized entirely (Drak and Adato, 2014). The total efficiency of the TC turbine and pump is about 50 to 80 % (Drak and Adato, 2014).

Different manufacturers produce TC for sea and brackish water RO systems. One of these manufacturers is Energy Recovery Inc. (ERI), which produces two types of TC low-pressure turbocharger(LPTC) for brackish water RO systems and a high-pressure turbocharger (HPTC) which is used for seawater desalination RO systems (Michas, 2013). LPTC delivers pressure up to 45 bar and can pass flow from 6.8 to 908 m³/h from TC, and the construction material for LPTC are AL6XN, bearings Graphitar 39, and casings SS304, 316, and Duplex 2205 (Michas, 2013). Figure 2.22 shows the 3D model of a TC with details.

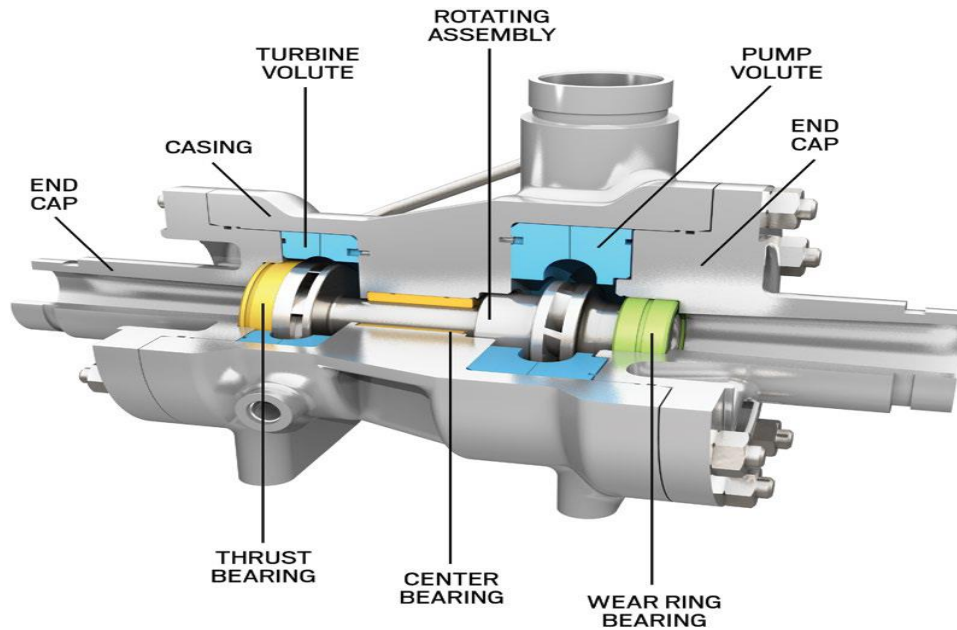
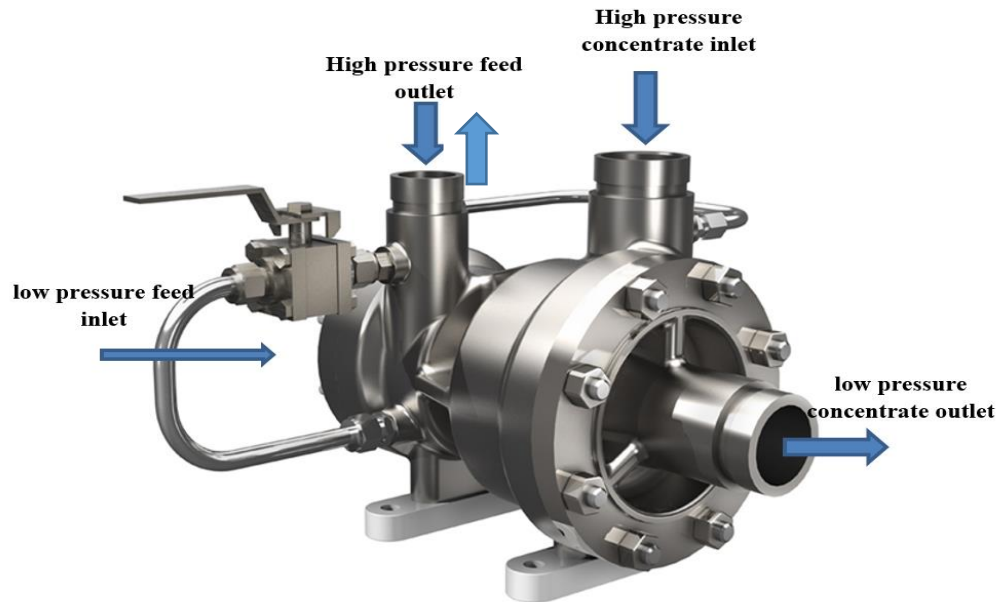


Figure 2.22 (a)source from the energy recovery manufacturer website (<https://energyrecovery.com/water/turbochargers/>) (b) shows the cutaway of TC, which ER Inc. manufactures.

Isobaric ERD is provided to avoid the efficiency losses associated with multiple energy conversion steps and use the positive displacement roles to achieve energy transfer from a high-pressure concentrate flow to a low-pressure incoming feed flow. (Farooque et al., 2004). It can call the Isobaric ERD as pressure exchanger (PX) and has two types rotary and piston. PX has its parts a rotor that rotates for pressure exchange, a sleeve, and end caps on both sides (Andrews, W. T and Laker, 2001; Huang et al., 2020). One of the most common uses of PX is rotary PX, which works as the high-pressure concentrate flow flows and has direct contact with low-pressure feed flow, and the energy transfer occurs in the rotor ducts (Drak and Adato, 2014).

The application of rotary PX is as first low-pressure feed flow rotate the ducts od rotor which fills the duct and displaces the concentrate water, and the duct rotate and displace the feed water and duct fills with concentrate water at high pressure (Drak and Adato, 2014; Farooque et al., 2004). In this kind of ERD, the feed and concentrate water contact directly causes to increase in the concentration of TDS in feed water which increases the feed pressure by 1-2 bar (Drak et al., 2014; Drak and Adato, 2014).

This technology can reduce the energy cost by up to 60 % for RO plants (Farooque et al., 2004). PX ERD is produced in two shapes, S and Q, made of ceramic and does not need any maintenance (Huang et al., 2020). Figure 2.23 shows the 3D model of a PX ERD devises.

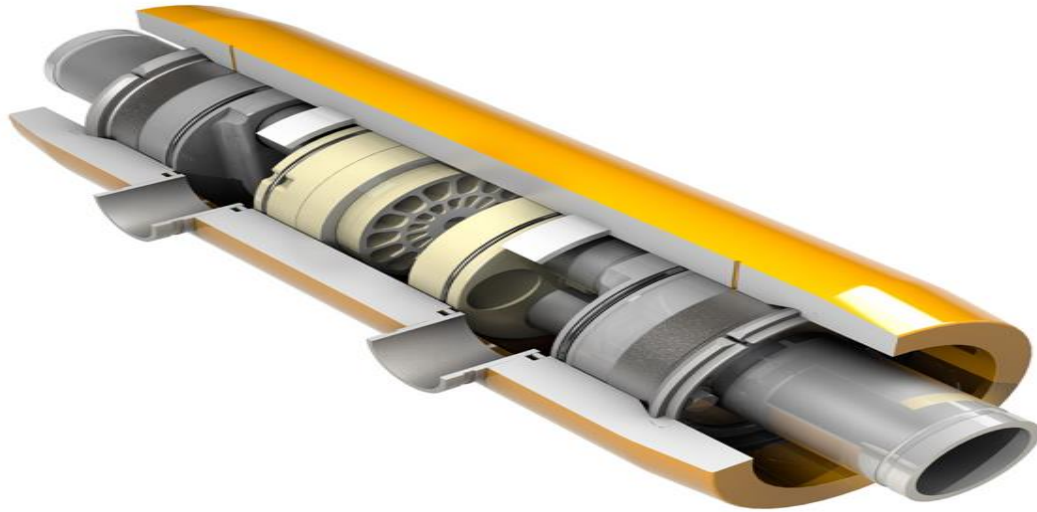


Figure 2.23. Pressure exchanger 3D model(<https://energyrecovery.com/water/turbochargers/>)

Figure 2.23 shows the installation part of the PX ERD device in the RO system.

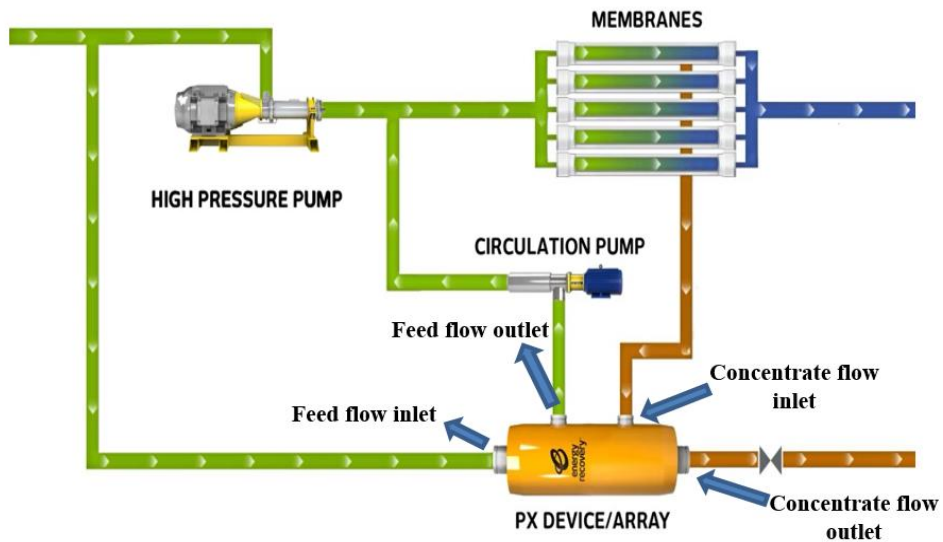


Figure 2.24. Schematic diagram of PX device installation in RO system

In the present study, we will design and calculate the energy demands for one of the RO-designed systems with TC energy recovery device.

2.6. Renewable Energy Source for RO System

RO membrane water treatment is the most popular and effective technology for water desalination (Peñate et al., 2012; Altaee, 2012). This technology has its advantages, but the main issue is the energy demand of this system, which needs high energy consumption. Water desalination technology is expensive; 1000m³ of water per day annually, it needs 1000 tons of fossil fuel (Methnani, 2007).

For the protection of climate and to reduce the emission of greenhouse gases (GHG), it is essential to replace the production of energy from fossil fuels with environmentally friendly green energy. Renewable energy is a kind of energy produced from natural sources easily and for a long time. This kind of energy has enormous potential to replace the demand for membrane water treatment systems (Mahmoudi et al., 2017). Recently different studies have been done on the importance of renewable-energy RO water treatment systems. Recent studies have indicated that 1% of total water desalination plants use renewable energy for their energy production (Gökçek, 2018). Different types of renewable energy sources are used to produce energy, such as wind, solar, and water. According to the International Renewable Energy Agency (IRENA), renewable energy grew by 50 in 2020 compared to 2019 (Bentouba et al., 2021).

Among these sources, photovoltaic(PV) solar energy is one of the efficient and eco-friendly energies for the RO desalination system. It plays a more influential role in the supply of fresh water (Mahmoudi et al., 2017). For the calculation of solar energy for a specific area, the site must be monitored for at least one year to find the average irradiation wind and temperature data for calculating energy from solar and wind sources. The present study is expected to calculate and simulate a solar energy plant for the demand of the Kirikkale RO water treatment plant.

3. MATERIAL AND METHODS

3.1. Study Area

The RO water treatment plant, which will design and simulate for the present study, is located in Kirikkale city in Turkey. Its located southeast 15 km of Kirikkale city in Hasandede town with $39^{\circ}45'03.5''N$ $33^{\circ}29'21.7''E$ coordinate (see Figure 3.1).



Figure 3.1. Shows the location of Hasandede water treatment plant in Kirikkale city of Türkiye (Google map).

In this area, two water treatment plants are located, the old one is a conventional water treatment plant, and the new one is a membrane drinking water treatment plant. The conventional water treatment plant was designed for seven districts of Kirikkale city in 2001, and the capacity of this water treatment plant was $200000 \text{ m}^3/\text{day}$. In 2008, membrane treatment units were added to the conventional water treatment unit to remove some contaminants in raw water, such as sulfate, chloride, arsenic, odor, hardness, and pesticides which are high in concentration in the raw water. The new RO water treatment plant capacity is up to $90000 \text{ m}^3/\text{day}$.

3.2. Water Source and Characterization

The Source of raw water for the Kirikkale RO plant is taken from Kaplukaya Dam, located on the Kızılırmak river in Kirikkale city (Koyuncu et al., 2018). The dam provides 45 hm³ of drinking water per year, and the RO plant is located near the dam side and uses water from the dam as feed water to produce drinking water for the city. The dam collects the surface water from the Kızılırmak river, and the surface water of this area has different parameters and pollutants in its body. Following are listed the main parameters of dam water.

Table 3.1 Main parameters of raw water for Kirikkale UF-RO plant (Koyuncu et al., 2018)

Parameters	Units	Values	Standard values by WHO (µg/l)
Hardness	mg CaCO ₃	40.8	
Calcium	mg/l	115.4	<250mg/l
Magnesium	mg/l	64.1	
Total alkalinity	mg CaCO ₃	108.5	
Nitrite	mg/l	0.07	3000(as per NO ₃ ⁻)
Nitrate	mg/l	0.5	50000(as per NO ₃ ⁻)
Chloride	mg/l	257.5	250 mg/l
Conductivity	µS/cm	1800	2500 µS/cm at 20°C
Total dissolved solids	mg/l	1100	-
Total suspended solids	mg/l	1.5	-
Turbidity	NTU	3.6	1
Sulfate	mg/l	364	<250mg/l
Sodium	mg/l	210	<200mg/l
Iron	mg/l	0.05	200 µg/l
Manganese	mg/l	-	400 µg/l
Potassium	mg/l	5.7	-
Bicarbonate	mg/l	108.5	-
Color	mg/l	3.1	-
Total organic compounds	mg/l	4.85	-
Boron	mg/l	<1	500
Arsenic	µg/l	13	10
Aluminum	µg/l	40.2	200

Copper	µg/l	0.3	2000
Mercury	µg/l	<1	1
Chromium	µg/l	0.5	50
Cadmium	µg/l	0.8	3
Lead	µg/l	<1	10
Nickel	µg/l	3.9	20
Selenium	µg/l	<1	10

As can indicate in Table 3.1, the main problem with the source water for drinking purposes is the high concentration of sulfate, hardness, chloride, and total organic compounds, which is a hazard to human health (Koyuncu et al., 2018). In addition, the arsenic value in raw water is slightly high; therefore, it is needed to clean water for drinking. Recently, WHO published water regulation for drinking purposes, which shows the values of different water parameters and sulfate, chloride, total organic compounds, total dissolved solids, and arsenic, as listed in Table 3.1. Therefore, removing the high concentration of these compounds from water is essential and should make water drinkable.

3.3. Existing Design of Kirikkale UF-RO Plant

Kirikkale city has two treatment plants; the first one is a conventional water treatment plant, and the second one is a membrane drinking water treatment plant. The conventional water treatment plant was designed for seven districts of Kirikkale city in 2001, and the capacity of this water treatment plant was 200000 m³/day. In 2008, membrane treatment units were added to the conventional water treatment unit to remove some contaminants in raw water, such as sulfate, chloride, arsenic, odor, hardness, and pesticides which are high in concentration in the raw water. The capacity of the new RO water treatment plant is about 90000 m³/day (Koyuncu et al., 2018). The new water treatment plant consists of the following parts;

A- Water intake structure: A Water Intake structure has been constructed to convey the raw water that has been ventilated, pre-chlorinated, and coarsely filtered in the existing treatment facility to the new facility from this point forward.

B- Raw Water Transmission Line: From the water intake structure, raw water is transmitted to the UF Unit's feeding tank via a 900 mm steel pipeline.

C- UF Feed Tank: To supply water to the UF unit 200 m³ RCC water tank was built.

D- UF Purification System: 6 UF modules have been installed to retain suspended solids and TOC (bacteria and viruses) that may be present in the water and reduce SDI to 2.5 to make water for the RO system suitable.

The UF Unit consists of the following main components:

- UF Feed Pumps,
- UF Modules
- UF Backwash system,
- Control Panels system
- Measurement and control devices

E- Reverse Osmosis Feed Tank: UF filtered water comes to a 3000m³ RCC tank to supply water for the RO system.

F- Reverse Osmosis Treatment System: The Reverse Osmosis unit, in which the pre-treated water is purified from all pollutants, mainly Sulphate, Chloride, Hardness, and Heavy Metals, consists of 5 online trains. The main components of the system are:

- Cartridge Filters
- High-Pressure Pumps
- Reverse Osmosis Modules
- Reverse Osmosis Washing and Rinsing System
- Reverse Osmosis Chemical dosing devices
- Control Rooms, Control Panels, Measurement, and Control devices

G- Final Treatment Unit (Remineralization): Lime and carbon dioxide dosage are made in the remineralization unit in order to ensure the suitability of the treated water to the palate, to keep the pH value between 7.5-8.5, and the hardness value at the level of 5-10 mg CaCO₃. The treated water is transferred by a pipe to a 22000 m³ storage tank and then conveyed to the water supply mains. The ultrafiltration system consists of 6 units in

total. There are 40 modules in each unit, a total of 240 modules. Each module has 4 UF membranes and a total of 960 UF membranes. In ultrafiltration units, the SDI value is reduced below three, the possibility of reverse osmosis membranes fouling is reduced, and operating efficiency is increased (Koyuncu et al., 2018). Then there are five pieces of filter cartridges containing 75 cartridge filters in total. The cartridge is given to the filter, and a third pre-treatment is performed before the reverse osmosis (Koyuncu et al., 2018). The reverse osmosis system has a total capacity of 90720 m³/day. The RO system consists of 5 units, and there are a total of 800 pressure vessels and 4800 reverse osmosis membranes in these pressure vessels (Paputçu et al., 2009 and Koyuncu et al., 2018). The permeate water and bypass water parameters which comes from conventional plant are listed in Table 3.2.

Table 3.2. Permeate and bypass water parameters of Kirikkale UF-RO plant (Koyuncu et al., 2018)

Parameters	Units	Raw water	RO permeate water	RO +bypass water values
Hardness	mg CaCO ₃	40.8	1.5	6.8
Calcium	mg/l	115.4	1.3	16.6
Magnesium	mg/l	64.1	0.3	8.8
Total alkalinity	mg CaCO ₃	108.5	6.5	20.1
Nitrite	mg/l	0.07	0	0
Nitrate	mg/l	0.5	0.2	0.1
Chloride	mg/l	257.5	42.3	71.1
Conductivity	µS/cm	1800	150	370.6
Total dissolved solids	mg/l	1100	76	212.9
Total suspended solids	mg/l	1.5	0.1	0.3
Turbidity	NTU	3.6	0.02	0.2
Sulfate	mg/l	364	1.8	50.2
Sodium	mg/l	210	120	132
Iron	mg/l	0.05	0.01	0
Manganese	mg/l	-	-	-
Potassium	mg/l	5.7	0.09	0.8
Bicarbonate	mg/l	108.5	40	49.2

Color	mg/l	3.1	-	-
Total organic compounds	mg/l	4.85	0.01	-
Boron	mg/l	<1	<0.02	<0.02
Arsenic	µg/l	13	<1	<1
Aluminium	µg/l	40.2	<0.5	<1
Copper	µg/l	0.3	<0.1	<0.1
Mercury	µg/l	<1	<0.1	<0.1
Chromium	µg/l	0.5	<0.1	<0.1
Cadmium	µg/l	0.8	<0.1	<0.1
Lead	µg/l	<1	<1	<1
Nickel	µg/l	3.9	<3	<3
Selenium	µg/l	<1	<4	<4

As seen in Table 3.2 concentration of treated water by bypassing filtered water got increased; therefore, there was no need to adjust the chemicals of treated water. The pore size of the reverse osmosis unit membranes is smaller than 0.0001 microns. Only water molecules can pass through this pore. Other pollutants such as toxic pollutant arsenic, organic substances, and dissolved substances cannot pass through the reverse osmosis membranes. Since the water passes through reverse osmosis, the plant becomes pure and aggressive water and has corrosive behavior. Therefore, carbon dioxide and calcium oxide minerals are added to the treated water from the RO system to prevent water's corrosive behavior. The final treated water is given to the city by water distribution networks. Figure 3.2 shows the RO pressure vessels in the train of the present plant (Koyuncu et al., 2018).



Figure 3.2. RO system of the present plant in Kirikkale city (Koyuncu et al., 2018)

3.4. Alternative Design of Plant

In the first part of this section, we will focus on the numerical design and calculation of the UF-RO system for the mentioned raw water data for Kirikkale city. It is expected to design different scenarios for the plant, calculate the energy consumption for the plant operation, the second part of this section simulated the system by WAVE software and applied different scenarios for checking the permeate water parameters and energy consumption.

3.4.1. Numerical design and calculation of UF-RO system

3.4.1.1. Design of ultra-filtration (UF) as a pre-treatment

A UF filtration system design consists of different parts and parameters such as selection of UF filters, calculation of Flux, transmembrane pressure, temperature, permeate pressure, feed pressure, permeate flow, and recovery rate for the system.

We will follow following flowchart for the numerical calculation of UF system as a pretreatment.

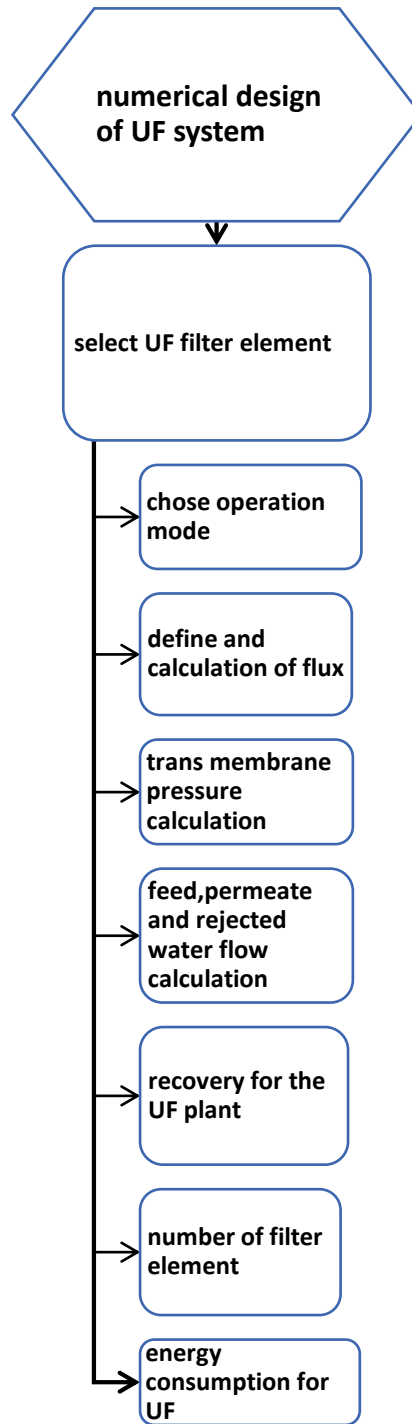


Figure 3.3. shows the flowchart for numerical design and calculation for UF system as a pretreatment for RO system

In the discussion part of the study it will follow the mentioned flowchart for the numerical calculation of UF system as a pretreatment for the RO system.

3.4.1.2. Numerical design and calculation of RO system

The design and calculation of an RO system for water treatment need some basic parameters of water, such as the plant's design capacity, the feed water's type, TDS, and the water temperature (Salinas-Rodríguez et al., 2021). Furthermore, the recovery of feed water is essential. In brackish water RO (BWRO), the scaling potential determines the maximum recovery (Salinas-Rodríguez et al., 2021). The factor which has the most significant influence on the membrane system design is the fouling tendency of the feed water (Koyuncu et al., 2018). The Silt Density Index (SDI) value of the pretreated feed water correlates reasonably well with the amount of fouling material present. The concentration of the fouling materials at the membrane surface increases with increasing permeate flux (the permeate flowrate per unit membrane area) and increasing element recovery (the ratio of permeate flow rate to feed flow rate for a single element). A system with high permeate flux rates is likely to experience higher fouling rates, requiring more frequent chemical cleaning. Only the amount of TDS is needed to design an RO system manually. Otherwise, commercial software for RO design considers different anions and cations, which we will discuss in the simulation part.

Large-scale water treatment plants generally used spiral wound elements in a pressure vessel between 6 to 8 elements in a single pressure vessel with a length of 1 meter and 8- inch wide vessel. Furthermore, for the design of RO treatment plants, different RO manufacturers published design manuals for the design of RO systems considering of years of experience of the company. In the present study, we will use DuPont manufacturer design guidelines to design and simulate the RO membrane process. Following are some steps for designing the membrane process used in this study.

Step 1- determine the feed source, feed water quality, feed and permeate flow, and required product quality (DuPont, 2020). In the present study, we select the Kirikkale UF-RO treatment plant site, and the water treatment plant uses surface water to treat water for

drinking purposes. The quality of the water used in the Kirikkale drinking water treatment plant is listed in Tables 3.1 and 4.1.

For the calculation of feed, permeate and concentrate flow and concentration of the system it will use the following equations;

$$R = \frac{Q_p}{Q_f} \text{ or } Q_f = \frac{Q_p}{R} \quad (\text{Eq. 1})$$

Where R is the recovery of plant, Q_p is the permeate flow which is plant capacity and Q_f is the feed flow of the plant.

$$Q_c = Q_f - Q_p$$

Where Q_c is the concentrate flow, Q_f is the feed flow and Q_p is the permeate flow of the plant.

For the concentrate concentration, we used the following equation;

$$C_c = \frac{C_f[1-R(1-SR)]}{1-R} \quad (\text{Eq. 2})$$

Where C_c is the concentrate concentration of the system, C_f is the feed concentration, R is the plant recovery percentage, SR is the salt or dissolved solid rejection of the selected membrane element, which is 99.3% from ESS, and we assume it is 100% for the present calculation.

$$C_{FC} = \frac{(C_f + C_c)}{2} \quad (\text{Eq. 3})$$

Where C_{fc} is the average feed and concentrate concentration for the system.

For the permeate concentration, we use the following equation

$$C_p = C_{FC}(1 - SR) \quad (\text{Eq. 4})$$

Step 2: select the flow configuration and number of passes

According to the DuPont RO design manual, the standard flow shape for a desalination plant is plug flow as the feed is passed through a membrane once. For the water with low TDS or small-scale drinking water treatment plant, the concentrate water recirculates to feed water in the pass for the second time through the membranes.

Furthermore, the RO system is mainly designed for continuous operation, which is constant for every membrane over time (DuPont, 2020).

Step 3: select membrane type:

Membrane elements are selected by considering different parameters such as; the application of the membrane or using purposes of the membrane, system capacity, feed water salinity or the TDS of the feed water, feed water fouling tendency, required rejection, and energy requirement (DuPont, 2020). The standard element size for systems producing permeate greater than 2.3 m³/h (10 gpm) is 8 inches in diameter and 40 inches long (DuPont, 2020). For large plants, 6 to 8 elements are placed in a single pressure vessel with 8-inch-wide and 40 inch (1m) long diameters (Salinas-Rodríguez et al., 2021).

It can use different types of membrane elements from different manufacturers. Different manufacturers published a product data sheet (PDS) or element specification sheet (ESS), which contains the specifications of membrane elements such as; the name of membrane, production company, area of the membrane element, dimensions of the elements, salt rejection percentage, pH range for the elements and standard test condition for the element. Each manufacturer provides a sheet for membrane elements, an element specification sheet (ESS), or a product data sheet (PDS). The information in the sheet will be used in the calculation and design process. Figure 4.2 shows a sample of a membrane sheet related to the DOW membrane manufacturer company for the BW30HRLE- 440i element product.



Product Data Sheet

FilmTec™ BW30HRLE-440i Element

Description

Ideal for: reverse osmosis plant managers and operators dealing with controlled-pre-treatment waters and seeking advanced membrane treatment with good water purity and low energy consumption.



FilmTec™ BW30HRLE-440i:

- Offers good salt-rejection with 33% lower pressures
- Delivers excellent silica, boron, nitrate, IPA and ammonium rejection
- Provides increased active area with the most effective cleaning performance, robustness and durability due to its widest cleaning pH range (1-13) and chemical tolerance and the support of DuPont technical representatives
- Includes iLEC™ interlocking end caps, reducing system operating costs and the risk of o-ring leaks that can cause poor water quality

Product Type

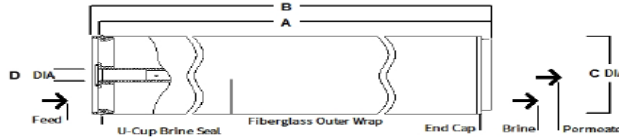
Spiral-wound element with polyamide thin-film composite membrane

Typical Properties

FilmTec™ Element	Active Area (ft ²)	Active Area (m ²)	Feed Spacer Thickness (mil)	Permeate Flow Rate (GPD)	Permeate Flow Rate (m ³ /d)	Typical Stabilized Salt Rejection (%)	Minimum Salt Rejection (%)
BW30HRLE-440i	440	41	28	12,650	48	99.3	99.1

- Permeate flow and salt (NaCl) rejection based on the following standard test conditions: 2,000 ppm NaCl, 150 psi (10.3 bar), 77°F (25°C), pH 8, 15% recovery.
- Flow rates for individual elements may vary but will be no more than ± 15%.
- Stabilized salt rejection is generally achieved within 24-48 hours of continuous use; depending upon feedwater characteristics and operating conditions.
- Sales specifications may vary as design revisions take place.
- Active area guaranteed ± 3%. Active area as stated by DuPont Water Solutions is not comparable to nominal membrane area often stated by some manufacturers.

Element Dimensions



FilmTec™ Element	Dimensions – inches (mm)						1 inch = 25.4 mm	
	A (in.)	A (mm)	B (in.)	B (mm)	C (in.)	C (mm)	D (in.)	D (mm)
BW30HRLE-440i	40.0	1,016	40.5	1,029	7.9	201	1.125 ID	29 ID

- Refer to [FilmTec™ Design Guidelines for multiple-element systems of 8-inch elements](#) (Form No. 45-D01695-en).
- Element to fit nominal 8-inch (203-mm) I.D. pressure vessel.
- Individual elements with iLEC™ endcaps measure 40.5 inches (1,029 mm) in length (B). The net length (A) of the elements when connected is 40.0 inches (1,016 mm).

Operating and Cleaning Limits

Maximum Operating Temperature ^a	113°F (45°C)
Maximum Operating Pressure	600 psig (41 bar)
Maximum Element Pressure Drop	15 psig (1.0 bar)
pH Range	
Continuous Operation ^a	2 – 11
Short-Term Cleaning (30 min.) ^b	1 – 13
Maximum Feed Silt Density Index (SDI)	SDI 5
Free Chlorine Tolerance ^c	< 0.1 ppm

- Maximum temperature for continuous operation above pH 10 is 95°F (35°C).
- Refer to [FilmTec™ Cleaning Guidelines](#) (Form No. 45-D01696-en).
- Under certain conditions, the presence of free chlorine and other oxidizing agents will cause premature

Figure 3.4. Product data sheet of Film tec BW30HRLE 440i element related to DuPont manufacturing company(<https://www.dupont.com/products/filmtecbw30hr440i.html>)

Step 4: calculation and selection of average membrane flux:

For the design of the membrane system, it needs to select average design flux based on pilot data and customer experience or suggestions from design limits by RO manufacturers. The flux of a RO plant is related to the fouling potential of the feed water, and if the flux is higher, it means the fouling rate is higher in the membrane, which needs frequent cleaning of the membrane with chemicals and increases the cost of the membrane by cleaning (Salinas-Rodríguez et al., 2021). The recommended flux of different elements for the RO system by the DuPont manufacturer company is listed in Table 3.3.

Table 3.3. Shows standard conditions for RO elements of DuPont manufacturer (DuPont, 2020).

Feed Source	RO Permeate	Well Water	Surface Water				Wastewater (Filtered Municipal Effluent or Industrial Effluent)				Seawater				
			With DuPont UF + B-free	Surface Water with Ultrafiltration	Generic membrane filtration or advanced conventional pretreatment	Generic conventional pretreatment	With DuPont UF + B-free	Ultrafiltration	Generic membrane filtration (MBR/MF/UF)	Conventional pretreatment	With DuPont UF + B-free	Well or Open Intake with Ultrafiltration	Open Intake with generic membrane filtration or advanced conventional pretreatment	Open Intake with generic conventional pretreatment	
Feed Silt Density Index (%/min)	SDI < 1	SDI < 3	SDI < 2.5	SDI < 2.5	SDI < 3	SDI < 5	SDI < 2.5	SDI < 2.5	SDI < 3	SDI < 5	SDI < 2.5	SDI < 2.5	SDI < 3	SDI < 5	
Maximum Element Recovery (%)	30	19	20	19	17	15	15	14	13	12	16	15	14	13	
Active Membrane Area	Maximum Permeate Flow, gpd														
365-ft ² elements	10,200	8,500	8,900	8,500	7,200	6,600	6,600	6,300	5,900	5,200	— Not Recommended —				
370-ft ² elements	10,200	8,500	8,900	8,500	7,200	6,600	6,600	6,300	5,900	5,200	8,100	7,800	7,400	7,000	
380-ft ² elements	10,700	8,900	9,300	8,900	7,500	6,900	6,800	6,500	6,000	5,300	8,200	7,900	7,600	7,200	
390-ft ² elements	10,920	9,200		— Not Recommended —				— Not Recommended —				— Not Recommended —			
400-ft ² elements	11,200	9,300	9,700	9,300	7,900	7,300	7,100	6,800	6,400	5,700	8,800	8,400	8,000	7,600	
440-ft ² elements	12,300	10,300	10,700	10,300	8,700	8,000	8,000	7,600	7,100	6,300	9,600	9,200	8,800	8,360	
Design Flux Range, gfd (lmh)	21 – 25 (36 – 43)	16 – 20 (27 – 34)	17 – 20 (29 – 36)	16 – 20 (27 – 34)	11 – 17 (22 – 29)	12 – 16 (20 – 27)	12 – 16 (20 – 27)	11 – 15 (19 – 26)	10 – 14 (17 – 24)	8 – 12 (14 – 20)	10 – 12 (17 – 21)	9 – 11 (15 – 19)	8 – 10 (14 – 17)	7 – 10 (12 – 17)	
Max. Element Flux, gfd (lmh)	28 (48)	22.7 (39)	24 (41)	22.7 (39)	20 (34)	18 (31)	18 (31)	17 (29)	16 (27)	14 (24)	22 (38)	21 (36)	20 (34)	19 (32)	

As shown in Table 3.3, the design flux range for surface water filtered by UF filters is between 27-34 LMH by DuPont manufacturer. For the determination of flow per element, we have;

$$Q_e = J_{avg} * A_e \quad \text{(Eq. 5)}$$

Where; Q_e is the flow per element, J_{avg} is the average design flux of the membrane, and A_e is the surface area of the selected element.

Step 5: calculate the number of needed elements

For the calculation of elements number that is needed in the membrane system, it used the following formula;

$$N_e = \frac{Q_p}{Q_e} \text{ or } Q_p J_{avg} * A_e \quad (\text{Eq. 6})$$

Where NE is the total number of elements, Qp is the design permeate flow rate, J is the average design flux, and Ae is the surface area of the selected elements.

Step 6: calculate the number of pressure vessels for the system.

For the calculation of pressure vessels that are needed in the system it is used the following equation;

$$N_V = \frac{N_e}{N_{epv}} \quad (\text{Eq. 7})$$

Where NV is the number of pressure vessels in the system, Ne is the number of elements for the system, and NEPV is the number of elements per single pressure vessel. For a large RO system, 6 elements per pressure vessel are standard, but up to 8 can be used (DuPont, 2020).

Step 7: Select the number of stages:

The number of stages defines how many pressure vessels in series which the feed will pass through until it exits the system and is discharged as concentrate. According to DuPont manufacturer, the number of stages is a function of the planned system recovery, the number of elements per vessel, and the feed water quality. The higher the system recovery and the lower the feed water quality, the longer the system will be with more elements in series. Table 4.4 indicates the number of stages according to system recovery percentage;

Table 3.4. Number of stages according to recovery for brackish water (DuPont, 2020)

System recovery	Number of elements in series	Number of stages (6 elements in the vessel)
40-60	6	1
70-80	12	2
85-90	18	3

For a higher recovery system, the single stage may also be used by recycling the concentrate into the feed (DuPont, 2020). This section will design a single-stage RO system with concentrate recycling and two stages RO with 80 % recovery. Following, we will discuss the RO treatment process step by step for the Kirikkale UF-RO drinking water treatment plant.

Step 8- Feed pressure for RO system:

To find the feed pressure for the plant, follow the following steps

1- find the average flux by the following equation

$$J = Q_{perm\ plant} / \#numbers * A_{mem\ plant} \quad (Eq. 8)$$

2- determine the flow per each element by the following equation

$$Q_e = Q_{perm\ plant} / N_{elements} \quad (Eq. 9)$$

3- find the average net driving pressure for a pressure vessel by the following equation

$$NDP = J / K_w \quad (Eq. 10)$$

4- determine the concentrate concentration of the plant.

5- osmotic pressure for 1000 mg/l of TDS is 0.8 bar

6- In the end, we can calculate the feed pressure by the following equation

$$P_{feed} = NDP + \frac{\Delta P}{2} + \Delta_{avg} + P_{perm} \quad (Eq. 11)$$

Step 9- feed, permeate, concentrate flow and recovery for each element:

We follow the following procedures for calculating feed and recovery flow in each element of the pressure vessel.

1- start from the first element in the feed side

2- calculate the feed pressure for the first element (we already have it from step 4)

3- find the feed flow for the first element by $Q_{F1} = Q_{perm\ plant} / N_{PV}$ (already calculated in step 2).

4- Cf 1 take from raw water data

5- Assume the R_e to calculate the osmotic pressure, then later on, we will check if it is correct or not; if not, revise the calculation.

6- Calculate the C_{c1} by $C_{c1} = C_{f1}/(1 - R_{e1 \text{ assumed}})$ equation

7- 1000mg/l of TDS is equal to 0.8 bar osmotic pressure

8- Calculate the NDP by $NDP_1 = P_{feed1} - \frac{\Delta P_{pe1}}{2} - \Delta\pi_{avg1} - P_{perm1}$ equation

9- Calculate the Q_{f1} for the first element by $Q_{p1} = NDP_1 * K_w * A_e$ Which is the main equation in this step.

10-Check the R_1 to R_1 assumed if these are equal, then continue for the next element. If not, then revise our calculation.

11-Calculate the concentrate flow by $Q_{c1} = Q_{f1} - Q_{p1}$

12-Calculate average feed and concentrate flow by $C_{Fc1} = (C_{f1} + C_{c1})/2$ and $Q_{Fc1} = (Q_{f1} + Q_{c1})/2$

13-For the second element, the feed pressure is $P_{f2} = P_{f1} - \Delta P$, $Q_{f2} = Q_{c1}$, $C_{f2} = C_{c1}$ and assume R_{e2} to calculate osmotic pressure

14- For the calculation of NDP for each element, using the following equation

$$NDP_i = P_{feedi} - \frac{\Delta P_{pei}}{2} - \Delta\pi_{avg_i} - P_{permi} \quad (Eq. 12)$$

Where P_{feedi} is the feed pressure for the “i” element, ΔP_{pei} is the head loss for the “i” element, $\Delta\pi_{avg_i}$ is the average osmotic pressure for the “i” element and P_{permi} is the permeate pressure for “i” element. Head loss in pressure vessels is in the range of 1.2 to 2 bar.

Step 10: Calculation of the concentration polarization factor (CPF) for each element:

CPF is The increase of the solute concentration over the bulk feed solution, which occurs in a thin boundary layer at the feed side of the membrane surface, resulting from the removal of the solvent. (Brover et al., 2022) CPF consists of forming a high concentration layer of dissolved and suspended particles near the membrane surface. According to DuPont manufacturer, for the calculation of CPF, we use the following equation.

$$\mathbf{CPF = EXP(0.7R_i)} \quad \mathbf{(Eq. 13)}$$

Step 11: For calculating energy consumption, it is essential to know about the general definition and conception of work as work is equal to energy, and energy is the displacement of force to a specific distance.

$$\mathbf{work = Energy = force * displacement = N * m = joule} \quad \mathbf{(Eq. 14)}$$

$$1 \text{ joule} = 1N * m = 1 \frac{Kg * m}{s^2} * m = 1 \frac{kgm^2}{s^2}$$

If we want to bring water to a higher level, then we need pressure as 1 bar= 10m, and the work be per m³ then we have;

$$\mathbf{F = m * g = (\rho * V) * g \text{ or force per } m^3 = (\rho * g)} \quad \mathbf{(Eq. 15)}$$

$$\text{work} = \text{Energy} = \text{force} * \text{distance} = (\rho * g) * h$$

$$= \left(1000 \frac{kg}{m^3} * 9.8 \frac{m}{s^2} \right) * 10 \text{ m} = 98000 \text{ joule}$$

$$\mathbf{Watt = joule/sec \text{ or } joule = Watt * sec \text{ or } Ws} \quad \mathbf{(Eq. 16)}$$

Then we have;

$$98000Ws = 98000Ws * \frac{h}{3600 s} * \frac{Kw}{1000 W} = 0.027 \text{ Kwh per } m^3$$

For total energy consumption of the plant, we have;

$$\mathbf{E = (0.0275 * P_{feed}) / (N_{pump} * R)} \quad \mathbf{(Eq. 17)}$$

Where; E is the total required energy by the RO system, Pf is the feed pressure of the system, Np is the pump's efficiency with the driver, and R is the plant recovery percentage.

3.4.2. Computer-Based Design and Simulation of Membrane Process

In the 20th century, computers became part of everyday life in most engineering fields. Major suppliers of reverse osmosis systems have developed design software programs that can simulate and optimize complex RO designs. A few of these programs can also conduct economic Calculations (Hoffman, 2008). Designing an RO system by hand calculation is complicated, complex, and tedious; therefore, different RO production companies launched quite easy, open-source, and free software to design and simulate different membrane processes. These softwares are different in presentation and application while the same in results. The limitation of these software is that it works to design and simulate their own manufacturing products. The selection of design software depends on the use of membrane manufacturers (Kucera, 2015). The DuPont manufacturer-produced membranes have been used in the present study, and we will simulate our design using water application value engine software (WAVE). WAVE program is released by DuPont water, and the process solution has the capability to model and design reverse osmosis (RO), ultrafiltration (UF), and ion exchange (IX) processes separately or in combination (Kucera, 2015). the main focus of WAVE software is to evaluate the performance of UF, RO, and IX resins (Hirsimaki et al., 2020). WAVE is integrated expert modeling software for water-treatment plant design, including wastewater-treatment plant design with a new membrane process. (DuPont, 2020) One of the main advantages of this software through others is that it can design and simulate more than one membrane technology at the same time.

On the other hand, WAVE can calculate the total electricity consumption used by the treatment plant. This software can also calculate the overall cost of the process (electric and chemicals) used during the process. Different studies have been published which have employed the WAVE software for the analysis, design, and simulation of water and wastewater treatment plants for different purposes, such as;

``Design and cost analysis of RO system (Ammar Alsheghri et al. 2015), Design of RO desalination plant (Abdel-Fatah MA et al 2016), An investigation on boiler feed water with RO and IX system (Asadi et al., 2021), modeling, simulation and optimization of a reverse osmosis desalination plant (Randy Ncube et al., 2021), Comparative

environmental life cycle assessment of alternative osmotic and mixing dilution desalination system configurations (P. Pazouki et al., 2021), Optimization of a Nano filtration and membrane capacitive deionization (NFMCDI), hybrid system: Experimental and modeling studies (K. Jeong, et al. 2020), Process improvement of sea water reverse osmosis (SWRO) and subsequent decarbonization (T. Altmann and R. Das et al., 2021), Influence of hydrodynamic operating conditions on organic fouling of spiral-wound forward osmosis membranes (C. Lee et al., 2020), Performance evaluation and boron rejection in a SWRO system under variable operating conditions (A. Ruiz-García and I. Nuez 2021), Process simulation of high pH reverse osmosis systems to facilitate reuse of coal seam gas associated water (C. Hirsimaki, et al., 2020), Renewable energy power reverse osmosis system for seawater desalination plant (M.A.M. Mahmoud et al., 2020), An investigation on boiler feed water treatment using reverse osmosis and ion exchange by WAVE software (Asadi et al. 2021), Water treatment technology performance for chemical enhanced oil recovery: modeling, simulation and optimization (Mahdi Chemil et al., 2021), Design of Reverse Osmosis Desalination Plant at Remote Coastal Area (Sutopo Purwono Fitri et al., 2020), Numerical Modeling and Dynamic Analysis of a Wave-Powered Reverse-Osmosis System (J. Mar. Sci. Eng. 2018), Conceptual Design and Numerical Analysis of a Novel Floating Desalination Plant Powered by Marine Renewable Energy for Egypt (J. Mar. Sci. Eng. 2020), Modelling and Optimization of Multi-Stage Flash Distillation and Reverse Osmosis for Desalination of Saline Process Wastewater Sources (Membranes 2020), A Hybrid NF-FO-RO Process for the Supply of Irrigation Water from Treated Wastewater: Simulation Study (Membranes 2021), Normalization of a reverse osmosis desalination plant (randy ncube 2021) and many more``.

By the review of all these articles, it cleared that WAVE software is one of reliable and dependable design and simulation software. Most of these articles were simulated and designed by WAVE, and their results were correct and acceptable. WAVE primarily focuses on the performance of ultrafiltration, reverse osmosis, and ion exchange resins (Hirsimaki et al., 2020). Furthermore, WAVE design software has different parts, including;

- a. section for project information
- b. feed water type and specification
- c. UF system configuration
- d. RO system configuration
- e. Chemical adjustment for washing
- f. Generation of the report for the UF and RO system
- g. Batch operation and cost calculation

In the project information section, we can allow inputting the project general information and details related to the project. In the feed water type section, we can specify feed water types, including surface water, groundwater, seawater, well water, municipal water, wastewater, and well water. In feed water specification is required to add different Anions and cations, TDS, TSS, TOC, pH, CO₂, etc. WAVE can design a UF system as a pretreatment for the RO system in UF system configuration. The design and simulation process contains designing and selecting the appropriate membrane filter element for the UF system, calculating the backwash (BW) time and pressure which need in BW, calculating the chemical enhanced backwash (CEB) for the UF system, and the time for washing and can calculate clean in place (CIP) for UF system. WAVE can analyze and design an RO system for feed flow or permeate flow, and we can analyze and design the following scenarios;

- 1- WAVE can design a single-pass or two-pass RO system.
- 2- WAVE can design up to five stages of an RO system for high recovery.
- 3- We can specify up to 8 elements per pressure vessel.
- 4- It can simulate different elements in a single pressure vessel, which is an internally staged design (ISD)
- 5- WAVE can evaluate the RO system for different design temperatures.
- 6- WAVE can design concentrate recycle to feed flow to increase the recovery for a single stage.
- 7- Moreover, WAVE can analyze and design the bypass RO system for the re-mineralization purpose.

Furthermore, WAVE can calculate feed pressure for the RO system and permeate back pressure for each stage if needed. In addition, WAVE can calculate and simulate the ERD effects on the RO system. For a new UF-RO system design by WAVE software, it is necessary to add complete basic information to be able to design a new plant. For the design and simulation of the UF-RO water treatment system by WAVE software, we can apply different scenarios; as in the present study, we are going to design and simulate the following three types of processes for the Kirikkale RO water treatment plant and compare these processes according to economic and energy consumption need for each process. The UF-RO system for the present study was designed for permeate flow of the water required for Kirikkale city of turkey, which is about 90000 m³/day from surface water, and the characteristic of surface water introduced to WAVE software is listed in Table 3.5.

Table 3.5. Raw water characteristics for WAVE software

Parameters	Names	Values	units
pH		8.13	
NH₄⁺	Ammonia		mg/l
K⁺	Potassium	5.70	mg/l
Na⁺	Sodium	210	mg/l
Mg⁺²	Magnesium	64.10	mg/l
Ca⁺²	Calcium	106	mg/l
Sr⁺²	Strontium	115.4	mg/l
Ba⁺²	Barium		mg/l
CO₃⁻²	Carbonate	1.97	mg/l
HCO₃⁻	Bicarbonate	108.50	mg/l
NO₃⁻	Nitrate	17	mg/l
F⁻	Fluorine	0	mg/l
Cl⁻	Chlorine	258	mg/l
Br⁻¹	Bromine		mg/l
SO₄⁻²	sulfate	364	mg/l
PO₄⁻³	Phosphate	0	mg/l
SiO₂	Silicon dioxide	0	mg/l
B	boron	1	mg/l

CO₂	Carbon dioxide	0.87	mg/l
TDS^a	Total dissolved solids	1200	mg/l
TOC	Total organic compounds	4.85	mg/l
TSS	Total suspended solids	1.5	mg/l
SDI₁₅	Silt density index	5	
turbidity		3.6	NTU
Temperature		25	°C

These raw water Parameters are used to identify the appropriate design for the site. As it can see, different anions and cations are in the feed water. For evaluation by WAVE, it is needed to adjust all anions and cations, and for the balance of anions and cations in the feed water, it is adding sodium and chlorine to feed water. In addition, WAVE has the icon to adjust all cations and anions and pH for the raw water to be able to continue the design process. WAVE can calculate the HCO₃, CO₃, and CO₂ equilibrium composition depending on the pH and temperature equilibrium (Kucera, 2015). This section will first discuss the UF system design by WAVE software and then design and simulate the RO system.

4. DISCUSSION AND PROCESS DESCRIPTION

4.1. Numerical Design of UF-RO Water Treatment Plant

4.1.1. Numerical design of ultrafiltration (UF) as a pretreatment

For the calculation of different parameters in UF system we will follow the flowchart which mentioned in the method part of this study. For the design of UF system as a pretreatment it will follow the flowchart

In Two ways can perform operation design of UF membranes;

- 1- dead-end flow
- 2- cross flow

In dead-end flow, there is only a feed and filtrate flow as it seems like a cartridge filter (Wenten and Ganessa, 1996). dead end flow is used feed stream has fewer suspended solids ($1 > \text{NTU}$). Crossflow mode is different from dead-end flow as there is an additional flow at the end of the operation by the name of concentrate, which is used in large scale water treatment plants. The present part is expected to briefly discuss different design factors and parameters for the UF process design. It then will calculate the appropriate parameters for our system of UF to remove organics, silt, and suspended solids from water to clean water and prepare for the RO system. Different manufacturers are making different forms of UF membranes from different materials. We used the DOW manufacturer UF membranes in the present study for our calculation. Furthermore, we will use the guideline for the UF system of DOW company for the application and cleaning process of the UF system.

We will follow the following steps for designing and calculating the UF system as a pretreatment for the RO process in drinking water.

Step 1: Feed water characteristics for the UF system

Feed water analysis is one of the vital steps in the design of a UF system. as it must clear the feed water type, different feed water parameters such as suspended solids, turbidity, COD, BOD, or total organic compounds (TOC), pH, temperature, total dissolved solids, nutrients contain and so on must be checked. For the present study, we selected the raw surface water for the UF-RO water treatment plant running in Kirikkale

city of Turkiye. The feed water for this plant is from surface water; different parameters were measured and listed in table 6. The essential parameter for UF system design is the turbidity of the water, which significantly influences the UF system's performance. Furthermore, organic contents influence to design of the UF system.

Step 2: Chose the operation mode

As we discussed, we use cross-flow mode for large-scale UF pre-treatment systems to operate the system. In cross-flow, the feed water cross from the membrane surface, filtrate passes through it and concentrate accumulates at the opposite end of the membrane. This flow creates a cutting effect for reducing fouling in membranes, and this flow does not drop permeate flux fast (Wenten and Ganesh, 1996). Figure 4.1 shows the difference between conventional and cross-flow feed for the UF system.

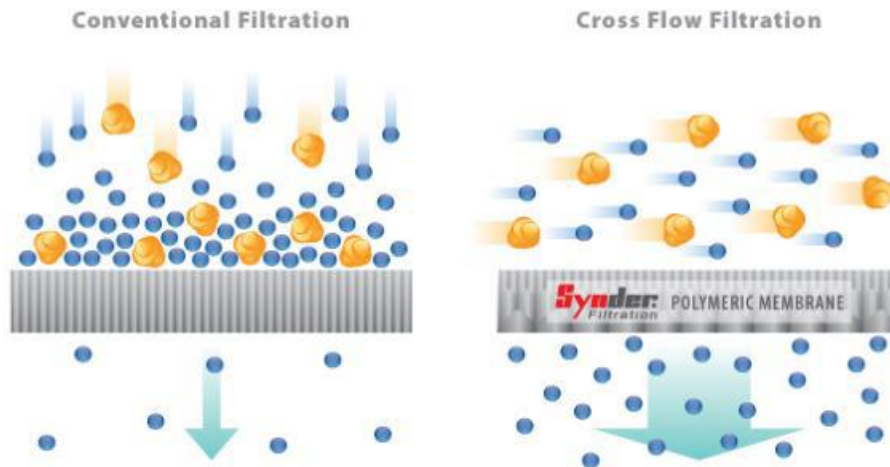


Figure 4.1. Conventional and cross flow in UF system (Source synderfiltration.com/learning-center/articles/module-configurations-process/crossflow-membrane-operations)

Step 3: Calculation of flux for membrane

Flux is an important parameter for designing a UF system where the flux is the water passing through one square meter of the membrane surface. For the calculation of flux for the UF system, we use the following equation;

$$J = \frac{Q}{A_{mem}} = \frac{TMP}{V * R_{total}} \quad (Eq. 18)$$

Where; J is UF membrane flux, Q is the volume of flux, A_{mem} is the area of the UF membrane, TMP is transmembrane pressure, V is dynamic viscosity and R_{total} Is the total resistance of the membrane. TMP is the difference between pressure across the membrane or feed and permeate pressure in the membrane element. Temperature affects the flux at certain TMP as one degree of temperature increases the flux by more than 3 % (Wenten and Ganesha, 1996). For the calculation of trans membrane pressure, we have;

$$TMP = P_{feed} - \frac{\Delta P_{hydro}}{2} - P_{perm} \quad \text{or} \quad (Eq. 19)$$

$$P_{TMP} = \frac{(P_{feed} + P_{conc})}{2} - P_{perm} \quad (Eq. 20)$$

TMP may be measured manually by placing a pressure transducer into the feed to obtain the pre-filter pressure, then placing the transducer in the retentate outside the membrane and taking note of the retentate pressure. In an ultrafiltration system, the hydraulic pressure is small and can ignore. Moreover, the permeate pressure is relatively small and near 0.1 bar. The pressure drop across the membrane can be calculated by the following equation.

$$P_{drop} = P_{feed} - P_{perm} \quad (Eq. 21)$$

The permeate pressure in the UF system is near 0.1 bar and can be neglected. And the total permeate flow in the system can be calculated by

$$Q_{perm} = F_w * A \quad (Eq. 22)$$

Where Q_{perm} is the permeate flow, F_w Is the transmembrane water flux rate and A membrane area. The following equation can calculate the recovery of the UF plant;

$$\%R = \frac{Q_{feed}}{Q_{perm}} * 100 \quad (Eq. 23)$$

Where Q_{feed} and Q_{perm} The feed and permeate flow of the system and R is the water recovery rate in the system.

As we can see, the calculation of the UF system is the same as the RO membrane calculation as we discussed in the RO calculation part, and for the UF system, we will

summarize the calculations in one step. In the present study, we selected membranes from DuPont manufacturer, which produce different UF and RO membranes. For the UF system, we selected the Integra Flux™ SFD-2880XP membrane, the specification of this membrane is collected in the ESS sheet in Figure 4.2.

IntegraFlux™ Ultrafiltration Modules

Model SFP-2860XP, SFD-2860XP, SFP-2880XP and SFD-2880XP

Description

IntegraFlux™ Ultrafiltration (UF) modules with XP fiber are made from high permeability, high mechanical strength, hollow fiber PVDF membranes. The modules provide excellent performance, industry leading membrane area with low energy and chemical consumption. IntegraFlux™ modules have the following general properties and characteristics:



- Up to 35% higher permeability than previous generation modules helping to improve operating efficiencies and productivity
- 0.03 µm nominal pore diameter for removal of bacteria, viruses, and particulates including colloids to protect downstream processes such as RO
- PVDF polymeric hollow fibers for high mechanical strength with excellent chemical resistance providing long membrane life and reliable operation
- Outside-In flow configuration allowing a wide range of solids in the feed water minimizing the need for pretreatment processes and reducing the backwash volume compared to Inside-Out configurations



These modules are an excellent choice for systems with capacities greater than 50 m³/hr (220 gpm). The shorter SFP-2860XP or SFD-2860XP modules are well suited for installations with limited height. Larger and longer, 8 inch diameter and 80 inch in length, the SFP-2880XP or SFD-2880XP modules offer a high effective membrane area combined with high permeability that provides the most economical and efficient membrane system design.

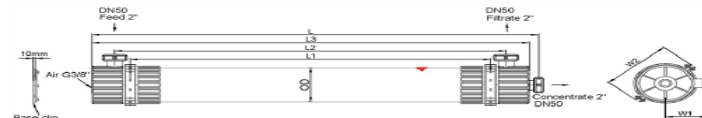
IntegraFlux™ Ultrafiltration Modules can be used for a wide variety of treatment applications such as industrial and municipal wastewaters, surface water, and seawater.

Typical Properties

Product	Type	Membrane Area		Volume		Weight (empty/water filled)	
		m ²	ft ²	liters	gallons	kg/lbs	kg/lbs
SFP-2860XP	Industrial	51	549	35	9.3	48/83	106/183
SFD-2860XP	NSF/ANSI 61 and 419	51	549	35	9.3	48/83	106/183
SFP-2880XP	Industrial	77	829	39	10.3	61/100	135/220
SFD-2880XP	NSF/ANSI 61 and 419	77	829	39	10.3	61/100	135/220

Dimensions

SFP-2860XP, SFD-2860XP, SFP-2880XP, and SFD-2880XP (8-inch diameter)



Product	Units	Length				Diameter	Width	
		L	L1	L2	L3		W1	W2
SFP-2860XP and SFD-2860XP	SI (mm)	1860±3	1500	1630±3	1820±3	225	180	342
	US (inch)	73.2±0.1	59.1	64.2±0.1	71.7±0.1	8.9	7.1	13.5
SFP-2880XP and SFD-2880XP	SI (mm)	2360±3	2000	2130±3	2320±3	225	180	342
	US (inch)	92.9±0.1	78.7	83.9±0.1	91.3±0.1	8.9	7.1	13.5

Suggested Operating Conditions

	SI Units	US Units
Filtrate Flux (25°C)	40 – 110 l/m ² hr	24 – 65 gfd
Flow Range Per Module ¹	2.0 – 8.5 m ³ /hr	8.8 – 37.4 gpm
Temperature	1 – 40°C	34 – 104°F
Maximum Inlet Module Pressure (20°C)	6.25 bar	90.65 psi
Maximum Inlet Module Pressure (40°C)	4.75 bar	68.89 psi
Maximum Operating TMP	2.1 bar	30.5 psi
Maximum Operating Air Scour Flow	12 Nm ³ /hr	7.1 scfm
Maximum Backwash Pressure	2.5 bar	36 psi
Operating pH	2 – 11	
Maximum NaOCl	2,000 mg/L	
Maximum Particle Size	300 µm	
Flow Configuration	Outside in, dead end flow	
Expected Filtrate Turbidity	≤ 0.1 NTU	
Expected Filtrate SDI	≤ 2.5	

¹ Flow range represents DUPONT™ Ultrafiltration SFP-2860XP, SFD-2860XP, SFP-2880XP, and SFD-2880XP Modules for filtrate flux range shown

Figure 4.2. ESS for UF filtration membrane from DOW manufacturer

We will use the following data for the UF system calculation according to the selected UF membrane.

Table 4.1. Basic information for the UF system design

Source water	Surface water	
The capacity of the plant	90000m ³ /day	
Total dissolved solids concentration	1200mg/l	
The effective area of membrane element	77m ²	From ESS
Average permeate flux for UF system	60LMH	Assumed according to standard
Recovery of system	97%	For cross-flow system
The temperature of the water	25 oC	

First, we will calculate the feed flow per element by the following equation;

$$Q_f = \frac{Q_{Plant}}{R} = \frac{112500m^3/day}{0.97} \Rightarrow 115979.3 \frac{m^3}{day}$$

$$Q_c = Q_f - Q_p \Rightarrow 115979.3 \frac{m^3}{day} - 112500 \frac{m^3}{day} = 3479.3 \frac{m^3}{day}$$

$$Q_e = J_{avg} * A_e \Rightarrow 60 \frac{L}{m^2 * h} * 77m^2 = 4620 \frac{L}{h} = 4.62m^3/h$$

The total membrane area that is required can be calculated as follow;

$$A = \frac{Q_{feed}}{J} = \frac{115979.3 \frac{m^3}{day} * 1000 L}{60 \frac{L}{m^2 * h} * 24} = 80541.18m^2$$

The number of membranes model at 77m² shape model can be as follow;

$$N_e = \frac{A_{total}}{A_{element}} = \frac{80541.18m^2}{77m^2} = 1045.98 \cong 1046$$

We can calculate the number of elements for the UF system by dividing the plant flow by element flow as follow;

$$N_e = \frac{Q_p}{Q_e} = \frac{115979.3 \frac{m^3}{day} * \frac{1 day}{24h}}{4.62m^3/h} \Rightarrow 1045.98 \cong 1046$$

As we can see, 1046 elements are needed for all plant to filter water for the RO system.

We can check the flux for the obtained number of elements and flow as follow.

$$J_{avg} = \frac{Q_p}{elements * A_e} \Rightarrow \frac{115979.3 \frac{m^3}{day} * \frac{1000 L}{m^3} * \frac{day}{24 h}}{1046 * 77m^2} \Rightarrow 59.99 \frac{L}{m^2 * h}$$

The obtained average flux is 59.77, which is almost 60LMH shows that the calculation is correct. All the elements should be installed in pressure vessels. The common UF system uses two pressure vessels, and the elements will be installed parallel in two line tracks or trains. The vessels should be installed at independent racks or trains; the number of trains is desirable and must be installed vertically (Cromphout et al., 2011).

$$N_{vessels} = \frac{N_{elements}}{2} = 522 + 1 vessels$$

For the present system, we divide the UF elements into 10 tracks. Every track or train has 105 UF elements that must be installed vertically. Among these tracks, one for backwash and one train out of service remain for cleaning, and we can call these trains as offline trains for backwash and cleaning purposes, at that time the average flux for the plant can be calculated for 8 online trains or tracks as follow.

$$J_{avg} = \frac{Q_p}{elements * A_e} \Rightarrow \frac{115979.3 \frac{m^3}{day} * \frac{1000 L}{m^3} * \frac{day}{24 h}}{8 * 105 * 77m^2} \Rightarrow 75.71 \frac{L}{m^2 * h}$$

The average flux for 8 trains is $75.71 \frac{L}{m^2 * h}$ which is within the acceptable range of the element given by the manufacturer, as seen in Figure 31. The racks must design such that the product of different manufacturers can be installed on these racks. Figure 4.3 shows a general install model of the UF system.



Figure 4.3. Installed models of UF filter from DOW manufacturer (Dow, 2011)

The capillary membranes are all operated inside-out. Each module has two feed / concentrate connectors (top and bottom) and one permeate connector. Consequently, filtration can be performed top-down, bottom-up, or with feeding from two sides, and backwash can be performed with the evacuation at the top, bottom, or two sides (Cromphout et al., 2011). The temperature affects the average flux; if the temperature decreases, the saline water viscosity increases. Water viscosity affects membrane ability, and more pressure is needed to clean water when the temperature decreases (Voutchkov, 2017). Typically, average design membrane flux is established for average annual temperature, flow, and turbidity and is then adjusted for the minimum monthly average temperature using the correction factor shown in Table 4.2.

Table 4.2. Correction factor for temperature difference in UF system (Voutchkov, 2017).

Temperature (°C)	Flux correction (%increase/decrease)
5	55
10	30
15	15
20	0
25	-10

Table 4.2 shows the correction factor for Flux in different temperatures source, for example, if the temperature is decreased to 15 °C then the average flux for the UF system decreases by 15 %, and the calculations for 15 °C become 51LMH. This correction factor is the thumb's rule and is based on practical experience. For the calculation of feed pressure, it needs to test the UF membrane and find TMP for raw water data which is not available at the time, but we can assume that TMP is maximum in a single element and the difference between feed and permeate pressure is near to 1.2, so we have;

$$\mathbf{TMP = P_{feed} - \frac{\Delta P_{hydro}}{2} - P_{perm} \text{ or} \quad (\text{Eq. 24})}$$

Typically, pretreatment systems operate at TMP between 0.2 and 1.0 bar (Voutchkov, 2017). Suppose we want to find feed pressure and TMP. In that case, we need the membrane permeability coefficient Most MF and UF membrane elements used for water pretreatment operate at membrane permeability of 75-500 LMH/bar (Voutchkov, 2017). We summarized all calculations for the UF system in Table 4.3.

Table 4.3. Pressure, TMP, and energy consumption for the UF pretreatment system.

Parameters	Values	Units	Details and equations
Javg (10°C)	42	$\frac{L}{m^2 * h}$	Javg- 30% decrease
J avg (25°C)	60	$\frac{L}{m^2 * h}$	
J avg (40°C)	72	$\frac{L}{m^2 * h}$	Javg +20% increase
<i>K_w average</i>	290	$\frac{L}{m^2 * bar * h}$	Assume an average between 75-500LMHbar
Qavg	5.25	m ³ /h	From DSS

TMP average(25°C)	0.20	bar	$TMP = \frac{J_{avg}}{K_w average}$	
TMP (10°C)	0.137	bar		
TMP (40°C)	0.24	bar		
	0.3	$\frac{m^3}{m^2 * bar * h}$		
	Δp_{PV}	0.1	bar	$\Delta p_{PV} = \Delta p_e * \#elements$
Permeate pressure	P_p	0.1	bar	Negligible
Estimated feed pressure	P_{feed}	1	bar	$P_{feed} = NDP + \Delta P_{PV} + \Delta \pi_{avg} + P_{perm}$
Energy required	E	0.037	Kwh / m^3	$E = (0.0275 * P_{feed}) / (N_{pump} * R)$

As we can see from Table 4.3, the feed pressure is not constant in all conditions, so we assume the feed pressure is 1 bar just for calculation; otherwise, it must be measured in the actual case. For the UF system, the total energy required can be calculated by the following equation.

Note: For a single-stage RO system with concentrate recycling, the feed water increase for the total feed water for the UF system it must add the recycled concentrate water to feed water which we found it as 25961.5 m³/day

$$Q_f = 112500 \frac{m^3}{day}$$

$$energy \text{ for } 1h \text{ of UF plant} = 4687.5 \frac{m^3}{h} * 0.037 \frac{Kwh}{m^3} = 173.43 \cong 174Kwh$$

$$energy \text{ for } 1 \text{ day of UF plant} = \frac{174Kwh}{h} * \frac{24 h}{1 \text{ day}} = 4176 \frac{Kwh}{day}$$

Figure 4.4 shows the general water filtration flow by the UF system.

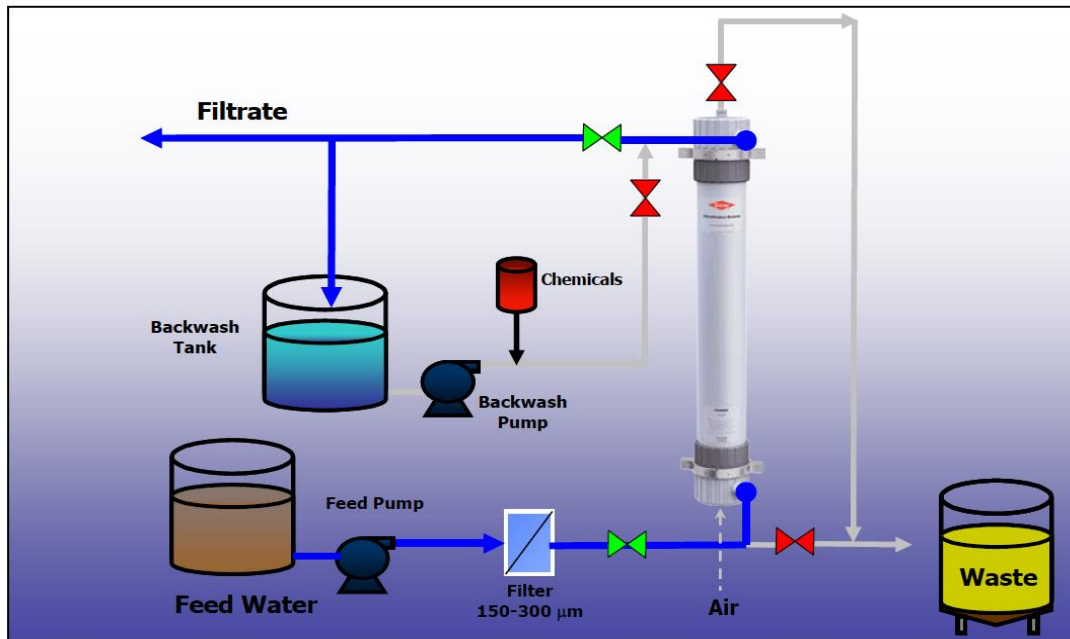


Figure 4.4 Water flow in UF system (DOW, 2011)

Figure 4.4 shows the operating mode for the UF system as the water is fed from the feed water tank by a low-pressure pump and comes to a strainer for screening the big particles, and then flows to the UF membrane from the bottom drain to the top drain of membrane and the filtered water flow to permeate tank. A regular UF system's operation time is 20-60 minutes (Dow, 2011). When the operation mode is complete, the filter removes 100 % of the contaminants. The TMP increases because of this; at the end of operation mode, the backwash process is triggered on the UF system.

4.1.2. Numerical design of RO membranes

For the numerical calculation of RO system with two different layouts in single stage with concentrate recycle and two stages systems we will follow the steps which mentioned in the method part of this study.

Step1: The primary data for the design of an RO treatment plant system is the plant's capacity, total dissolved solids, the temperature of design, and total recovery, which are taken from Table 3.1 and listed in Table 4.4 (Salinas-Rodríguez et al., 2021).

Table 4.4. Basic information for the RO system design

Source water	Surface water
The capacity of the plant	90000 m ³ /day
Total dissolved solids concentration	1200 mg/l
Recovery of the plant	80%
The temperature of the water	25 °C

The feed water flow for the selected plant is approximately 1200 l/sec, the needed permeate water flow is approx. 1000 l/sec, and the required water treatment plant capacity is around 90000 m³/day. We will calculate the feed flow, concentrate flow, concentrate concentration, and average feed-conc. Concentration permeate concentration. The calculation for the plant is summarized in Table 4.5 and Figure 4.4.

Table 4.5. Summary of calculation for feed, concentrate flow with their concentration

Parameters	Value	Equations
Feed flow of the plant	$112500 \frac{m^3}{day}$	$Q_f = \frac{Q_p}{R}$
Concentrate flow of the plant	$22500 \frac{m^3}{day}$	$Q_c = Q_f - Q_p$
Concentrate concentration	$6000 mg L^{-1}$	$C_c = \frac{C_f}{1 - R}$
Avg feed-conc. Concentration	$3600 mg L^{-1}$	$C_{FC} = \frac{(C_f + C_c)}{2}$
Permeate concentration	$25.2 mg L^{-1}$	$C_p = C_{FC}(1 - SR)$

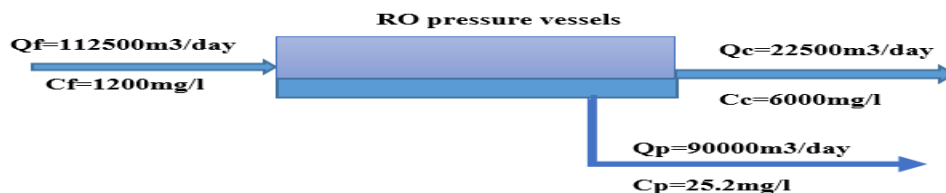


Figure 4.4. Feed, concentrate, and permeate flow with a concentration

Step 2: calculation of membrane elements and pressure vessels

For calculating membrane elements and pressure vessels, it is essential to select the average design flux for the membrane. According to DuPont manufacturer, the average design flux for the selected membrane is between 27-34 LMH (Table 3.3). It assumed the average design flux for our RO system elements is 27LMH.

We have;

$$Q_e = J_{avg} * A_e \Rightarrow 27 \frac{L}{m^2 * h} * 41m^2 = 1107 \frac{L}{h} = 1.107m^3/h$$

For the number of elements for the plant, we have;

$$N_e = \frac{Q_p}{Q_e} = \frac{90000 \frac{m^3}{day} * \frac{1 day}{24h}}{0.943m^3/h} \Rightarrow 3387$$

For the number of pressure vessels in the plant, we have;

$$N_v = \frac{N_e}{N_{epv}} = \frac{3387}{6} = 564.5 = 565$$

The number of elements for the plant becomes 3390 elements which are located in 565 pressure vessels.

It can be checked design flux for the calculated elements as follows;

$$J_{avg} = \frac{Q_p}{elements * A_e} \Rightarrow \frac{90000 \frac{m^3}{day} * \frac{1000 L}{m^3} * \frac{day}{24 h}}{3390 * 41m^2} \Rightarrow 26.98 \frac{L}{m^2 * h}$$

As we can see, the design flux for the estimated elements is 26.98, which is almost 27 $\frac{L}{m^2 * h}$. The difference is low than 0.5, which shows the elements are sufficient for the feed flow of the plant. Furthermore, we can check the flow of each element by considering the new number of elements and design flux;

$$Q_e = J_{avg} * A_e \Rightarrow 26.98 \frac{L}{m^2 * h} * 41m^2 = 1106.18 \frac{L}{h} = 1.106m^3/h$$

For the calculation of feed, permeate, and concentrate flow per pressure vessel, we have;

$$Q_{feed pv} = \frac{Q_{feed plant}}{\# pv} \Rightarrow \frac{112500 \frac{m^3}{day}}{565} = 199.11 \frac{m^3}{day} = 8.29 \frac{m^3}{h} \text{ (without Cc recycle)}$$

$$\frac{138461.5 \frac{m^3}{day}}{565} = 245.06 \frac{m^3}{day} = 10.21 \frac{m^3}{h}$$

Note: further, we must add the recycled concentrate flow to feed flow to calculate the correct feed per pressure vessel. The calculation of feed pressure will revise in step 4.

$$Q_{perm\ pv} = R * Q_{feed\ pv} = \frac{80}{100} * 7.07 \frac{m^3}{h} = 5.656 \frac{m^3}{h}$$

$$Q_{conc\ pv} = Q_{feed\ pv} - Q_{perm\ pv} \Rightarrow 7.07 - 5.656 \Rightarrow 1.414 \frac{m^3}{h}$$

the manufacturer gives the Maximum feed flow for the first element in ESS, which is $17 \frac{m^3}{h}$ the designed feed flow for the first element is less than the maximum value, showing the number of elements suitable for the plants. All the above calculation is summarized in Table 4.6 and Figure 4.5.

Table 4.6. Flux, pressure vessels number of elements, and flow per pressure vessels

	Values	Formula
Average design flux		$27 \frac{L}{m^2 * h}$
flow per element	$1.107 m^3 / h$	$Q_e = J_{avg} * A_e$
Number of elements in plant	3390	$N_e = \frac{Q_p}{Q_e}$
number of pressure vessels in the plant	565	$N_v = \frac{N_e}{N_{epv}}$
Flux check	$26.98 \frac{L}{m^2 * h}$	$J_{avg} = \frac{Q_p}{elements * A_e}$
Flow per element check	$1.106 m^3 / h$	$Q_e = J_{avg} * A_e$
Feed flow per pressure vessel without CC recycle	$8.29 \frac{m^3}{h}$	$Q_{feed\ pv} = \frac{Q_{feed\ plant}}{\#\ pv}$
Feed flow per pressure vessel with Cc recycle	$10.21 \frac{m^3}{h}$	$Q_{feed\ pv} = \frac{Q_{feed\ plant} + C_c\ recycle}{\#\ pv}$
Permeate flow per pressure vessel	$8.168 \frac{m^3}{h}$	$Q_{perm\ pv} = R * Q_{feed\ pv}$
Concentrate flow per pressure vessel	$2.042 \frac{m^3}{h}$	$Q_{conc\ pv} = Q_{feed\ pv} - Q_{perm\ pv}$

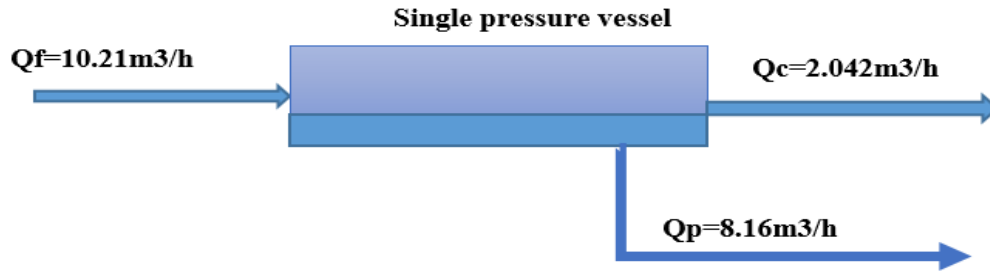


Figure 4.5. Feed, permeate, and concentrate flow per pressure vessel

Step 3 - Membrane permeability coefficients for water and salt

To determine the membrane permeability coefficient for water (K_w), we use standard design test condition data from PDS.

We will go through the following steps to find the membrane permeability coefficient for water(K_w)

- use following equation

$$Q = NDP * K_w * A \quad (\text{Eq. 25})$$

Where Q is the permeate flow of element, NDP is the net driving pressure, and A is the net area of the membrane element

- for net driving pressure, NDP uses the following equation;

$$NDP = P_{feed} - \frac{\Delta P}{2} - \Delta\pi_{avg} - P_{perm} \quad (\text{Eq. 26})$$

Where P_{feed} is the applied pressure in the standard condition, which is 10.3 bar for BW30 HRLE 440i element, ΔP is pressure loss per element we have it from PDS which assumes 0.2 bar, R is the recovery at the standard condition which is 15 % (see PDS), P_{perm} is the permeate pressure of element and for $\Delta\pi_{avg}$ we use the following equation;

$$\Delta_{avg} = (\Delta\pi_{feed} + \Delta\pi_{conc})/2 \quad (\text{Eq. 27})$$

- Use standard conditions for the above equation

➤ For the concentrate concentration in standard conditions, use the following equation;

$$C_{\text{conc stand}} = C_{\text{feed stand}} / (1 - R_{\text{e stand}}) \quad (\text{Eq. 28})$$

- Assume osmotic pressure for 1000 mg/l of concentrate 0.8 bar
- use the nominal capacity of permeate flow of element (Qs) from ESS
- calculate the design flux for standard conditions by the following equation;

$$J_{\text{stand}} = \frac{Q_{\text{stand}}}{A_e} \quad (\text{Eq. 29})$$

➤ for the calculation of membrane permeability (Kw), we have the following equation;

$$K_w = \frac{Q_{\text{stand}}}{(\text{NDP} * A_e)} \quad (\text{Eq. 30})$$

- for the membrane productivity, we use the following equation

$$\text{membrane productivity} = K_w * A_e \quad (\text{Eq. 31})$$

The calculation for the membrane permeability coefficient for water is summarized in Table 4.7.

Table 4.7. Summary of calculation for water permeability coefficient

Parameters	Values	Units	Details and equations
T_{stand}	25	°C	From the product data-sheet
$P_{feed\ stand}$	10.3	bar	From the product data-sheet
ΔP_e	0.2	bar	Assumed head loss per element
$C_{feed\ stand}$	2000	mg/l	From the product data-sheet standard test condition
R_e	15	%	From the product data-sheet standard test condition
$C_{conc\ stand}$	2338.82	mg/l	$C_{conc\ stand} = \frac{C_{feed\ stand} * (1 - R)(1 - SR)}{1 - R_{e\ stand}}$
1000 mg/l	0.7	bar	Equivalence for osmotic pressure
π_{fs}	1.4	bar	$\pi_{fs} = C_{fs} * \left(\frac{0.7}{1000}\right)$
π_{cs}	1.64	bar	$\pi_{cs} = C_{cs} * \left(\frac{0.8}{1000}\right)$
π_{avg}	1.523	bar	$\pi_{avg} = (\pi_{feed} + \pi_{conc})/2$
π_{ps}	0.076	bar	$\pi_{ps} = 0.05\Delta_{avg}$ (for brackish water)
$\Delta\pi_{avg\ s}$	1.447	bar	$\Delta\pi_{avg\ s} = \pi_{avg} - \pi_{ps}$
P_{ps}	0	bar	
NDP	8.753	bar	$NDP = P_{feed} - \frac{\Delta P_e}{2} - \Delta\pi_{avg\ s} - P_{perm}$
Qs	48	m ³ /day	Nominal feed capacity(permeate flow)from PDS
	2	m ³ /h	
$J_{W\ stand}$	48.78	$\frac{L}{m^2 * h}$	$J_{W\ stand} = \frac{Q_{stand}}{A_e}$
K_w	5.675	$\frac{L}{m^2 * bar * h}$	$K_w = J_{w\ s}/NDP_s$
	0.0055	$\frac{m^3}{m^2 * bar * h}$	
	232.67	$\frac{L}{bar * h}$	membrane productivity = $K_w * A_e$

The temperature affects the K_w value; the higher the temperature, the higher the permeability; one degree of °C increase 3% of water permeability (Salinas-Rodríguez et al., 2021). Recently manufacturers have the RO membranes with different permeability of water as the value of water permeability for brackish water RO system is 2-8 LMH/bar (Yang et al., 2018; Okamoto and Lienhard, 2019). Furthermore, K_w is linked with water viscosity; when the temperature is high, the required pressure decreases for the specific flux and water capacity. For the calculation of the membrane permeability coefficient for salt, we will use the following equation.

$$K_s = \frac{C_{p s} * J_{w s}}{C_{f c s}} \quad (\text{Eq. 32})$$

Where K_s is the membrane permeability coefficient for salt, C_p is the permeate concentrate concentration, J is flux under standard conditions, and $C_{f c}$ is the concentrate and feed concentration. the calculation for K_s is summarized in Table 4.8

Table 4.8. Summary of membrane permeability coefficient for salt

Parameters	Values	Units	Details and equations
T_{stand}	25	oC	From the product data-sheet
$C_{feed stand}$	2000	mg/l	From ESS standard test condition
R_e	15	%	From ESS standard test condition
$C_{conc stand}$	2353	mg/l	$C_{conc stand} = C_{feed stand} / (1 - R_e stand)$
$C_{f c s}$	2176.5	mg/l	$C_{f c s} = (C_{f s} + C_{c s}) / 2$
SR	99.3%		Salt rejection performance from PDS
$C_{p s}$	15.235	mg/l	$C_{p s} = C_{f c s} * (1 - SR)$
Q_{ws}	48	m ³ /day	Nominal feed capacity(permeate flow)from PDS
	2	m ³ /h	
$J_{W stand}$	48.75	$\frac{L}{m^2 * h}$	$J_{W stand} = \frac{Q_{stand}}{A_e}$ (flux under standard condition)
K_s	0.3412	$\frac{L}{m^2 * h}$	$K_s = \frac{C_{p s} * J_{w s}}{C_{f c s}}$

The membrane permeability coefficient for salt is 0.3412 LMH. KS depends on water temperature and the higher salt passage, and different Ions have different Ks, so SR is different for each ion. However, the calculations became very complicated, so we calculated only for salt rejection (Salinas-Rodríguez et al., 2021). High salt rejection is related to both Ks and Kw, while low values for both Ks and Kw reject a high percentage of salt, but on the other hand, a low value of Kw increases energy consumption. (Salinas-Rodríguez et al., 2021; Okamoto and Lienhard, 2019).

Furthermore, we can calculate different ions separately in permeate water for the selected membrane. The big problem for the selected water is the Cl, SO₄, and Arsenic, and the amount of these parameters in the influent water is exceeded from WHO standard for water, as we can see the value of these parameters in Table 3.1.

For the calculation of Cl, we have;

Table 4.9. The chloride concentration in permeate water

Parameters	Values	Units	Details and equations
$C_{feed\ Cl}$	258	mg/l	Table 6
R_e	15	%	From product data-sheet standard test condition
$C_{conc\ Cl}$	303.52	mg/l	$C_{conc\ Cl} = C_{feed\ Cl} / (1 - R_{e\ stand})$
$C_{avg\ Cl}$	280.76	mg/l	$C_{fc\ Cl} = (C_{f\ Cl} + C_{c\ Cl}) / 2$
SR	99.3%		Salt rejection performance from PDS
$C_{permeate\ Cl}$	1.965	mg/l	$C_{permeate\ Cl} = C_{avg\ Cl} * (1 - SR)$

The value of Cl in permeate water is 1.965 mg/l in one element with 15 % standard recovery by using the BW30 HRLE 440i membrane element. For the overall RO plant, the permeate concentration of Cl is 5.418 mg/l because the recovery of the plant is 80%.

For SO₄, we have;

Table 4.10. SO₄ concentration in permeate water

Parameters	Values	Units	Details and equations
$C_{feed\ SO_4}$	364	mg/l	
R_e	15	%	From product data-sheet standard test condition from PDS
$C_{conc\ SO_4}$	428.23	mg/l	$C_{conc\ SO_4} = C_{feed\ SO_4} / (1 - R_{e\ stand})$
$C_{avg\ SO_4}$	396.11	mg/l	$C_{avg\ SO_4} = (C_{f\ SO_4} + C_{c\ SO_4}) / 2$
SR	99.3%		Salt rejection performance from PDS
$C_{permeate\ SO_4}$	2.772	mg/l	$C_{permeate\ SO_4} = C_{avg\ SO_4} * (1 - SR)$

The value of SO₄ in permeate water is 2.772 mg/l in one element using BW30 HRLE 440i membrane element. For the overall RO plant, the permeate concentration of SO₄ is 7.644 mg/l because the recovery of the plant is 80%.

For Arsenic, we have;

Table 4.11. Arsenic concentration in permeate water

Parameters	Values	Units	Details and equations
$C_{feed\ As}$	15	µg/l	
R_e	15	%	From product data-sheet standard test condition from PDS
$C_{conc\ As}$	17.64	µg/l	$C_{conc\ As} = C_{feed\ As} / (1 - R_{e\ stand})$
$C_{avg\ As}$	16.32	µg/l	$C_{avg\ As} = (C_{f\ As} + C_{c\ As}) / 2$
SR	99.3%		Salt rejection performance from PDS
$C_{permeate\ As}$	0.114	µg/l	$C_{permeate\ As} = C_{avg\ As} * (1 - SR)$

The As value in permeate water is 0.114 µg/l in one element using the BW30 HRLE 440i membrane element. For the overall RO plant, the permeate concentration of Arsenic is 0.315 µg/l because the recovery of the plant is 80%. For total dissolved solids(TDS), we have for one element of membrane;

Table 4.12. TDS concentration in permeate water

Parameters	Values	Units	Details and equations
TDS	1200	mg/l	
Re	15	%	From product data-sheet standard test condition from PDS
C_{conc TDS}	1411.76	mg/l	$C_{conc\ TDS} = C_{feed\ TDS} / (1 - R_{e\ stand})$
C_{avg TDS}	1305.88	mg/l	$C_{avg\ TDS} = (C_{f\ TDS} + C_{c\ TDS}) / 2$
SR	99.3%		Salt rejection performance from PDS
C_{permeate TDS}	9.141	mg/l	$C_{permeate\ TDS} = C_{avg\ TDS} * (1 - SR)$

The value of TDS in permeate water for one element in the standard condition is 9.141 mg/l. For all plant, the permeate concentration of TDS is 25.2 mg/l for a single stage without concentrate recycling, but after concentrate recycling, the permeate concentration will be 28.35 mg/l.

Step 4- Select the number of stages

The number of stages is related to the system recovery percentage and concentrate recycling to feed water. According to DuPont manufacturer, if the system recovery is low than 70 percent, then one stage RO system is suitable for producing drinking water from brackish water. If the system recovery is up to 80%, then the RO system can be designed in two ways;

A- Single stage with concentrate recycling

in this layout, single-stage pressure vessels will be installed and the concentrate water must be recycled to the feed system to increase the system recovery. The concentrate water is pumped back to the feed water and treated again to increase the system recovery percentage. DuPont says the maximum system recovery for a single stage is 40-65% for 6 elements in a pressure vessel for brackish water (DuPont, 2020). If we assume that the single stage works with 65% of the recovery, then the feed flow of the plant will be;

$$Q_{f\ plant} = \frac{Q_P}{R} = \frac{90000 \frac{m^3}{day}}{0.65} = 138461.5 \frac{m^3}{day}$$

And for 80% of recovery system the $Q_{f\ plant}$ is $112500 \frac{m^3}{day}$ so we have;

$$138461.5 \frac{m^3}{day} - 112500 \frac{m^3}{day} = 25961.5 \frac{m^3}{day}$$

As a result, we need to recycle $25961.5 \frac{m^3}{day}$ Of concentrate water to feed to reach the system recovery up to 80 % and it became more than 50 % of concentrate water that must be recycled. The advantage of this system is to reduce the feed water volume and recycle the concentrate water for the second time, and the volume of the concentrate water will decrease. The main disadvantage of the single-stage with concentrate recycling is the high energy consumption because concentrate recycling increases the concentration of feed water, resulting in increased feed pressure. Figure 4.6 shows the general layout of a single-stage RO system with concentrate recycling to the feed water.

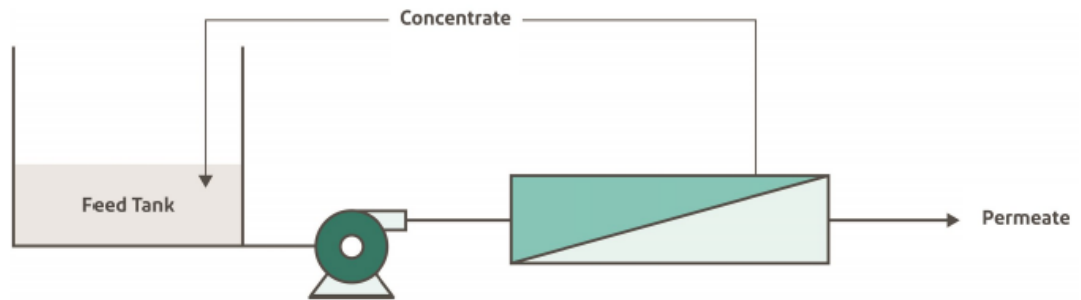


Figure 4.6. Schematic diagram of single stage RO system with concentrate recycles (DuPont, 2020)

The present RO plant in Kirikkale city is a single-stage RO system in which more than 50 % of concentrate is recycled to feed to increase the system recovery (AKSU, 2019). If we want to design a single-stage pressure vessel with 80 % system recovery, then recycling the concentrate water to feed flow is essential. Suppose we assume that 53.5 % of concentrate water recycle into the feed system. In that case, the permeate water quality will change the calculation for a single stage with 80 % recovery, and 53.5 % recycling of concentrated water is summarized in Table 4.13.

Table 4.13. Summary of calculation for single stage RO system with concentrate recycle

Parameters	Value	Equations
Feed concentration	1200mg/l	
Feed flow of the plant without Concentrate recycling with 80% recovery	$112500 \frac{m^3}{day}$	$Q_f = \frac{Q_P}{R}$
Feed flow of the plant without Concentrate recycling with 65% recovery	$138461.5 \frac{m^3}{day}$	$Q_f = \frac{Q_P}{R}$
Concentrate flow of the plant for 65% recovery	$48461.5 \frac{m^3}{day}$	$Q_c = Q_F - Q_p$
Recycled concentrate water needed	$25961.5 \frac{m^3}{day}$	53.3% of Q_c
C_c without recycling with 80% recovery	$6000 mg L^{-1}$	$C_c = \frac{C_F}{1 - R}$
C_c without recycling with 65% recovery	$3428.5 mg L^{-1}$	$C_c = \frac{C_F}{1 - R}$
$Q_{c\ recycle}$	$25962 \frac{m^3}{day}$	53.5% of Q_c
Feed flow with $Q_{c\ recycle}$	$138462 \frac{m^3}{day}$	$Q_{f\ avg} = Q_f + Q_{c\ recycle}$
Feed flow per pressure vessel	$10.21 \frac{m^3}{h}$	$Q_{feed\ pv}$ $= \frac{Q_{feed\ plant+Cc\ recycle}}{\#\ pv}$
Feed concentration after recycle	$2100 mg L^{-1}$	$C_{F+recycle}$ $= \frac{155769kg + 135000kg}{138461.5m^3}$
C_c after recycle with 65% recovery = 80% recovery	$6000 mg L^{-1}$	$C_{c\ recycle} = \frac{C_{F\ recycle}}{1 - R}$
Avg feed-conc +recycle. Concentration	$4050 mg L^{-1}$	$C_{FC\ rec}$ $= \frac{(C_{F+rec} + C_{c\ recycle})}{2}$
Permeate concentration after recycling	$28.35 mg L^{-1}$	$C_p = C_{FC}(1 - SR)$

B- Two stage RO system

two stage RO systems are using for that plants, which the recovery of the plant is between 70-80 %. In this system the concentrate of first stage become the feed for second stage to achieve high recovery percentage water. generally, in this system 6 pressure

vessels are used. Typical staging ratios for 6-element pressure vessels in brackish water applications are 2:1 (DuPont, 2020). Figure 4.7 shows us the two stage RO system for brackish water treatment.

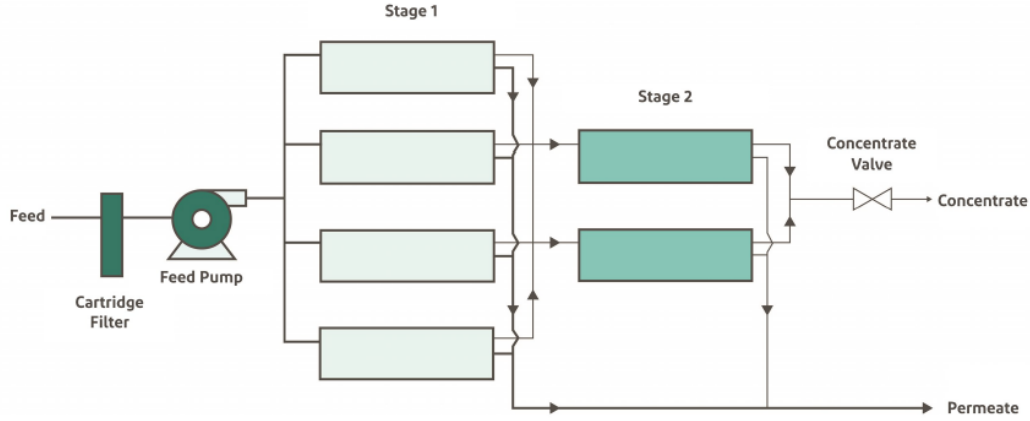


Figure 4.7. Schematic diagram of two stages RO system (DuPont, 2020)

For the determination of 80 % recovery of the plant in the two-stage system, apply the 2:1 ratio as in 80 % recovery, the first stage produces 60 % of permeate water, and the second stage produces 40 % of permeate water. The number of pressure vessels for the first and second stages can be calculated by the following equation.

$$Y = \left\{ \frac{1}{1-R} \right\}^{1/n} = 2.23 \quad (\text{Eq. 33})$$

Where; Y is the staging ratio for the two-stage system, R is the system recovery, and n is the number of stages. For the number of vessels in the first stage, we have;

$$N_{vessel\ 1st\ stage} = \frac{N_{v\ plant}}{1 + Y^{-1}} = \frac{565}{1 + 0.4472} = 390.40 \cong 390$$

And for the number of pressure vessels in the 2nd stage, we have;

$$N_{vessel\ 2nd\ stage} = \frac{N_{v\ 1st\ stage}}{Y} = \frac{390}{2.23} = 174.88 \cong 175$$

As a result, it is near to 2:1 ratio, so we accept that ratio as 390 pressure vessels will be installed in the first stage, and 175 pressure vessels will be installed in the second stage. The calculation for the two-stage RO system is summarized in Table 4.14.

Table 4.14. Feed, concentrate, and permeate flow and concentration for two stages RO system

Parameters	Value	Equations
Feed concentration for 1 st stage	1200mg/l	
Q_f Feed flow for 1 st stage	$112500 \frac{m^3}{day}$	$Q_f = \frac{Q_P}{R}$
Permeate flow of 1 st stage (60% of total recovery)	$67500 \frac{m^3}{day}$	$Q_P = Q_f * \frac{2}{3} R$
Concentrate flow of the 1 st stage	$45000 \frac{m^3}{day}$	$Q_c = Q_f - Q_p$
C_c (concentrate concentration) of 1 st stage	$3000mg L^{-1}$	$C_c = \frac{C_f}{1 - R}$
Avg feed-conc. Concentration for 1 st stage	$2100mg L^{-1}$	$C_{FC\ 1st} = \frac{(C_f + C_c)}{2}$
Permeate concentration for 1 st stage	$14.7 mg L^{-1}$	$C_p = C_{FC\ 1st} (1 - SR)$
Feed flow for 2 nd stage	$45000 \frac{m^3}{day}$	Q_c of 1 st stage
Permeate flow of 2 nd stage (40% of recovery)	$22500 \frac{m^3}{day}$	$Q_{P\ 2nd} = Q_f * \frac{1}{3} R$
Feed concentration for 2 nd stage	$3000mg L^{-1}$	C_c of 1 st stage
C_c (concentrate concentration) of 2 nd stage (40 %of recovery)	$5000mg L^{-1}$	$C_{c\ 2nd} = \frac{C_{f\ 2nd}}{1 - R}$
Avg feed-conc. Concentration for 1 st stage	$4000mg L^{-1}$	$C_{FC\ 2st} = \frac{(C_{f\ 2nd} + C_{c\ 2nd})}{2}$
C_p for 2 nd stage	$28 mg L^{-1}$	$C_p = C_{FC\ 2nd} (1 - SR)$
Average C_p	$21.35 mg L^{-1}$	$(C_{p\ 1} + C_{p\ 2})/2$

Step 5: Feed pressure calculation

Required feed pressure for the plant (Pf) is dependent on different parameters of the RO plant, such as design average flux(Jw), the osmotic pressure in the membrane(π), water permeability coefficient (Kw), RO membrane, and pressure loss in channel feed/concentrate. The feed pressure, Pf, should overcome all the resistances present in the

system to diffuse salts and overcome the osmotic pressure. The net driving pressure is the effective pressure to push water only (Salinas-Rodríguez et al., 2021). for the determination of feed pressure, use the following equation;

$$J_w = (P_f - \pi) * K_w \text{ or} \quad (\text{Eq. 34})$$

$$P_f = \frac{J_w}{K_w} + \pi \quad (\text{Eq. 35})$$

Where P_f is the feed pressure, $(P_f - \pi)$ Is the net driving pressure or NDP, K_w is water permeability, and π is the osmotic pressure. However, the flux in the RO elements in a system depends on the element's position inside the pressure vessel because the NDP depends on pressure losses and osmotic pressure (Salinas-Rodríguez et al., 2021). For the determination of NDP, use the following equation;

$$NDP = P_f - \Delta P - \Delta\pi - P_p \quad (\text{Eq. 36})$$

Where NDP is the net driving pressure, P_f is the feed pressure, ΔP is the head loss across one element (assume 0.2 bar), $\Delta\pi$ is the difference of osmotic pressure in membrane vessel(feed-permeate), and P_p is the product pressure.

The calculation for feed pressure for a single-stage RO system is summarized in Table 4.15.

Table 4.15. Pressure for single-stage RO system

For single stage				
The average flux per element	J_{avg}	26.98	$\frac{L}{m^2 * h}$	$J_{avg} = \frac{Q_p}{elements * A_e}$
Flow per element	Q_e	1.107	m^3/h	$Q_e = J_{avg} * A_e$
	NDP	4.9	bar	$NDP = J_{avg}/K_w$
Feed concentration	C_F	2100	$mg L^{-1}$	From raw water data
	R%	80%		Plant design recovery
Concentrate concentration	C_c	6000	$mg L^{-1}$	$C_c = \frac{C_F}{1 - R}$
Osmotic pressure		0.7	bar	1000mg/l equivalent 0.7 bar
Osmotic pressure for C_F	π_f	1.47	bar	$\pi_f = C_f \left(\frac{0.7}{1000} \right)$
osmotic pressure for C_c	π_c	4.2	bar	$\pi_c = C_c \left(\frac{0.7}{1000} \right)$
Average of equivalence osmotic pressure for C_c and C_F	π_{FC}	2.83	bar	$\pi_{FC} = (\pi_f + \pi_c)/2$
	π_p	0.141	bar	$\pi_p = 0.05\pi_{FC}$ (for brackish water)
	$\Delta\pi_{avg}$	2.689	bar	$\Delta\pi_{avg} = (\pi_{FC} - \pi_p)$
Head loss per elements	Δp_e	0.2	bar	Assumed head loss per element
	Δp_{PV}	1.2	bar	$\Delta p_{PV} = \Delta p_e * \#elements$
Permeate pressure	P_p	0	bar	Negligible
Estimated feed pressure	P_{feed}	8.18	bar	$P_{feed} = NDP + \frac{\Delta P_{PV}}{2} + \Delta\pi_{avg} + P_{perm}$
	say	8.3	bar	Round up

Feed pressure for two stages RO system is summarized in Table 4.16.

Table 4.16. Summary of pressure calculation for two stages Ro system

For two stages with 80% recovery				
The average flux per element	J_{avg}	26.98	$\frac{L}{m^2 * h}$	$J_{avg} = \frac{Q_p}{elements * A_e}$
Flow per element	Q_e	1.107	m^3/h	$Q_e = J_{avg} * A_e$
	NDP	4.90	bar	$NDP = J_{avg}/K_w$
For 1st stage				
Feed concentration	C_F	1200	$mg L^{-1}$	From raw water data
	R%	60% of recovery		1 st stage design recovery
Concentrate concentration	C_C	3000 $mg L^{-1}$	$mg L^{-1}$	$C_C = \frac{C_F}{1 - R}$
Osmotic pressure		0.7	bar	1000mg/l equivalent 0.7 bar
Osmotic pressure for C_F	π_f	0.84	bar	$\pi_f = C_f(\frac{0.7}{1000})$
osmotic pressure for C_c	π_c	2.1	bar	$\pi_c = C_c(\frac{0.7}{1000})$
Average of equivalence osmotic pressure for C_c and C_F	π_{FC}	1.47	bar	$\pi_{FC} = (\pi_f + \pi_c)/2$
	π_p	0.073	bar	$\pi_p = 0.05\pi_{FC}$ (for brackish water)
	$\Delta\pi_{avg}$	1.397	bar	$\Delta\pi_{avg} = (\pi_{FC} - \pi_p)$
Head loss per elements	Δp_e	0.2	bar	Assumed head loss per element
	Δp_{PV}	1.2	bar	$\Delta p_{PV} = \Delta p_e * \#elements$
Permeate pressure	P_P	0	bar	Negligible
Estimated feed pressure	P_{feed}	6.89	bar	$P_{feed} = NDP + \frac{\Delta P_{PV}}{2} + \Delta\pi_{avg} + P_{perm}$
	say	7.1	bar	Round up
For 2nd stage $P_{feed} 2nd = P_{feed} 1st - 1.2 bar = 5.9bar$ say 6bar				

The feed pressure for a single stage with more than 50 % of concentrate water recovery is 8.5 bar. Furthermore, for the two-stage RO system, the estimated feed pressure for 1st stage is 7.1 bar, and for 2nd stage, the Fp is 6 bar because we have a 1.2 bar pressure drop along the element, so the pressure of the second stage is 6 bar. In the two stages RO system, if the pressure drop in the second stage is maximum than the standard pressure drop value at that time, it is better to install boost pressure to increase the concentrate feed pressure for the second stage.

Step 5: calculation of flow, recovery for each element

We can calculate the feed flow and permeate flow for each element in a pressure vessel. Figure 4.7 show a schematic diagram for step 5.

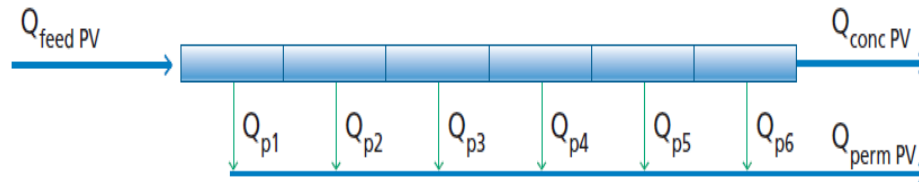


Figure 4.8. The schematic diagram for flow and recovery for each element (Salinas-Rodríguez et al., 2021)

In this study, we assume that the head loss in one element is 0.2 bar. Furthermore, we calculate the concentrate concentration in the middle of the element. Because of that, it takes the average concentration as in $C_{FC} = \frac{(C_F + C_C)}{2}$ equation. All the calculation is summarized in Table 4.17.

Table 4.17. Specifications of each element in a single pressure vessel 1st element

1 st element		Units	
P_{fi}	8.3	bar	
ΔP_{ei}	0.2	bar	Head loss per element
Q_{fi}	10.21	$\frac{m^3}{h}$	$Q_{f1} = Q_{f pv}, Q_{f2} = Q_{c1}, \text{ etc.}$
C_{fi}	2100	$mg L^{-1}$	$C_{f1} = C_{f pv}, C_{f2} = C_{c1} \text{ etc}$
R_{ei}	12	%	Assume to start the calculation
C_{ci}	2371.56	$mg L^{-1}$	$C_{ci} = \frac{C_{fi}[1 - R_{ei}(1 - SR)]}{1 - R_{ei}}$

$\pi_{f i}$	1.47	bar	$\pi_{f i} = C_{f i} \left(\frac{0.7}{1000} \right)$
$\pi_{c i}$	1.66	bar	$\pi_{c i} = C_{c i} \left(\frac{0.8}{1000} \right)$
$\pi_{F C i}$	1.56	bar	$\pi_{F C i} = (\pi_{f i} + \pi_{c i})/2$
$\pi_{p i}$	0.07	bar	$\pi_{p i} = 0.05 \pi_{F C i}$ (for brackish water)
$\Delta \pi_{avg i}$	1.49	bar	$\Delta \pi_{avg i} = (\pi_{F C i} - \pi_{p i})$
NDP_i	6.71	bar	$NDP_i = P_{feed i} - \frac{\Delta P_{P e i}}{2} - \Delta \pi_{avg i} - P_{perm i}$
$Q_{p 1}$	1.513	$\frac{m^3}{h}$	$Q_{p 1} = NDP_1 * K_w * A_e$
$R_{e i}$	14.81	%	$R_{e i} = Q_{p i} / Q_{f i}$
Check for obtained $R_{e i}$			
$C_{c i}$ 2nd time	2450.57	$mg L^{-1}$	$C_{c i} = \frac{C_{F i} [1 - R_{e i} (1 - SR)]}{1 - R_{e i}}$
Difference	79	$mg L^{-1}$	$C_{c i}$ 2nd time - $C_{c i}$ 1st time < 100, then OK
$\pi_{c i}$ 2nd time	1.71	bar	$\pi_{c i} = C_{c i} \left(\frac{0.7}{1000} \right)$
Difference	0.05	bar	$\pi_{c i}$ 2nd time - $\pi_{c i}$ 1st time < 0.5 OK
$\pi_{F C i}$ 2nd time	1.59	bar	$\pi_{F C i} = (\pi_{f i} + \pi_{c i})/2$
$\pi_{p i}$ 2nd time	0.079	bar	$\pi_{p i} = 0.05 \pi_{F C i}$ (for brackish water)
$\Delta \pi_{avg i}$ 2nd time	1.511	bar	$\Delta \pi_{avg i} = (\pi_{F C i} - \pi_{p i})$
NDP_i 2nd time	6.689	bar	$NDP_i = P_{feed i} - \frac{\Delta P_{P e i}}{2} - \Delta \pi_{avg i} - P_{perm i}$
$Q_{p 1}$ 2nd time	1.508	$\frac{m^3}{h}$	$Q_{p 1} = NDP_1 * K_w * A_e$
Difference	0.002		$Q_{p 1}$ 2nd time - $Q_{p 1}$ 1st time < 0.25 OK
$R_{e i}$	14.77	%	$R_{e i} = Q_{p i} / Q_{f i}$
$Q_{c 1}$	8.702	$\frac{m^3}{h}$	$Q_{c 1} = Q_{f 1} - Q_{p 1}$
$C_{f c 1}$	2275.28	$mg L^{-1}$	$C_{f c 1} = (C_{f 1} + C_{c 1})/2$
$P_{c 1}$	8.1	bar	$P_{c 1} = P_{f 1} - \Delta P_{e 1}$

From the 2nd to the sixth element it is summarized in Table 4.18.

Table 4.18. Specification of elements from 3rd to 6th

elements	2 nd	3 rd	4 th	5 th	6 th	units	
P_{f2}	8.1	7.9	7.7	7.5	7.3	bar	
ΔP_{ei}	0.2	0.2	0.2	0.2	0.2	bar	
Q_{f2}	8.702	7.299	6.03	5	4.1	m^3/h	
C_{f2}	2450.57	2906.7	3507.2	4305.1	5314.9	$mg L^{-1}$	
R_{ei}	13.5	16	17.7	18.5	19	%	
C_{c2}	2815.74	3439.9	4236.7	5252.58	6524.2	$mg L^{-1}$	
π_{fi}	1.705	2.03	2.45	3.01	3.72	bar	
π_{ci}	1.97	2.40	2.96	3.68	4.56	bar	
π_{FCi}	1.838	2.22	2.71	3.35	4.15	bar	
π_{pi}	0.091	0.111	0.135	0.167	0.207	bar	
$\Delta\pi_{avg i}$	1.747	2.109	2.58	3.184	3.943	bar	
NDP_i	6.253	5.691	5.02	4.216	3.257	bar	
Q_{p1}	1.410	1.28	1.12	0.95	0.81	m^3/h	
R_{ei}	16.2	17.6	18.5	18.9	19.7	%	
Check for obtained R_{ei}							
C_{ci} 2nd time	2906.7	3507.2	4305.1	5314.9	6581.07	$mg L^{-1}$	
Difference	91.02	67.3	68.49	62.8	56.87	$mg L^{-1}$	<100 OK
π_{ci} 2nd time	2.03	2.45	3	3.72	4.6	bar	
Difference	0.06	0.05	0.04	0.04	0.04	bar	<0.5 OK
π_{FCi} 2nd time	1.867	2.24	2.72	3.54	4.16	bar	
π_{pi} 2nd time	0.093	0.112	0.136	0.177	0.208	bar	
$\Delta\pi_{avg i}$ 2nd time	1.774	2.128	2.58	3.37	3.952	bar	
NDP_i 2nd time	6.226	5.672	5.02	4.03	3.248	bar	
Q_{p1} 2nd time	1.403	1.27	1.125	0.9	0.734	m^3/h	
Difference	0.006	-0.01	0.007	0.05	-0.07		<0.25 OK
R_{ei}	16.12	17.5	18.5	18.88	19.04	%	
Q_{c1}	7.299	6.03	4.91=5	4.1	3.3	m^3/h	
C_{fc1}	2678.63	3206.9	3906.15	4810	5947.9	$mg L^{-1}$	
P_{c1}	7.9	7.7	7.5	7.3	7.1	bar	

The following graphs summarize the values of Qf, Qp, Qc and recovery of the elements.

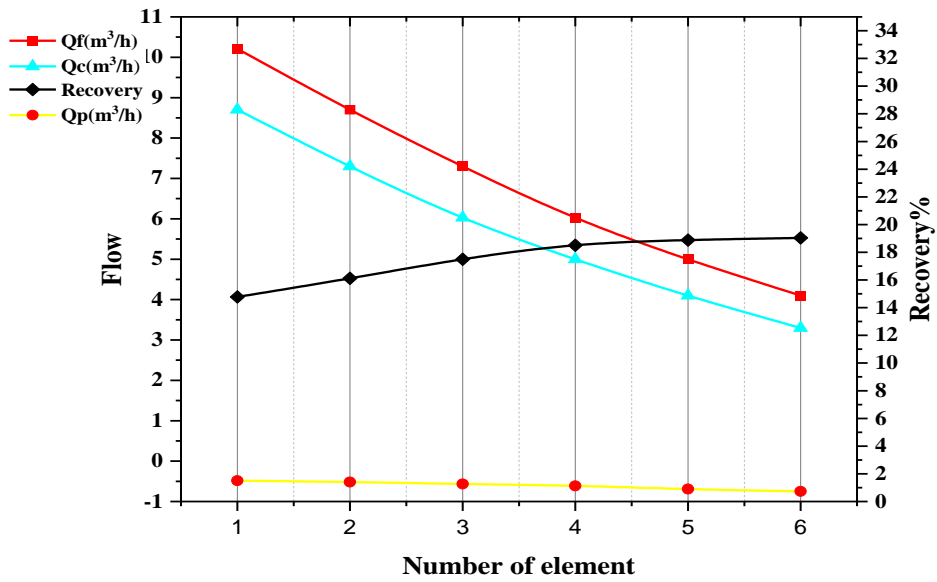


Figure 4.9. Shows flow and recovery per element along the vessel

As seen in Figure 4.9, the first element of pressure vessel can produce more permeate water than others, and the recovery and permeate flow are not stable along the vessel. Furthermore, we summarized the Pf, Pc, osmotic pressure, and NDP in the following Figure.

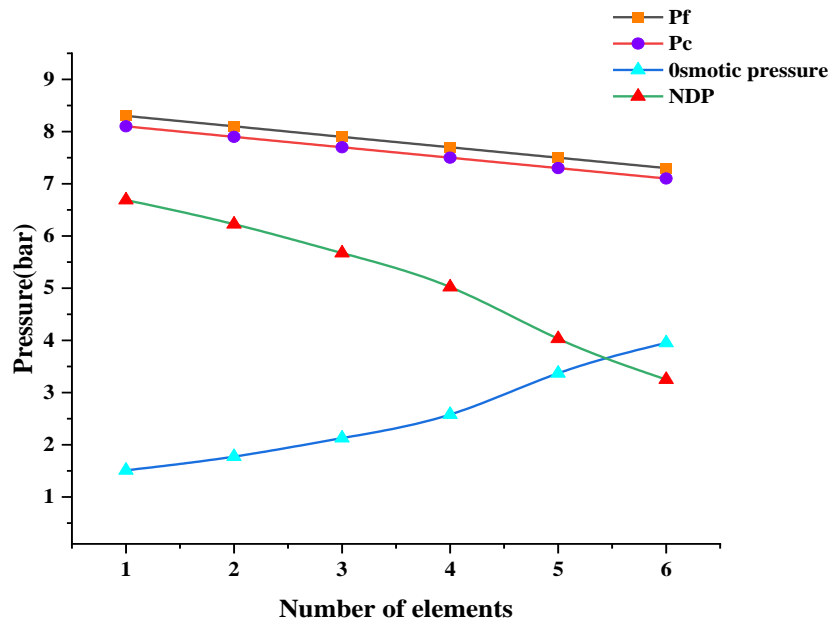


Figure 4.10. Feed, permeate, and osmotic pressure of elements along the pressure vessel

Furthermore, we can calculate the flux per each element according to founded Q_p per each element, in Figure 4.11 shows the flux per each element in a pressure vessel.

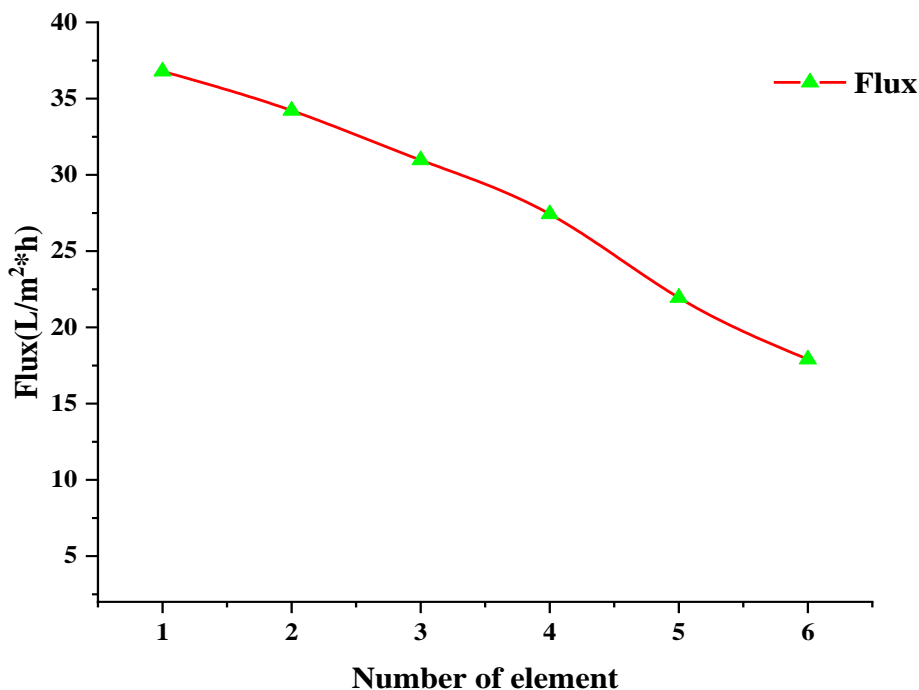


Figure 4.11. Flux for each element in a pressure vessel

As illustrated in Figure 4.11, the net driving pressure decreased along the pressure vessel, and the NDP effects on the flux per element as it can have observed that the flux for the first element is 36.78 LMH, and for the last element, the average flux is 17.9 LMH.

Step 6: Calculation of CPF for each element: it summarized in the following table.

Table 4.19. CPF for each element in the pressure vessel

Elements	1 st	2 nd	3 rd	4 th	5 th	6 th	Equation
CPF	1.108	1.119	1.130	1.138	1.141	1.142	$CPF = EXP(0.7R_i)$

For all elements, the CPF factor is less than 1.2, and all manufacturers require a CPF value less than 1.2 which is correct for the calculation.

Step 7: Calculation of permeate quality in plant

The permeate quality for RO treated water can be calculated in two ways;

A- Assuming that there are no flux effects and constant the salt rejection

B- Include the flux effects on salt rejection

For step A we follow the following steps;

- 1- Find the average feed concentrate concentration (C_{fci}) for each element (we already found it in step 5).
- 2- Calculate the permeate concentration by $C_{pi} = C_{fci} * (1 - SR)$ equation
- 3- Calculate the Q_p for each element (we found it in step 5)
- 4- Find the produced concentration for the plant

$$C_{produced} = \frac{C_{p1} * Q_{p1} + C_{p2} * Q_{p2} + C_{p3} * Q_{p3} + C_{p4} * Q_{p4} + C_{p5} * Q_{p5} + C_{p6} * Q_{p6}}{Q_{p1} + Q_{p2} + Q_{p3} + Q_{p4} + Q_{p5} + Q_{p6}} \quad (\text{Eq. 37})$$

It summarized the calculation in Table 4.20.

Table 4.20. Summary of permeate flow and concentration of each element in a pressure vessel with stable flux

Parameters	1	2	3	4	5	6	units	equation
C_{fci}	2275.28	2678.63	3206.9	3906.15	4810	5947.9	$mg L^{-1}$	$C_{fci} = (C_{f1} + C_{c1}) / 2$
C_{pi}	15.92	18.75	22.44	27.34	33.67	41.63	$mg L^{-1}$	$C_{pi} = C_{fci} * (1 - SR)$
Q_{pi}	1.508	1.403	1.27	1.125	0.9	0.734	$\frac{m^3}{h}$	$Q_{pi} = NDP_i * K_w * A_e$

$$C_{produced} = \frac{15.92 * 1.508 + 18.75 * 1.403 + 22.44 * 1.27 + 27.34 * 1.125 + 33.67 * 0.9 + 41.63 * 0.734}{1.508 + 1.403 + 1.27 + 1.125 + 0.9 + 0.734}$$

$$= \frac{170.42}{6.94} = 24.55 mg L^{-1}$$

For the calculation of permeate concentration by including the flux of membrane, we follow the following steps;

1- Find the average feed concentrate concentration C_{fci} For each element (we already found it in step 5).

2- Calculate the flux for each element of flux by $J_i = Q_{pi} / A_e$ (we found it before).

3- Find the permeate concentration for each element by involving the flux and salt permeability factor in the following equation

$$C_{p i} = \frac{C_{f c i} * K_s}{J_i} \text{ (Ks is 0.341LMH)}$$

4- Calculate the permeate concentration of the plant by the following equation

$$C_{produced} = \frac{C_{p 1} * J_1 + C_{p 2} * J_2 + C_{p 3} * J_3 + C_{p 4} * J_4 + C_{p 5} * J_5 + C_{p 6} * J_6}{J_1 + J_2 + J_3 + J_4 + J_5 + J_6} \quad \text{(Eq. 38)}$$

We summarized the calculation in Table 4.21.

Table 4.21. Summary of permeate concentration with flux

Parameters	1	2	3	4	5	6	Units	Equations
$C_{f c i}$	2275.28	2678.63	3206.9	3906.15	4810	5947.9	$mg L^{-1}$	$C_{f c 1} = (C_{f 1} + C_{c 1})/2$
J_i	36.78	33.21	30.97	27.43	21.95	17.9	$\frac{L}{m^2 * h}$	$J_i = \frac{Q_{p i}}{A_e}$
$C_{p i}$	21.09	27.50	35.31	48.55	74.72	113.3	$mg L^{-1}$	$C_{p i} = \frac{C_{f c i} * K_s}{J_i}$

We have;

$$C_{produced} = \frac{21.09 * 36.78 + 27.5 * 33.21 + 35.31 * 30.97 + 48.55 * 27.43 + 74.72 * 21.95 + 113.3 * 17.9}{36.78 + 33.21 + 30.97 + 27.43 + 21.95 + 17.9}$$

$$= \frac{7782.41}{168.24} = 46.25 mg L^{-1}$$

It summarized the calculation for Cp, Cc, and Cf for each element in Figure 4.12.

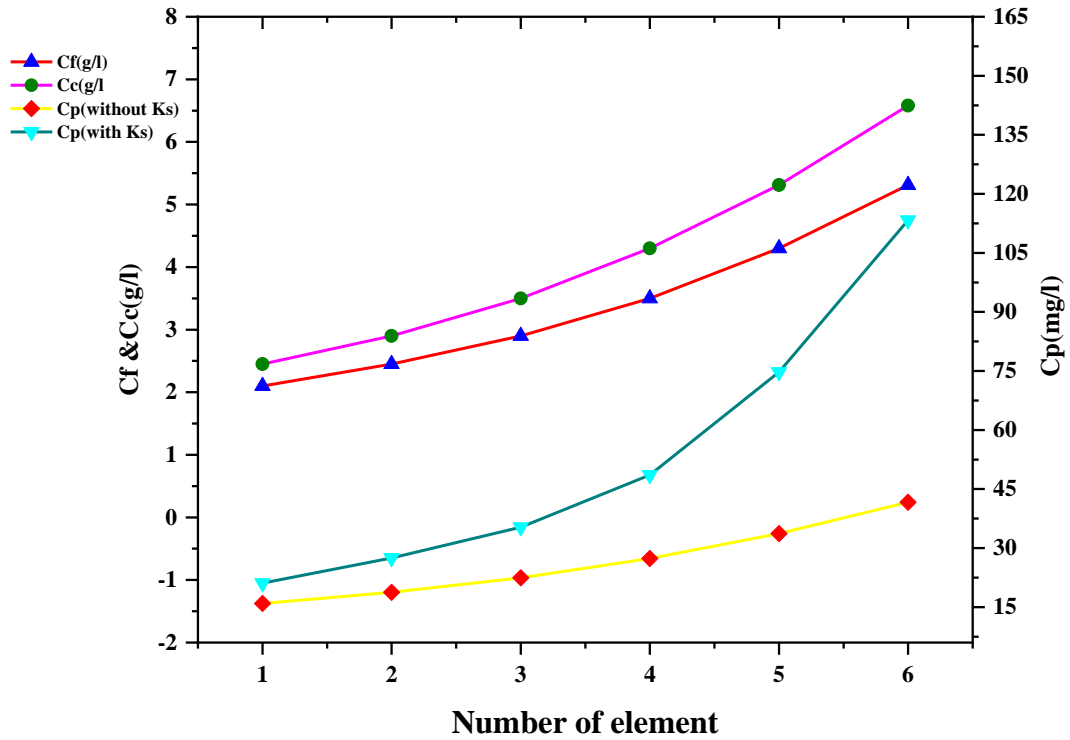


Figure 4.12. Feed permeate and concentrate concentration of each element with flux

Feed concentration, concentrate concentration, permeate concentration considering constant salt rejection and include flux effects on permeate per element on the pressure vessel. As we can see, the salinity of the permeate water along the elements increases because of flux that decreases in elements along the vessel. The salinity in the feed or concentrate flow increases by increasing recovery.

Step 8: Calculation of cross-flow velocity (CFV)

For the calculation of cross-flow velocity along the elements in the pressure vessel, we need the area of the element, length, height of the feed spacer, and porosity factor for the feed spacer, which is summarized in Table 4.22.

Table 4.22. Element factors for CFV

Membrane type	SW30 HRLE 440i	
Area of element	41m ²	
Length of RO membrane element	1m	
Height of feed spacer	0.00071 m	Source ESS
Porosity factor for feed spacer ϵ	0.8-0.85	Vrouwenvelder, 2009

For the calculation of cross-flow velocity, we follow the following steps.

1- Find the average feed concentrate flow in each element by $Q_{fci} = (Q_{fi} + Q_{ci})/2$ equation.

2- Find the total spacer width by $W = \frac{A_e}{L_e/2}$ equation.

3- Calculate the effective area for feed spacer by $A_{effective} = \epsilon * h_{spacer} * W$ equation

4- Find the cross-flow velocity for each element by $V_{fci} = Q_{fci} / A_{effective}$

All the calculation for cross-flow velocity is summarized in Table 4.23.

Table 4.23. Cross-flow velocity for each element of the pressure vessel.

Factors	1	2	3	4	5	6	Units	Equation
Q_{fci}	9.45	8	6.664	5.515	4.55	3.7	$\frac{m^3}{h}$	$Q_{fci} = (Q_{fi} + Q_{ci})/2$
W	20.4	20.4	20.4	20.4	20.4	20.4	m	$W = \frac{A_e}{L_e/2}$
$A_{effective}$	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	M ²	$A_{effective} = \epsilon * h_{spacer} * W$
V_{fci}	768.29	650.40	541.78	448.37	369.91	300.81	m/h	$V_{fci} = Q_{fci} / A_{effective}$
	0.213	0.18	0.15	0.12	0.102	0.083	m/sec	

Figure 4.13 indicated better the CFV of each membrane in a pressure vessel.

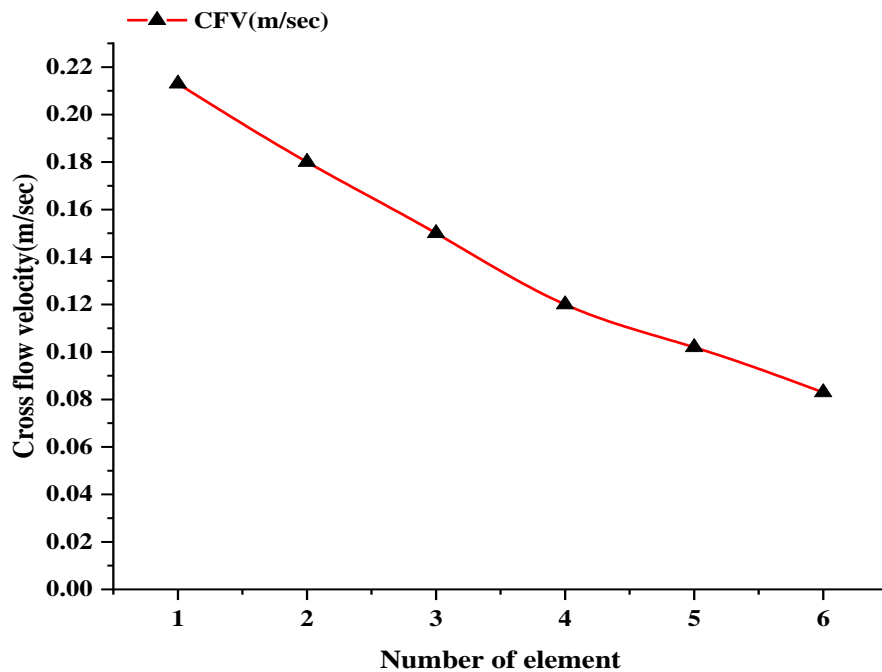


Figure 4.13. CFV for pressure vessel

As shown in Figure 4.13, the cross-flow velocity for all elements is between 0.2 to 0.1 which is considered normal in RO system installation (Salinas-Rodríguez et al., 2021). To keep the CFV constant, the feed pressure must be increased over the extra resistance due to membrane fouling.

Step 9: Calculation of energy consumption for RO system

We summarized the calculation for energy consumption in Table 4.24.

Table 4.24. Energy consumption for 1m³ of water for single-stage RO

Parameters	Values	Units	Remarks
	0.0275	Kwh/ m^3	The energy required to raise the pressure of 1 m ³ water to 1 bar
P_{feed}	8.3	bar	Feed pressure of RO system
N_{pump}	0.80		The efficiency of a pump with a driver (45)
TDS	1200	Mg/l	Total dissolved solid of feed water
R	80	%	Recovery of plant
E	0.35	Kwh/ m^3	The energy required for 1 m ³ of water without ERD devices

As it can see that 0.35 Kwh energy is required to pump 1m³ of feed water to RO system, furthermore we can calculate the daily need of energy for the total RO plant as follows;

a- Energy consumption for single-stage RO system with 80 % recovery and more than 50 % of concentrate water recycle;

Plant capacity per day $90000 \frac{m^3}{day}$

Plant capacity for 1 hour $3750 \frac{m^3}{h}$ $Q_{p \text{ per } h} = \frac{Q_{feed \text{ plant}}}{24h}$

$$energy \text{ for } 1h \text{ of plant} = 3750 \frac{m^3}{h} * 0.35 \frac{Kwh}{m^3} = 1312.5 \cong 1313Kwh$$

As we can see, 2020 KWh energy is required for one hour in the RO system, and for one day, the energy required is;

$$energy \text{ for } 1 \text{ day of plant} = \frac{1313Kwh}{h} * \frac{24 \text{ h}}{1 \text{ day}} = 31512 \frac{Kwh}{day}$$

b- Two-stage RO system energy calculation

If we install a two-stage RO system, then the energy required for the system can be calculated as follow;

As we discussed, 2/3 of recovery is related to the first stage, and 1/3 of %R is done by the second stage, so we have for E;

Table 4.25. Energy consumption for two stages RO system

Parameters	Values	Units	Remarks
For the first stage			
	0.0275	Kwh/ m ³	The energy required to raise the pressure of 1 m ³ water to 1 bar
<i>P_{feed 1st stage}</i>	7.1	bar	Feed pressure of RO system
<i>P_{feed 2nd stage}</i>	5.9	bar	Feed pressure of RO system
<i>N_{pump}</i>	0.80		The efficiency of a pump with a driver

TDS	1200	mg/l	Total dissolved solid of feed water
R	80	%	Of Recovery of total plant
E	0.3	Kwh/ m^3	The energy required for 1 m3 of water without ERD devices
For 2nd stage			
R	80	%	Of total plant recovery
E	0.263	Kwh/ m^3	
E average	0.289	Kwh/ m^3	
Q_f Feed flow for 1st stage		$90000 \frac{m^3}{day}$	$Q_f = \frac{Q_P}{R}$
Q_f For 1 hour at 1st stage		$3750 \frac{m^3}{h}$	

$$energy\ for\ 1h\ of\ plant = 3750 \frac{m^3}{h} * 0.289 \frac{Kwh}{m^3} = 1083.75 \cong 1084Kwh$$

As we can see, for the whole plant, the required energy for one hour is 1358Kwh, and for one day, the energy required is;

$$energy\ for\ 1\ day\ of\ plant = \frac{1084Kwh}{h} * \frac{24\ h}{1\ day} = 26016 \frac{Kwh}{day}$$

4.2. Design and simulation of UF-RO system by WAVE software

4.2.1. Design and Simulation of UF pretreatment unit by WAVE

In the UF pretreatment system, WAVE has the ability to calculate the number of the filter elements for the required feed water by the RO system. It can adjust in desired trains, and it can select different types of membrane filters for the pretreatment purpose. For the UF system, it was selected the Integra Flux™ SFD-2880XP membrane which has a big surface area (77 m²), and the design flux range for the selected membrane is 40- 110 LMH. WAVE gives choices for the distribution of membrane elements in trains. For the present study, it has been chosen 10 trains, and in each train, 110 membranes are located. Two of these online trains are selected as offline trains for CEB and CIP, which were discussed in the UF system design section earlier.

Table 4.26. Recommend trains number for UF by WAVE

Recommended configuration for the trains							
Online trains	Standby trains	Total trains	Maximum offline trains (for CEB and CIP)	Models/skids	Models/trains	Online models	Total models
10	0	10	2	-	110	1100	1100

Furthermore, it can be selected as the storage tank for filtered water of RO system in WAVE software and as the storage tank for backwash and filtrate water. WAVE summarized the calculation and selection of the UF membrane for the feed water. Table 4.27 shows the number of specifications and details of the UF membrane elements.

Table 4.27. Details of UF membrane models by WAVE

Name: IntegraFlux SFD-2880XP		
Membrane Area	77	m ²
Length	2.360	m
Diameter	0.225	m
Weight (empty)	61	kg
Weight (water filled)	100	kg
Water Volume	39.0	L

Table 4.27 indicates the area, length, diameter, and weight of UF membrane elements without water and with water and the capacity of the membrane (volume of water which can pass in UF membrane housing). The summary of the UF system design as a pretreatment for Kirikkale drinking water treatment by WAVE software is shown in Figure 4.14 and Table 4.28.

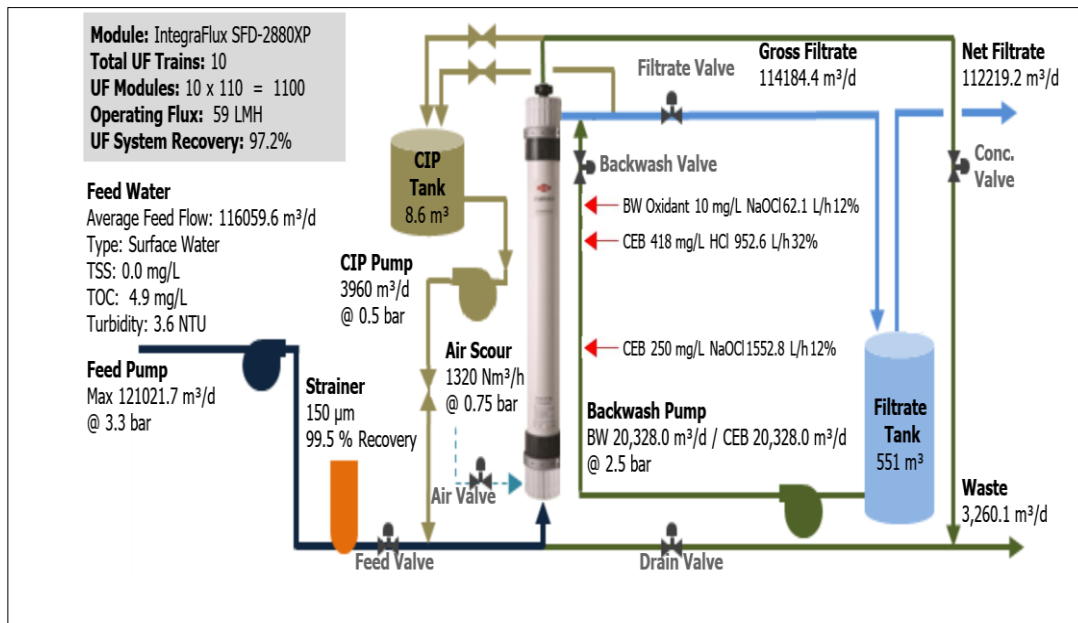


Figure 4.14. Summary of UF system design by WAVE

Table 4.28. Summary of UF design flow and elements

Module Type		IntegraFlux SFD-2880XP			
# Trains		Online =	10	Standby =	0
				Redundant =	0
# Modules		Per Train =	110	Total =	1100
System Flow Rate	(m ³ /d)	Gross Feed =	116476.7	Net Product =	112288.8
Train Flow Rate	(m ³ /d)	Gross Feed =	11647.7	Net Product =	11228.9
UF System Recovery	(%)	96.89			
TMP	(bar)	0.50 @ 10.0 °C		0.34 @ 25.0 °C	
Utility Water		Forward	Pretreated	Backwash:	UF filtrate water
		Flush:	water		
		CEB Water	UF filtrate	CIP Water	UF filtrate water
		Source:	water	Source:	

In Figure 4.14, we can see the overall UF system, which was designed by WAVE software. The system includes the UF elements in trains, backwash for elements and specifications, CEB for UF system, CIP for UF system, and tanks for filtered water storage and CIP. In addition, WAVE calculated TMP for the system in low and high temperatures

as TMP at 10 °C is 0.5 bar, and for 25 °C it was 0.34 bar. The system is designed to have 10 online trains; each train filters 11228.9 m³/day and the volume of filtered water for the RO system is 112288.8 m³/day. All the designed parts will be discussed briefly in the upcoming sections. Figure 4.15 shows the general view of the UF system with storage tank and RO membranes.

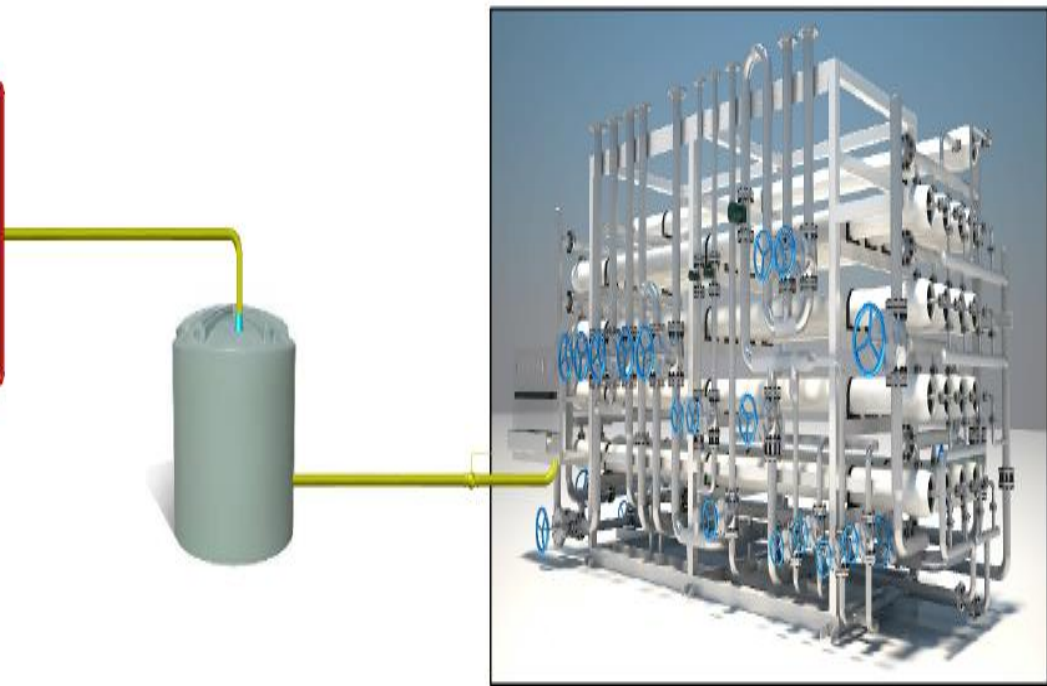
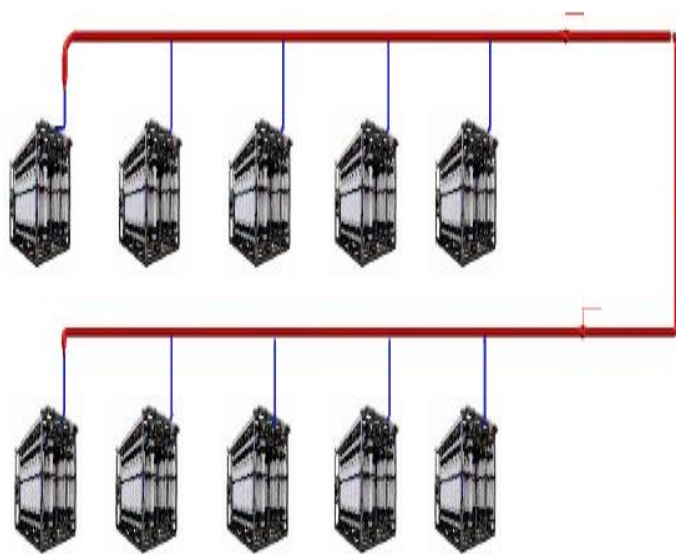


Figure 4.15 shows the UF RO system schematic 3D

4.2.1.1. Calculation of UF membrane backwash by WAVE

WAVE software can calculate the backwash time and duration of air scour, top backwash, and forward flush for the UF membrane system, and it can select the oxidant for the backwash if needed. As it can be seen in Table 4.29, the overall duration of BW for UF membranes is 2.1 minutes which 30 seconds take air scour, 30 seconds take top backwash, and 35 seconds are related to forward flush, as we discussed before the first air scour done automatically for 30 seconds to remove particulate from the membrane elements and then top BW for 30 seconds after that second BW will apply to remove backwashed water from the element housing and at the end forward flash will apply to continue the flow throughout the filter elements. The interval for BW has estimated 52.1 minutes, which means that BW must apply once an hour for UF filter membranes to stabilize the TMP and design flux in the process. Table 4.29 shows the operating condition of the UF system.

Table 4.29. Operating conditions for the UF system given by WAVE

	Duration	Interval	Flux/Flow
Filtration:	50.0 min	52.1 min	-
Instantaneous			
10 Online Trains			60 LMH
10 Total Trains			60 LMH
Average			55 LMH
Net			54 LMH
Backwash	2.1 min	52.1 min	100 LMH

As can see from Table 4.29, the filtration duration for the UF system is 50 minutes. After the first filtration, BW will apply automatically for 2.1 minutes, and then the filtration process will normally revise again. In addition, WAVE selected design flux for the process as 60 LMH for each element, and the average design flux is 55 LMH for all processes. During BW and CEB process, the average flux for the system increases up to 100 LMH for the enhanced cleaning of the membrane surface and element housing purposes.

4.2.1.2. Calculation of CEB for UF system by WAVE

When the BW is not enough to clean the UF membranes, a chemical-enhanced backwash will apply to UF membranes. In the present study, WAVE calculated the type, time, and interval of CEB for the UF system. Table 5.6 shows the details of CEB calculation for the UF system.

Table 4.30. The operation condition of CEB for the UF system by WAVE

Types of CEB	Duration	Interval	Flux/Flow
Acid CEB	14.3 min	36 h	100 LMH
Alkali CEB	14.3 min	12 h	100 LMH

As indicated in Table 4.30, WAVE separately calculated the acid and alkali CEB for the UF system. The time for CEB depends on the feed water characteristic and parameters. The duration for acid CEB is 14.3 minutes in 36-hour intervals, which shows that after 36 hours, the elements must be backwashed with acids, and the solution of acids must remain in the filter housing to reach all parts of the UF membrane element and react with microorganisms which are located on the surface of the filter elements. In addition, the alkali CEB must apply to the UF system after 12 hours for 14.3 minutes, shocking elements in the alkali, and then backwashed with filtered water and ran the regular operation of UF filtration again. Furthermore, WAVE calculated the dose of the chemicals for CEB and the storage duration and tanks for these chemicals (see chemical calculation section). The average design flux for CEB is estimated at 100 LMH during the operation.

4.2.1.3. Calculation of CIP for UF system by WAVE

BW and CEB cannot remove all contaminants from the surface of the UF filter membrane; therefore, a clean-in-place is needed for the UF process. WAVE can calculate the duration and interval of CIP according to the feed water characteristics as Table 4.31 shows the CIP operation condition for the UF system by WAVE.

Table 4.31. CIP operation condition for UF system given by WAVE

Operation	Duration	Interval	Flux/Flow
CIP	306.3 min	90 d	36.00 m ³ /d

In the present study, the CIP is carried out every 90 days, the duration of the CIP process is 306.3 minutes, and the flow for CIP is 36m³/day. The CIP solution pumps from the CIP tank to the system and cleans the system to keep the TMP and flux at desired value for the operation. The temperature for the CIP process is 35 °C to clean and remove all contaminants from the filter surface and UF element housing.

4.2.1.4. Filtered water quality by UF system in WAVE

The main purpose of the UF system as a pretreatment is to remove particulates, organics, and turbidity and reduce the SDI to less than 2.5 for the RO system. WAVE gave the filtered water quality suitable for RO system feed. Table 4.32 shows the filtered water quality given by WAVE.

Table 4.32. UF filtered water quality given by WAVE

Stream Name		Kirikkale UF-RO system	
Water Type		Surface Water (10.0 - 40.0 °C)	
		Feed	Expected UF Product Water Quality
Temperature	(°C)	25.0	25.0
Turbidity	(NTU)	3.6	≤ 0.1
TSS	(mg/L)	1.5	-
Organics (TOC)	(mg/L TOC)	4.8	4.4
SDI ₁₅		5.0	≤ 2.5
TDS	(mg/L)	1180	1180
pH		8.1	8.1

As can see from Table 4.32, the expected water quality of filtered water is desirable for the RO feed water. The UF membranes decreased the SDI from 5 to 2.5 and removed all suspended solids and organics.

4.2.1.5. Determine of flow for the UF system by WAVE

Determination of feed flow, filtrate flow, flow for BW, CEB water flow, and CIP flow during the UF system operation is an essential factor of the UF system design. WAVE can determine the desired flow for each UF operation system and also can predict the maximum flow for these operating conditions.

Table 4.33. Flow for all operations in the UF system given by WAVE

Stream		Maximum Flow ^a	Average Flow
Feed (Gross)	(m ³ /d)	135554.7	116545.6
Feed Water Used for	(m ³ /d)		
Pretreatment	(m ³ /d)		582.7
Forward Flush and Process Streams	(m ³ /d)		1292.2
Feed (Net)	(m ³ /d)	123388.9	114670.6
Filtrate (Gross)	(m ³ /d)	123388.9	114670.6
Filtrate Used for Cleaning	(m ³ /d)		2381.8
Filtrate (Net)	(m ³ /d)		112288.8
Air	(N m ³ /h)	2688.0	3282.0
Backwash (BW)	(m ³ /d)	41395.2	1925.8
Forward Flush Flowrate	(m ³ /d)	23826.9	1292.2
CEB 1 (Acid)	(m ³ /d)	41395.2	112.6
CEB 2 (Alkali and/or Oxidant)	(m ³ /d)	41395.2	341.6
CIP Recycle	(m ³ /d)	4032.0	1.9

As it can be seen in Table 4.33, WAVE calculated flow for all operating conditions such as average net flow for UF system is estimated as 116545.6 m³/day which 582.7 m³/day of this water flow is as a pretreatment for the system, 1292.2 m³/day is consumed for forward flush operation, 2381.8 m³/day is used for cleaning purposes and 112288.8 m³/day is filtered and flow to the storage tank and become as feed flow for RO system. In addition, WAVE gives the average airflow for the air scour in the cleaning process as 3282 N m²/h is needed for the UF system during BW, CEB, and CIP operation processes. Furthermore, WAVE calculated the pump specification during the different operation processes. The maximum flow rate for pumps during different operation processes can be seen in Table 4.34.

Table 4.34. Pump specification for operation processes of UF

BW NaOCl(12%) Metering Pump	(L/h)	126.5	
CEB HCl (32%) Metering Pump	(L/h)	2212.4	
CEB NaOCl(12%) Metering Pump	(L/h)	3162.0	
CIP HCl (32%) Metering Pump	(L/h)	215.5	
CIP Citric Acid(100%) Metering Pump	(L/h)	2018.0	
CIP NaOH (50%) Metering Pump	(L/h)	144.7	
CIP NaOCl(12%) Metering Pump	(L/h)	2463.9	

4.2.1.6. Calculation of electricity, pressure, and costs for UF system by WAVE

in the simulation of the present study by WAVE, the software calculated the pressure during different operations, such as the pressure for feed flow is 1.33 bar, pressure for backwash and CEB operation is 1.06 bar, pressure for CIP operation is 0.5 bar, and pressure for air compressor is 0.75 bar. In addition, WAVE calculated the energy consumption for UF system operations as the energy consumption for each operation and the total energy consumption for all UF systems. Total energy consumption for the UF system as a pretreatment is 6193.11 KWh/day.

Furthermore, WAVE calculated the energy cost for the energy consumption, but for this calculation, it needs to put the cost for 1 Kwh energy price in the plant area. The 1 KWh energy cost in turkey for May of 2022 is about 1.89 Turkish lira; therefore, the overall energy cost for the UF system for one day is near 11702.49 Turkish Lira. The calculation for electric, pressure, and energy costs is summarized in Table 4.35.

Table 4.35. electric, pressure, and energy calculation for the UF system by WAVE

Pump	Peak Flowrate	Average Pressure	Mechanical Power	Electrical Power	Energy	Cost
	(m³/d)	(bar)	(kW)	(kW)	(kWh/d)	(£/d)
Feed	135,554.68	1.33	179.51	243.90	5,853.57	11,060.90
Backwash	41,395.20	1.06	50.56	68.69	153.39	289.84
NaOCl(12%) Metering Pump	3.04		0.00	0.01		
CEB	41,395.20	1.06	50.56	68.69	18.09	34.18
HCl (32%) Metering Pump	53.10		0.08	0.10		
NaOCl(12%) Metering Pump	75.89		0.11	0.14		
CIP	4,032.00	0.50	2.33	3.17	0.67	1.27
HCl (32%) Metering Pump	5.17		0.00	0.00		
Citric Acid(100%) Metering Pump	48.43		0.05	0.06		
NaOH (50%) Metering Pump	3.47		0.00	0.00		
NaOCl(12%) Metering Pump	59.13		0.04	0.05		
CIP Solution Heating				101.12	21.48	40.59
Air Compressor	64,512.00	0.75	45.91	99.81	121.86	230.27
Electrical Valves				0.00	0.00	0.00
PLC and Instrumentation				1.00	24.00	45.35
Total Electrical Cost					6,193.11	11,702.49

4.2.1.7. Comparison of operation pressure to maximum operation rating

One of the positive points in designing the UF system by WAVE software is to compare the operation condition with the maximum operation rating, which is given for membrane elements by the manufacturer.

For the present study, WAVE compares the feed pressure for different operation conditions, TMP, filtrate pressure, and pressure drop, to suggested operating conditions for the selected element. Furthermore, WAVE calculated feed pressure in minimum, design, and maximum temperature for the UF system. Table 4.36 shows the comparison of different conditions to the suggested operating conditions.

Table 4.36. Comparison of different operating conditions to suggested conditions from manufacturer

Process	T	TMP ^a	Fouling Max ΔP	Piping ΔP	Filtrate Pres.	Feed Pres. ^b	Pres. Rating	OK? ^c
	(°C)	(bar)	(bar)	(bar)	(bar)	(bar)	(bar)	
Filtration								
Minimum Temp.	10.0	0.49	0.00	0.73	0.50	1.72	6.25	√
Design Temp.	25.0	0.33	0.00	0.50	0.50	1.33	6.00	√
Maximum Temp.	40.0	0.24	0.00	0.37	0.50	1.11	4.75	√
BW	25.0	0.56	0.00	0.50		1.06	6.00	√
CEB	25.0	0.56	0.00	0.50		1.06	6.00	√
CIP	35.0			0.50		0.50	5.25	√

As shown in Table 4.36, the operation condition for the UF system is less than the DOW manufacturer's suggested condition for the UF filter element, so the system is running well. In addition, it can see that feed pressure changed in different operating temperatures. Figure 4.16 shows the difference in feed pressure in minimum, design, and maximum temperature.

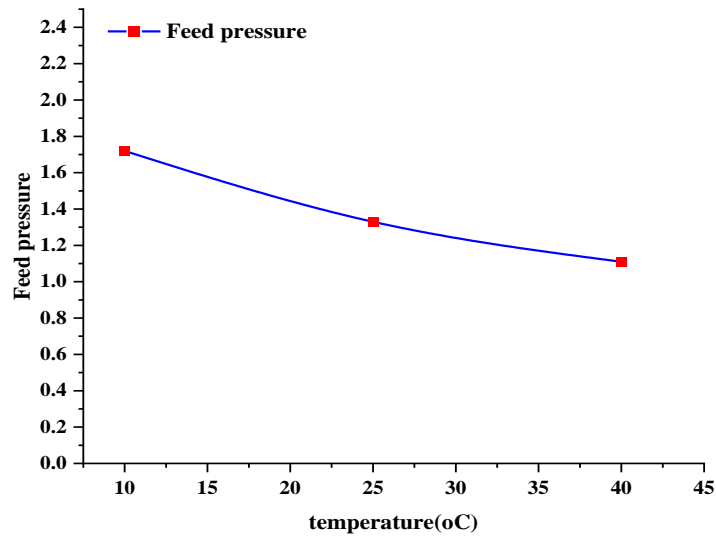


Figure 4.16. Difference of feed pressure in low and high temperature

As discussed before, temperature is a key factor for the UF-RO system and affects the design flux and feed pressure. Water viscosity increases with decreasing feed water temperature, and this water viscosity affects the membrane performance to produce filtered water. More pressure is needed to pass cold water through the membrane surface; therefore, at low temperatures, feed pressure increases (Voutchkov, 2017). As shown in Figure 4.16, feed pressure increased at low temperature, but at high temperature, feed pressure decreased because of more salinity in high temperature.

4.2.1.8. Design of UF storage tanks

WAVE estimated they required storage tanks for filtered water, CIP operation, and the storage of different chemicals. As shown in table 5.13, filtered water needs a tank with 422 m³ volume capacity. For CIP operation tank with an 8.7 m³ capacity is needed. Furthermore, for storage of citric acid 0.33 m³, Hydrochloric Acid (HCl) 4.4 m³, Sodium Hypochlorite (NaOCl) 23 m³, and Sodium Hydroxide (NaOH) 0.024 m³ storage tanks are needed. The storage time of chemicals is estimated at about 30 days.

Table 4.37. UF storage tanks details

Name	Bulk Concentration	Minimum Recommended Volume
	(%)	(m ³)
Water ^a		422
CIP Tank		8.7
Chemical Storage ^b		
Citric Acid (C ₆ H ₈ O ₇)	100%	0.33
Hydrochloric Acid (HCl)	32%	4.4
Sodium Hypochlorite (NaOCl)	12%	23.0
Sodium Hydroxide (NaOH)	50%	0.024

4.2.1.9. Description of filtration, backwash, CEB, and CIP modes and parameters for the UF system

WAVE describes all operation modes for the UF system in detail and shows the time, flow rate, and steps for each operation condition to run the UF model correctly. Table 4.38 shows the filter and backwash mode operations for the UF system.

Table 4.38. Filter and backwash mode operation is given by WAVE

Normal Operation	Process Mode of Operation	Operation		Backwash (B/W)					Return to	Stop ^c
		1	2	3	4	5	6	7	2	-
Operating Steps	Steps	Forward Flush at Start-up ^b	Filtration Mode	Air Inlet ^c	Drain	Backwash 1	Backwash 2	Forward Flush (FF)	Filtration Mode	Stop
	Feed Pump	o	o					o	o	
	Backwash Pump					o	o			
	Chem. Dosing Pump ^a					o	o			
	CEB Dosing Pump									
	CIP Recycle Pump									
	Feed Valve	o	o					o	o	
Pump and Valve Conditions	Filtrate Valve		o						o	
	Conc. Valve	o		o	o	o		o		
	Backwash Inlet Valve					o	o			
	Drain Valve				o		o			
	Air Inlet Valve			o						
	Duration	~2.0-3.0 min.	50.0 min.	30 s	0 s	30 s	0 s	35 s	50.0 min.	
	Flow Rate	106.4 m ³ /d	60 LMH	12.0 N m ³ /h	By gravity	100 LMH	100 LMH	106.4 m ³ /d	60 LMH	
Remarks	1. The filtration mode follows Steps 2-3-4-5-6-7-8. Backwash can be repeated several times according to the fouling degree of UF membrane modules. 2. The valve opening and closing time for each process step should be considered when programming is designed.									

	3. "o" = valve or pump is opened or operating.
Footnotes	<p>^a Use of chemical dosing pump during backwash is based on feed water source and quality. Refer to DuPont UF Design Guidelines.</p> <p>^b Forward flush flow rate displayed on a per-module basis.</p> <p>^c Use of air scour, and frequency is based on feed water source and quality. The airflow rate is displayed on per-module basis.</p> <p>^d May need to waste a portion of permeate to remove residual chemicals, depending on design and application.</p> <p>^e If taken out of operation, add preservative and close all valves. Stop should occur only after backwash.</p>

As seen in Table 4.38, the filtration mode follows 2, 3, 4, 5, 6, 7, and 8 steps for 52 minutes. After that, backwash mode must apply for 2.1 minutes, and the filtration will continue for the second time as the first time.

At the end of this table, WAVE gave some remarks and footnotes for running the modes.

Table 4.39. CEB operation mode steps given by WAVE

		1	2	3	4	5	6	7	8	9	10	11	1
Operating Steps	Steps	Filtration Mode	Air Inlet ^b	Drain	Backwash 1	Backwash 2	Soak	Air Inlet ^b	Drain	Backwash 1	Backwash 2	Forward Flush (FF) ^c	Filtration Mode
	Feed Pump	o										o	o
	Backwash Pump				o	o				o	o		
	CEB Dosing Pump ^a				o	o							
	Feed Valve	o										o	o
Pump and Valve Conditions	Filtrate Valve	o											o
	Conc. Valve		o	o	o			o	o	o		o	
	Backwash Inlet Valve				o	o				o	o		
	Drain Valve			o		o			o		o		
	Air Inlet Valve		o					o					
	Duration	50.0 min.	30 s	0 s	30 s	45 s	10.0 min.	30 s	0 s	30 s	0 s	35 s	50.0 min.
	Flow Rate	60 LMH	12.0 N m ³ /h	By gravity	100 LMH	100 LMH	0.0 m ³ /d	12.0 N m ³ /h	By gravity	100 LMH	100 LMH	106.4 m ³ /d	60 LMH
Remarks	1. Frequency of CEB is based on feed water source and quality. Refer to DuPont UF Design Guidelines. 2. For a CEB, follow Steps 2-3-4-5-6-7-8-9-10-11.												

	3. "o" = valve or pump is opened or operating.
Footnotes	<p>^a Chemicals and concentrations used during CEB are based on feed water source and quality. Refer to DuPont UF Design Guidelines.</p> <p>^b Air flow rate displayed on per-module basis.</p> <p>^c Forward flush flow rate displayed on per-module basis.</p> <p>^d May need to waste a portion of permeate to remove residual chemicals, depending on design and application.</p>

Table 4.40. Operation mode and steps for CIP operation condition given by WAVE

CIP	CIP Mode of Operation	Operation	Backwash (B/W) ^b				CIP ^c				Backwash (B/W) ^b				Return to Operation ^e
			1	2	3	4	5	6	7	8	9	10	11	12	
	Steps	Filtration Mode	Air Inlet ^a	Drain	Backwash 1	Backwash 2	Drain	CIP Recycle ^d	Soak ^e	CIP Recycle ^d	Drain	Backwash 1	Backwash 2	Forward Flush (FF) ^f	Filtration Mode
	Feed Pump	o												o	o
	Backwash Pump				o	o						o	o		
	Chem. Dosing Pump														
	CEB Dosing Pump														
	CIP Recycle Pump							o		o					
	Feed Valve	o												o	o
Pump and Valve Conditions	Filtrate Valve	o													o
	Conc. Valve		o	o	o		o		o		o	o		o	
	Backwash Inlet Valve				o	o						o	o		
	Drain Valve			o		o	o				o		o		
	Air Inlet Valve		o												
	Duration	50.0 min.	30 s	0 s	30 s	0 s	0 s	30.0 min.	90.0 min.	30.0 min.	0 s	30 s	0 s	35 s	50.0 min.
	Flow Rate	60 LMH	12.0 N m ³ /h	By gravity	100 LMH	100 LMH	By gravity	36.0 m ³ /d	0.0 m ³ /d	36.0 m ³ /d	By gravity	100 LMH	100 LMH	106.4 m ³ /d	60 LMH

	1. Frequency of CIP is 1-3 months, adjusted according to operating conditions.
	2. Start CIP with backwash sequence; complete CIP with backwash sequence.
Remarks	3. CIP is done manually.
	4. "o" = valve or pump is opened or operating.
	^a Air flow rate displayed on per-module basis.
	^b This step should be repeated 2 times.
	^c This step and duration are shown for a single chemical cleaning. If acid and base cleaning are both required, repeat Steps 6-13.
Footnotes	^d CIP recycles the flow rate displayed on a per-module basis.
	^e The duration of this step might be longer, up to overnight (12 hours), if the fouling is severe.
	^f Forward flush flow rate displayed on per-module basis.
	^g May need to waste a portion of permeate to remove residual chemicals, depending on design and application.

4.2.1.10. Electricity and chemical cost calculation for UF system

As discussed before, WAVE software has the cost calculation section but needs to put local chemicals and electricity costs, and then the WAVE gives the total chemical cost for the UF system. Tables 4.41 and 4.42 summarize the cost of electricity and chemicals which consume during operations.

Table 4.41. Electricity cost for UF system given by WAVE

Peak Power	(kW)	527.32
Energy	(kWh/d)	6,193.11
Electricity Unit Cost	(₺/kWh)	1.8900
Electricity Cost	(₺/d)	11,702.49
Specific Energy	(kWh/m ³)	0.06

As illustrated in Table 4.41, the total cost for required energy is about 11702.49 Turkish Lira, and the cost for 1 m³ of filtered water is about 0.06 Turkish lira.

Table 4.42. Chemical cost for UF system given by WAVE

Chemical	Unit Cost	Dose 100%	Volume	Cost
	(₹/kg)	(mg/L)	(L/d)	(₹/d)
Citric Acid (100%)	100.000		11.1	1855.71
CIP		20000		
HCl (32%)	52.000		145.6	8785.98
CEB1		476		
CIP		476		
NaOCl (12%)	30.000		767.5	26165.20
BW		10		
CEB2		250		
CIP		2000		
NaOH (50%)	90.000		0.8	109.62
CIP		656		
Total Chemical Cost				36,916.51

Table 4.42 indicates the total cost of chemicals used in the UF operation system. (cost of chemicals is taken from the internet, and it may change over time) The total cost for plant operation and chemicals are listed in Table 4.43.

Table 4.43. Operation cost for the UF plant

Utility and Chemical Cost	(₹/d)	53,661.92
Specific Water Cost	(₹/m ³)	0.478

Note: that these values are approximate values for the 1 m³ of filtered water. It may change due to changes in energy consumption and rate and chemicals costs in the local market.

4.2.2. RO System Design by WAVE

The present study used the water application value engine (WAVE) software package to calculate the RO system for the surface water in Kirikkale city of Turkiye. As discussed, WAVE modeling software is a comprehensive platform among other modeling software (Toth, 2020). Although WAVE software's calculation method is not published, some papers discussed its RO system analysis details with 95% accuracy (Nagy et al., 2019; Toth, 2020). In the 4th chapter of the present study, we manually discussed the RO system design. This section expects to evaluate and simulate a RO system for the mentioned surface water by WAVE modeling software and apply different scenarios to find the economic layout of the RO system design. Following it will discuss three different layouts for RO system design by WAVE.

4.2.3. Design of single-stage RO system with concentrate recycle by WAVE

As mentioned in the 4th chapter, the RO system was designed by hand as a single-stage RO system with a recovery of more than 65% not possible, but if the concentrate water is recycled to feed the water of the Ro system, water can recover up 80 %. WAVE software has this option by which it can design a single-stage RO system with recycled water with up to 80 % recovery. The filtered water which comes from the UF pretreatment system is introduced to the RO system. In the WAVE RO system, the design water temperature, flow factor, number of stages, selection of elements for system, average design flux for the system, concentrate percentage of water and type of membrane element can be selected. As we calculated by hand for a single stage with concentrated water recycling, we will apply the same parameters to simulate the design. It must introduce the following parameters to WAVE.

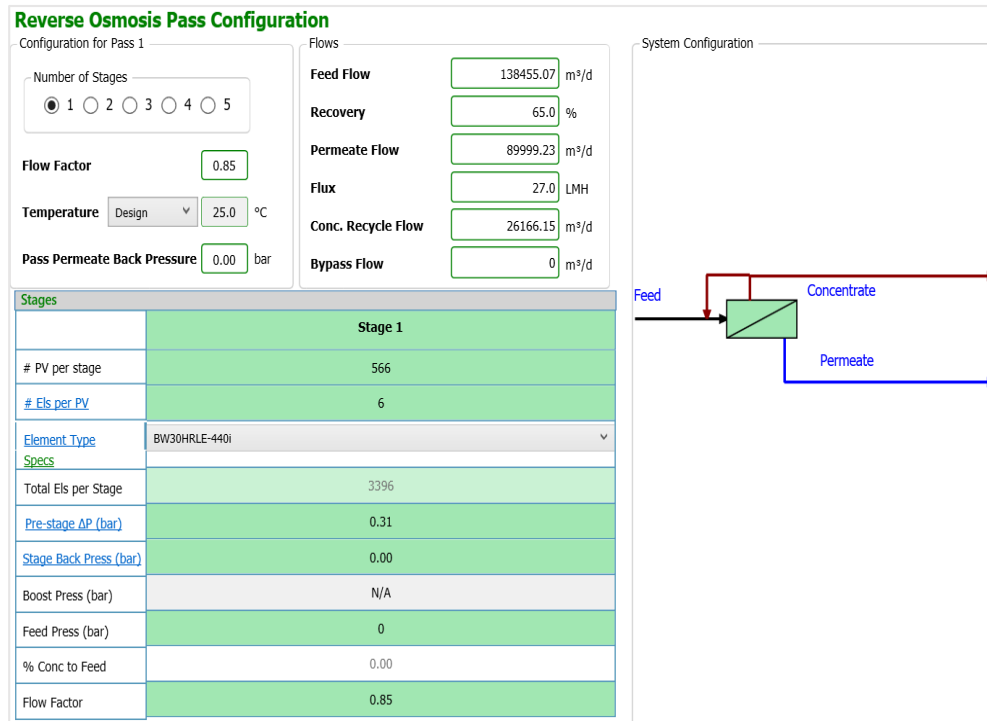


Figure 4.17. Input parameters for RO system design in WAVE

The system is a single-stage system. A pressure vessel with 6 elements will be used in this simulation, and filtered water flows from the UF system is 112289.88 m³/day. To reach up to 80 % recovery of water it's expected to recycle concentrate water more than 50 percent, which becomes 26166.15 m³/day. The total feed water flow for the RO system is 138455.07 m³/day, and we use BW30HRLE 440i membrane element from DuPont manufacturer, which was used before in this study. The average design flux for the present study is 27L MH. According to this average design flux, we put the number of pressure vessels to reach the desirable flux, which is 566 pressure vessels with 6 elements in each pressure vessel for the selected membrane element. The result of this simulation will be discussed in the following sections.

4.2.3.1. General RO system flow diagram

WAVE draws a general flow diagram for the RO system, which shows feed water that comes from the UF system, recycled concentrate water, which is recycled back to feed flow, concentrate water, and permeate water. Figure 4.18 shows the RO system diagram.

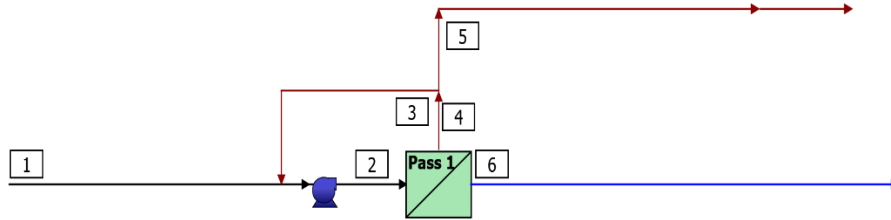


Figure 4.18. Schematic diagram of single stage RO system with concentrate recycled (given by WAVE)

This diagram is described in the following table.

Table 4.44. Description of RO diagram in WAVE

#	Description	Flow (m ³ /d)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	112,289	1,179	0.0
2	Net Feed to Pass 1	138,403	2,049	8.2
3	Concentrate Recycle from Pass 1 to Pass 1	26,158	5,781	6.8
4	Total Concentrate from Pass 1	48,441	5,781	6.8
5	Net Concentrate from RO System	22,283	5,781	6.8
6	Net Product from RO System	89,999	37.74	0.0

Table 4.44 Shows feed, recycled, concentrate and permeate flow for the RO system and also it indicates the concentration of TDS for each flow. Furthermore, the table shows the system's feed, permeate and concentrate pressure.

The feed pressure for the system is calculated at 8.2 bar and the permeate pressure at 6.8 bar. The difference between feed and permeate pressure is 1.4 bar, which is normal in the RO system and does not need back pressure. The software gave the general overview of the RO system as follows.

Table 4.45. General overview of the RO system given by WAVE

Pass		Pass 1
Stream Name		RO system for Kirikkale city
Water Type		Surface With DuPont UF, SDI < 2.5
Number of Elements		3396
Total Active Area	(m ²)	138819
Feed Flow per Pass	(m ³ /d)	138,403
Feed TDS^a	(mg/L)	2,049
Feed Pressure	(bar)	8.2
Flow Factor Per Stage		0.85
Permeate Flow per Pass	(m ³ /d)	89,999
Pass Average flux	(LMH)	27.0
Permeate TDS^a	(mg/L)	37.74
Pass Recovery		65.0 %
Average NDP	(bar)	5.3
Specific Energy	(kWh/m ³)	0.44
Temperature	(°C)	25.0
pH		8.1
Chemical Dose		-
RO System Recovery		80.1 %
Net RO System Recovery		80.1%

As indicated in Table 4.45, 3396 membrane elements were used in 566 pressure vessels with 27 LMH average design flux. The total area of these elements is 138819 m², feed water TDS concentration after concentrate is recycled is 2049 mg/l, and the permeate water TDS concentration is 37.74 mg/l. Feed pressure for the system is 8.2 bar, and the average NDP for the system is estimated at 5.3 bar. The total system recovery is 80.1 %. Table 4.46 shows the specification of membrane element, feed flow, concentrate and permeate flow conditions.

Table 4.46. Specification of membrane elements in pressure vessel given by WAVE

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow	Recirc Flow	Feed Press	Boost Press	Conc Flow	Conc Press	Press Drop	Perm Flow	Avg Flux	Perm Press	Perm TDS
				(m ³ /d)	(m ³ /d)	(bar)	(bar)	(m ³ /d)	(bar)	(bar)	(m ³ /d)	(LMH)	(bar)	(mg/L)
1	BW30HRLE-440i	566	6	138,404	26,158	7.9	0.0	48,441	6.8	1.1	89,999	27.0	0.0	37.74

1. Feed, permeate, and concentrate water concentration

WAVE software can check the feed, permeate and concentrate water quality and specifications as in the following table.

Table 4.47. Feed, permeate, and concentrate water quality given by WAVE

Concentrations (mg/L as ion)						
	Raw Feed	Adjusted Feed		Concentrate	Permeate	
		Initial	After Recycle	Stage1	Stage1	Total
NH ₄ ⁺	0.00	0.00	0.00	0.00	0.00	0.00
K ⁺	5.19	5.19	8.93	24.97	0.29	0.29
Na ⁺	191.1	191.1	330.8	929.8	8.22	8.22
Mg ⁺²	58.33	58.33	102.3	290.7	0.80	0.80
Ca ⁺²	105.0	105.0	184.1	523.5	1.41	1.41
Sr ⁺²	0.00	0.00	0.00	0.00	0.00	0.00
Ba ⁺²	0.00	0.00	0.00	0.00	0.00	0.00
CO ₃ ⁻²	1.81	1.81	4.43	17.43	0.00	0.00
HCO ₃ ⁻	108.9	108.9	184.7	507.0	6.59	6.59
NO ₃ ⁻	18.68	18.68	31.18	84.80	2.32	2.32
F ⁻	0.00	0.00	0.00	0.00	0.00	0.00
Cl ⁻	283.5	283.5	493.1	1,392	9.16	9.16
Br ⁻¹	0.00	0.00	0.00	0.00	0.00	0.00
SO ₄ ⁻²	400.0	400.0	702.0	1,997	4.67	4.67
PO ₄ ⁻³	0.00	0.00	0.00	0.00	0.00	0.00
SiO ₂	0.00	0.00	0.00	0.00	0.00	0.00
Boron	1.10	1.10	1.37	2.51	0.75	0.75
CO ₂	0.91	0.91	1.21	3.25	1.53	1.53
TDS ^a	1,179	1,179	2,049	5,781	37.74	37.74
Cond.µS/cm	2,038	2,038	3,409	8,702	60	60
pH	8.1	8.1	8.2	8.1	6.8	6.8

Table 4.47 indicates that the RO system removes nearly all pollutants from feed water and all hazards from the water. For example, the TDS in raw water was 1200 mg/l, but in permeate water, it is 37.74 mg/l, and sulfate in feed water was 400 mg/l, while in the permeate water, it was 4.67 mg/l which shows the removal percentage more than 95 %. One of the advantages of UF system installation as a pretreatment is to remove all suspended solids and turbidity from water; with RO system it removes all other hazardous contaminants from water, as seen in table 4.47.

4.2.3.2. Membrane element specifications

WAVE can calculate the membrane elements' behavior in a pressure vessel as the software gave us each element recovery, feed flow for each element, feed pressure for each element, feed water TDS for each element, concentrate flow for each element, permeate flow for each element, permeate flux for each element and permeate TDS for each element as in the following Table 4.48.

Table 4.48. Feed, Permeate, concentrate, pressure and concentration with flux for each element of the RO system

Stage	Element	Element Name	Recovery	Feed Flow	Feed Press	Feed TDS	Conc Flow	Perm Flow	Perm Flux	Perm TDS
			(%)	(m ³ /d)	(bar)	(mg/L)	(m ³ /d)	(m ³ /d)	(LMH)	(mg/L)
1	1	BW30HRLE-440i	13.3	244.5	7.9	2,049	212.0	32.5	33.2	18.72
1	2	BW30HRLE-440i	14.2	212.0	7.6	2,361	181.8	30.2	30.8	23.44
1	3	BW30HRLE-440i	15.3	181.8	7.4	2,748	154.0	27.9	28.4	30.04
1	4	BW30HRLE-440i	16.6	154.0	7.2	3,240	128.5	25.5	26.0	39.63
1	5	BW30HRLE-440i	17.8	128.5	7.0	3,874	105.6	22.9	23.3	54.25
1	6	BW30HRLE-440i	18.9	105.6	6.9	4,702	85.6	20.0	20.4	77.71

Figure 4.19 Shows the recovery difference between elements along the pressure vessel.

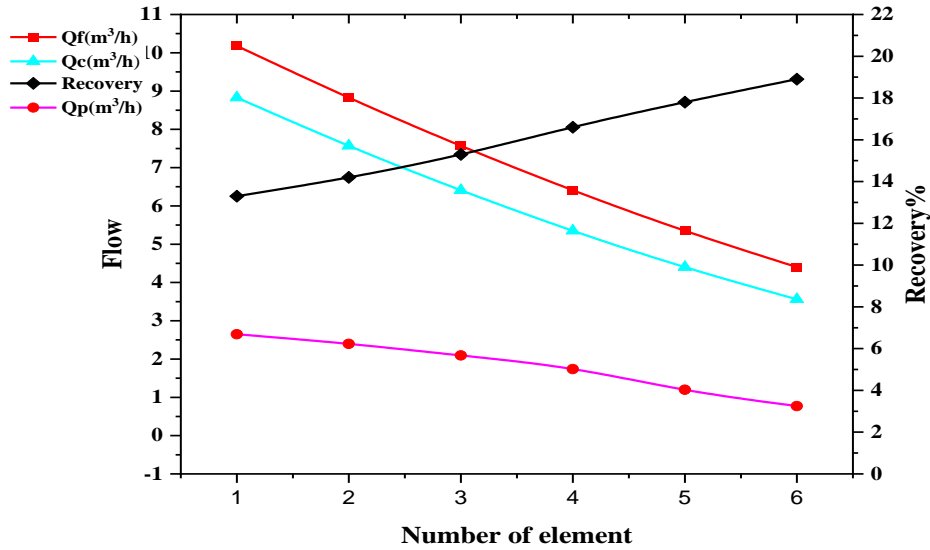


Figure 4.19. Flow and recovery difference along pressure vessels between elements

Figure 4.19 indicates that recovery is getting high from membrane 1 to 6 because of the high concentration of feed for the elements, where the maximum recovery for BW39 HRLE 440i element is 19 % (from ESS) which is suitable for this design. In addition, the permeate recovery along the vessel decreased between elements due to the high feed water concentration. Figure 4.20 shows the difference between feed and concentrate pressure along the membranes in a single pressure vessel.

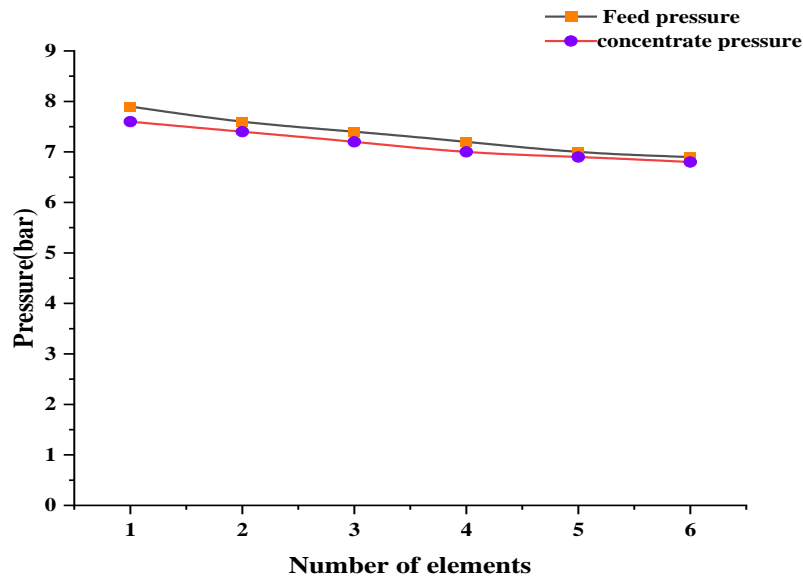


Figure 4.20. The pressure difference in feed and concentrate for elements

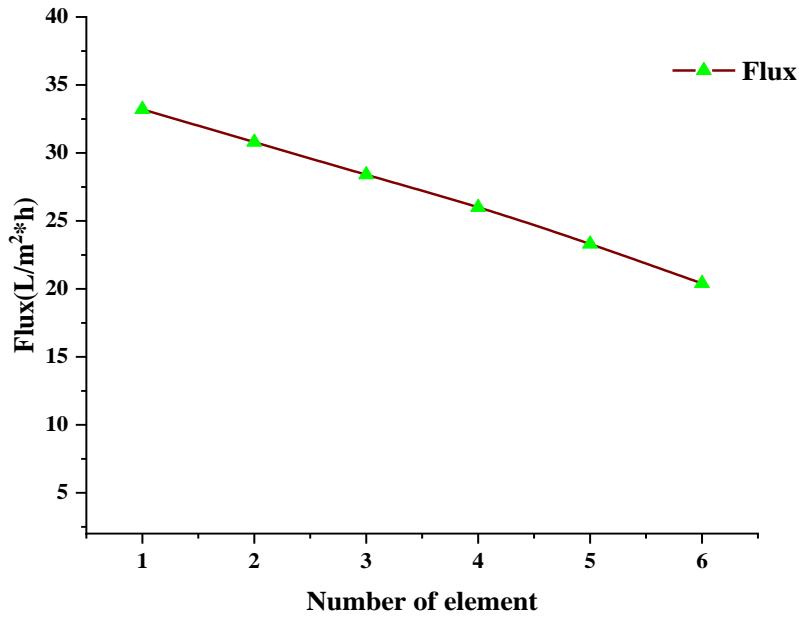


Figure 4.21. Shows the flux of each element in a pressure vessel

As it can be seen, the flux is decreased along the elements due to the net driving pressure drop in the pressure vessel; therefore, the flux for the first element is high than the last one, but the average design flux for the system is 27 LMH which is suitable for the selected element flux range (27-34 LMH). (DuPont 2020). Figure 4.22 shows the removal of TDS for each element along the pressure vessel.

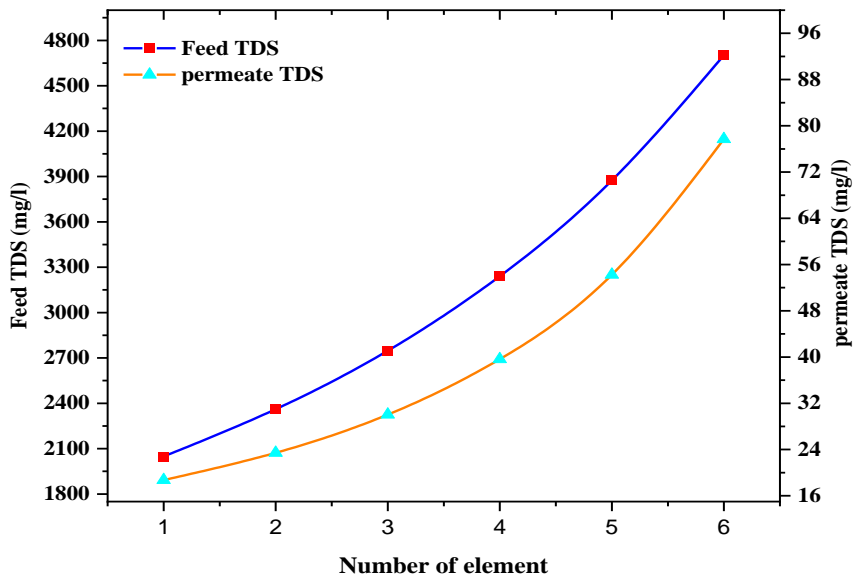


Figure 4.22. Feed and permeate TDS concentration for each element

As shown in Figure 4.22, the current RO membrane element removed the TDS concentration near 99 percent, which is the best removal of all pollutants from feed water.

4.2.3.3. The energy required for the RO system

The software can calculate the total energy consumption for the RO system. For this purpose, the cost of electricity in the local area must be input. For May of 2022, the cost for 1KWh of electricity in Turkey is about 1.89 Turkish Lira. Table 4.49 shows the total energy requirements for the RO system with its cost.

Table 4.49. Energy and cost requirements for RO system given by WAVE

Peak Power	(kW)	1,647
Energy	(kWh/d)	39,516
Electricity Unit Cost	(₺/kWh)	1.8900
Electricity Cost	(₺/d)	74,685
Specific Energy	(kWh/m ³)	0.44

The total peak power requirement for the RO system is 1647 kW in one hour, and for 24 hours, the total electricity of 39516 Kwh/ day is needed. The total cost for a one-day energy requirement is 74685 Turkish Lira, and 0.44 KWh energy is needed for 1 m³ water treatment.

4.2.3.4. Disposal of wastewater from the site

If we assume the cost of 1m³ of wastewater disposal is 0.3 Lira, then the total cost of wastewater disposal is given by software as follows.

Table 4.50. Wastewater disposal cost for RO system given by WAVE

	Flow Rate	Unit Cost	Hourly Cost	Daily Cost
	(m ³ /d)	(₺/m ³)	(₺/h)	(₺/d)
Waste Water Disposal				
Pass 1	22,283	0.3000	279.28	6702.62
Total Waste Water Disposal	22,283		279.28	6702.62
Total Service Water Cost				6702.62

The total operating cost for the RO plant is summarized as follows;

Utility and Chemical Cost	(₺/d)	81387.62
Specific Water Cost	(₺/m ³)	0.9

As indicated, the cost for 1m³ of permeate water is 0.9 Turkish Lira. This cost is without chemical adjustment and maintenance cost and may change during the month of the year because electricity costs change.

4.2.3.5. Chemical adjustment for RO system by WAVE

To prevent different fouling and scaling in the RO system and the corrosion of the water supply pipe system, it is important to adjust the permeate water chemicals and pH to prevent these problems. As observed, the flux and pressure drop are normal along the operation, so the risk of fouling and scaling is not at a high value, but to prevent the membrane elements from fouling and scaling, it needs to use anti scalant in the feed water and adjust pH for feed water to ensure for the forming of the scaling and fouling along the elements and prevent the corrosion of the water supply pipes.

WAVE software can be aware of the designer's use of anti scalants if needed as it appears a warning in the project report which says if there is needed to adjust the water chemicals.

Table 4.51. Warning for the scaling and fouling given by WAVE

Warning	Pass No	
Langelier Saturation Index > 0	1	
Antiscalant may be required. Consult your antiscalant manufacturer for dosing and maximum allowable system recovery.	1	
	Pass 1 Feed	RO 1 st Pass Conc
pH	8.1	8.1
Langelier Saturation Index	0.58	1.88
Stiff and Davis Stability Index	0.82	1.53
TDS ^a (mg/l)	1,179	5,781
Ionic Strength (molal)	0.03	0.14
HCO ₃ ⁻ (mg/L)	108.9	507.0
CO ₂ (mg/l)	0.91	3.25
CO ₃ ⁻² (mg/L)	1.81	17.43
CaSO ₄ (% saturation)	7.5	75.5
BaSO ₄ (% saturation)	0.00	0.00
SrSO ₄ (% saturation)	0.00	0.00
CaF ₂ (% saturation)	0.00	0.00
SiO ₂ (% saturation)	0.00	0.00
Mg(OH) ₂ (% saturation)	0.07	0.49

RO manufacturers commonly use Langelier Saturation Index and Stiff and Davis stability index to predict the calcium carbonate scaling (Kucera, 2015). LSI is a method for measuring water's scaling and corrosion trend based on the pH, TDS concentration in the feed water, the temperature of the feed water, hardness, and the alkalinity of feed water (Kucera, 2015). If LSI is 0, then the water is chemically balanced. If greater than zero, water may cause calcium scaling in membranes; if LSI is less than zero, the water is corrosive (Kucera, 2015). To prevent calcium scaling and corrosion of the pipes, we adjust the pH of feed water to the RO system by adding HCL 32% to the feed flow.

Note: that most membrane manufacturers recommend an LSI of +1.8 or lower in the concentrate with antiscalant feed to control scaling (Kucera, 2015). WAVE can calculate the adjustment of chemicals as follow.

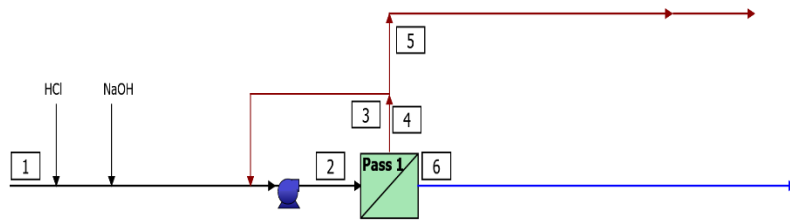


Figure 4.23. RO diagram after adding antiscalant.

Table 4.52. Water characteristics after chemical adjustment

pH		7.5 (After Adjustment)		
Chemical Dose		9.8 mg/L HCl		6.8 mg/L NaOH
	Pass 1 Feed before pH Adjust	Pass 1 Feed After pH Decrease	Pass 1 Feed After pH Increase	RO 1 st Pass Conc
pH	8.1	7.0	7.5	7.8
Langelier Saturation Index	0.58	-0.61	-0.07	1.57
Stiff and Davis Stability Index	0.82	-0.37	0.17	1.21
TDS ^a (mg/l)	1,179	1,174	1,188	5,821
Ionic Strength (molal)	0.03	0.03	0.03	0.14
HCO ₃ ⁻ (mg/L)	108.9	96.56	106.3	495.9
CO ₂ (mg/l)	0.91	11.06	3.85	6.38
CO ₃ ⁻² (mg/L)	1.81	0.12	0.41	8.51
CaSO ₄ (% saturation)	7.5	7.5	7.5	75.2
BaSO ₄ (% saturation)	0.00	0.00	0.00	0.00
SrSO ₄ (% saturation)	0.00	0.00	0.00	0.00
CaF ₂ (% saturation)	0.00	0.00	0.00	0.00
SiO ₂ (% saturation)	0.00	0.00	0.00	0.00
Mg(OH) ₂ (% saturation)	0.07	0.00	0.00	0.12

As we can see from Table 4.52, by adding 9.8 mg/l HCL 32% and 6.8 mg/l NaOH to feed water, the water will be adjusted chemically, and the permeate water characteristic change is as follow.

Table 4.53. Different parameters concentration in water after chemical adjustment

Concentrations (mg/L as ion)						
		Adjusted Feed		Concentrate	Permeate	
	Raw Feed	After Chemicals	After Recycle	Stage1	Stage1	Total
NH ₄ ⁺	0.00	0.00	0.00	0.00	0.00	0.00
K ⁺	5.19	5.19	8.92	24.91	0.30	0.30
Na ⁺	191.1	195.0	337.3	947.4	8.76	8.76
Mg ⁺²	58.33	58.33	102.2	290.5	0.85	0.85
Ca ⁺²	105.0	105.0	184.1	523.2	1.49	1.49
Sr ⁺²	0.00	0.00	0.00	0.00	0.00	0.00
Ba ⁺²	0.00	0.00	0.00	0.00	0.00	0.00
CO ₃ ⁻²	1.81	0.41	1.33	8.51	0.00	0.00
HCO ₃ ⁻	108.9	106.3	181.2	495.9	6.57	6.57
NO ₃ ⁻	18.68	18.68	31.09	84.31	2.44	2.44
F ⁻	0.00	0.00	0.00	0.00	0.00	0.00
Cl ⁻	283.5	293.1	509.3	1,436	10.04	10.04
Br ⁻¹	0.00	0.00	0.00	0.00	0.00	0.00
SO ₄ ⁻²	400.0	400.0	701.8	1,996	4.94	4.94
PO ₄ ⁻³	0.00	0.00	0.00	0.00	0.00	0.00
SiO ₂	0.00	0.00	0.00	0.00	0.00	0.00
Boron	1.10	1.10	1.34	2.38	0.78	0.78
CO ₂	0.91	3.85	3.90	6.38	4.39	4.39
TDS ^a	1,179	1,188	2,065	5,821	39.85	39.85
Cond.	2,038	2,059	3,442	8,785	64	64
μS/cm						
pH	8.1	7.5	7.7	7.8	6.4	6.4

Note: For better water adjustment chemically, Consult your antiscalant manufacturer for dosing and maximum allowable system recovery. The total amount of chemicals needed in the adjustment of chemicals and antiscalants are summarized in Table 4.54.

Table 4.54. Chemical consumption amount for adjustment given by WAVE

Chemical	Dose 100%	Volume
	(mg/L)	(L/d)
HCl (32%)		
Pass 1	9.8	2,973
NaOH (50%)		
Pass 1	6.8	1,007
Total Chemical Cost		

4.2.4. Design of double stages RO system by WAVE

If the permeate recovery is needed more than 70 %, it uses a two-stage RO system as the concentrate of the first stage becomes the feed for the second stage (DuPont 2020). we discussed before related to staging ratio and distribution of pressure vessels between two stages (chapter 4). WAVE can design multiple-stage system to increase the recovery percentage of water. The present study applied the two stages RO system to simulate and compare with one-stage system based on economic issues. The input data for the two stages RO system is shown in Figure 4.24.

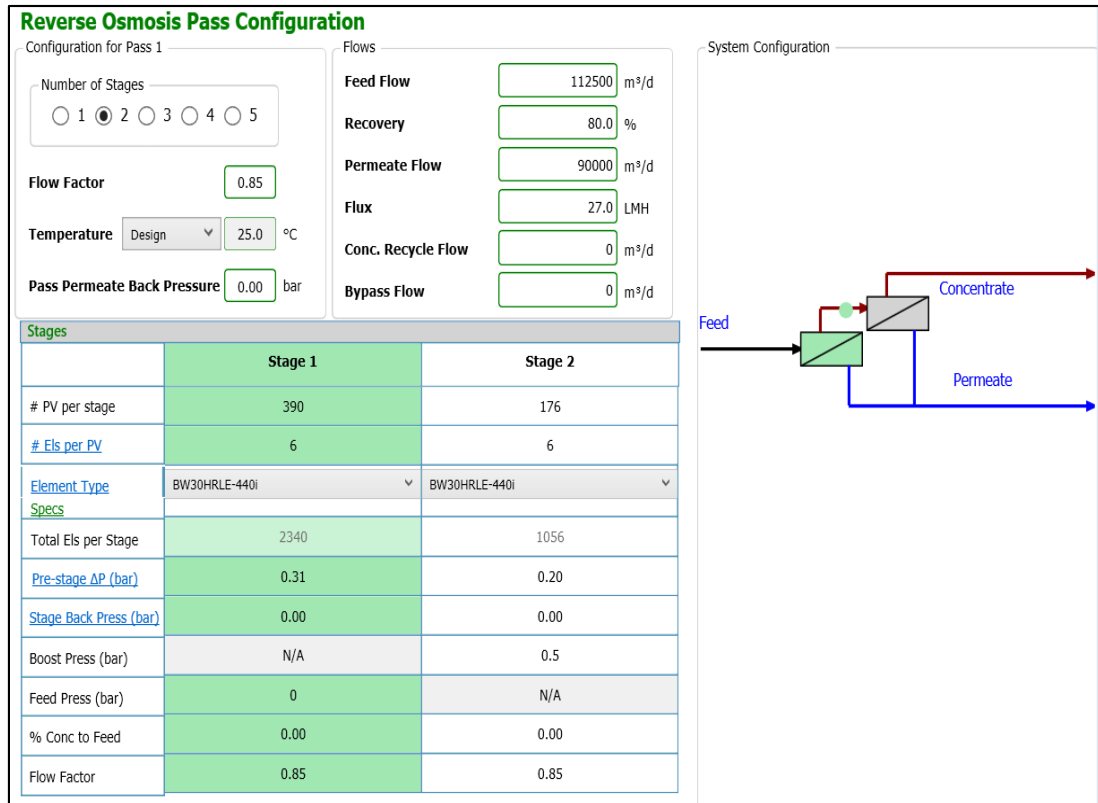


Figure 4.24. Input data for two stages RO system in WAVE

As shown in Figure 4.24, the average design flux for the two stages RO system is 27LMH, recovery for the system 80 %, in the first stage, 390 pressure vessels, and the second stage has 176 pressure vessels with 6 elements. To increase the feed flow for the second stage, it needs to apply boost pressure for the feed flow of the second stage. (DuPont, 2020) therefore we applied 0.5 bar boost pressure for the second stage and analyzed the system. The following briefly discusses WAVE software's output design of the two-stages RO system.

4.2.4.1. General RO double stages system overview

The summary of the two stages of the RO system, which was designed by WAVE software, is listed in the following tables.

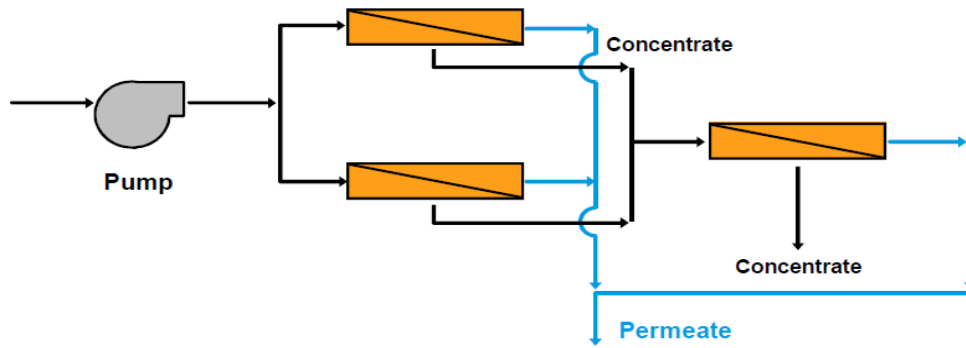


Figure 4.25. Shows the general layout of two stages RO system.

Table 4.55. Summary of two stages of RO system design

Pass		Pass 1
Stream Name		Two stages RO system for Kirikkale city
Water Type		Surface With DuPont UF, SDI < 2.5
Number of Elements		3396
Total Active Area	(m ²)	138819
Feed Flow per Pass	(m ³ /d)	112,456
Feed TDS ^a	(mg/L)	1,179
Feed Pressure stage 1	(bar)	7.8
Feed Pressure stage 1	(bar)	6.7
Flow Factor Per Stage		0.85, 0.85
Permeate Flow per Pass	(m ³ /d)	89,995
Pass Average flux	(LMH)	27.0
Permeate TDS ^a	(mg/L)	28.16
Pass Recovery		80.0 %
Average NDP	(bar)	5.2
Specific Energy	(kWh/m ³)	0.36
Temperature	(°C)	25.0
pH		8.1
Chemical Dose		-
Net RO System Recovery		80.0%

As shown in Table 4.55 total of 3396 elements are used in the system in two stages. The total area of the elements is 138819 m², and feed TDS is 1179 mg/l; feed pressure for the first stage is 7.8 bar, and for the second stage, 6.7 bar.

4.2.4.2. Flow, pressure, and TDS concentration description for two stages

WAVE can calculate the feed, concentrate and permeate flow for both stages and can calculate feed and concentrate pressure for stages one and two. Table 4.56 shows the summary of the calculation for two stages.

Table 4.56. Pressure, concentration, and flux calculation for two stages RO system given by WAVE

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow	Recirc Flow	Feed Press	Boost Press	Conc Flow	Conc Press	Press Drop	Perm Flow	Avg Flux	Perm Press	Perm TDS
				(m ³ /d)	(m ³ /d)	(bar)	(bar)	(m ³ /d)	(bar)	(bar)	(m ³ /d)	(LMH)	(bar)	(mg/L)
1	BW30HRLE-440i	390	6	112,457	0.00	7.8	0.0	42,539	6.4	1.4	69,947	30.5	0.0	18.24
2	BW30HRLE-440i	176	6	42,538	0.0	6.7	0.5	22,498	5.5	1.3	20,048	19.4	0.0	62.77

Table 4.57 indicates that the feed flow for the first stage is 112457m³/day, the concentrate flow for the first stage is 42539m³/day, and the permeate flow for the first stage is 69947m³/day. For the second stage RO system, the concentrate of the first stage becomes the feed for the second stage as we can see from the table feed flow for the second stage is 42538m³/day, which is the concentrate of the first stage.

In addition, the feed pressure for the first stage is 7.8 bar, and for the second stage is 6.7 bar and the pressure drop is less than 2 bar between stages which shows the accuracy of the design.

4.2.4.3. RO solute concentrations

As discussed before, the RO system can remove nearly all anions and cations from water and is one of the best technology for water purification. WAVE checkout the concentration of water parameters for both stages of the system as follows.

Table 4.57. Feed, permeate water quality for stages 1 and 2 given by WAVE.

Concentrations (mg/L as ion)						
	Feed	Concentrate		Permeate		
		Stage1	Stage2	Stage1	Stage2	Total
NH ₄ ⁺	0.00	0.00	0.00	0.00	0.00	0.00
K ⁺	5.19	13.50	25.08	0.13	0.50	0.21
Na ⁺	191.1	499.3	931.6	3.69	13.99	5.98
Mg ⁺²	58.33	153.7	289.4	0.35	1.32	0.57
Ca ⁺²	105.0	276.7	521.1	0.62	2.34	1.00
Sr ⁺²	0.00	0.00	0.00	0.00	0.00	0.00
Ba ⁺²	0.00	0.00	0.00	0.00	0.00	0.00
CO ₃ ⁻²	1.81	7.10	16.54	0.00	0.01	0.00
HCO ₃ ⁻	108.9	278.9	512.0	2.98	11.00	4.76
NO ₃ ⁻	18.68	47.62	86.51	1.09	3.97	1.73
F ⁻	0.00	0.00	0.00	0.00	0.00	0.00
Cl ⁻	283.5	743.2	1,391	4.07	15.67	6.65
Br ⁻¹	0.00	0.00	0.00	0.00	0.00	0.00
SO ₄ ⁻²	400.0	1,055	1,987	2.06	7.68	3.31
PO ₄ ⁻³	0.00	0.00	0.00	0.00	0.00	0.00
SiO ₂	0.00	0.00	0.00	0.00	0.00	0.00
Boron	1.10	1.97	2.75	0.57	1.10	0.69
CO ₂	0.91	1.92	3.49	1.11	2.13	1.34
TDS ^a	1,179	3,086	5,776	18.24	62.77	28.16
Cond. μS/cm	2,038	4,950	8,691	27	101	43
pH	8.1	8.2	8.1	6.6	6.9	6.8

As we can see in Table 4.57 concentration of basic water parameters, concentrate concentration of the first and second stages, and the permeate concentration for different parameters of the two stages. This two stages system can remove nearly all contaminants from the water body.

4.2.4.4. Elements specifications for two stages

WAVE can calculate each element specification for both stages and determine the feed, permeate and concentrate flow, pressure, and concentration of TDS for the elements of the two stages separately. Table 4.58 shows the summary of the calculation for two stages of membrane elements.

Table 4.58. Feed, Permeate, and Concentrate pressure and concentration of each element given by WAVE

Stage	Element	Element Name	Recovery (%)	Feed Flow (m ³ /d)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m ³ /d)	Perm Flow (m ³ /d)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	BW30HRLE-440i	12.1	288.4	7.8	1,179	253.5	34.9	35.5	10.91
1	2	BW30HRLE-440i	12.9	253.5	7.5	1,340	220.9	32.7	33.3	12.83
1	3	BW30HRLE-440i	13.9	220.9	7.2	1,536	190.2	30.7	31.3	15.36
1	4	BW30HRLE-440i	15.2	190.2	6.9	1,781	161.3	28.9	29.4	18.85
1	5	BW30HRLE-440i	16.8	161.3	6.7	2,096	134.2	27.1	27.6	23.86
1	6	BW30HRLE-440i	18.8	134.2	6.5	2,514	109.1	25.2	25.7	31.47
2	1	BW30HRLE-440i	10.1	241.7	6.7	3,086	217.2	24.5	25.0	36.35
2	2	BW30HRLE-440i	10.2	217.2	6.4	3,429	195.1	22.1	22.5	44.74
2	3	BW30HRLE-440i	10.2	195.1	6.2	3,812	175.2	19.9	20.3	55.41
2	4	BW30HRLE-440i	10.2	175.2	6.0	4,238	157.4	17.8	18.1	69.13
2	5	BW30HRLE-440i	10.0	157.4	5.8	4,709	141.7	15.8	16.1	86.87
2	6	BW30HRLE-440i	9.8	141.7	5.6	5,223	127.8	13.9	14.1	110.0

For better understanding, it described the table in the following graphs.

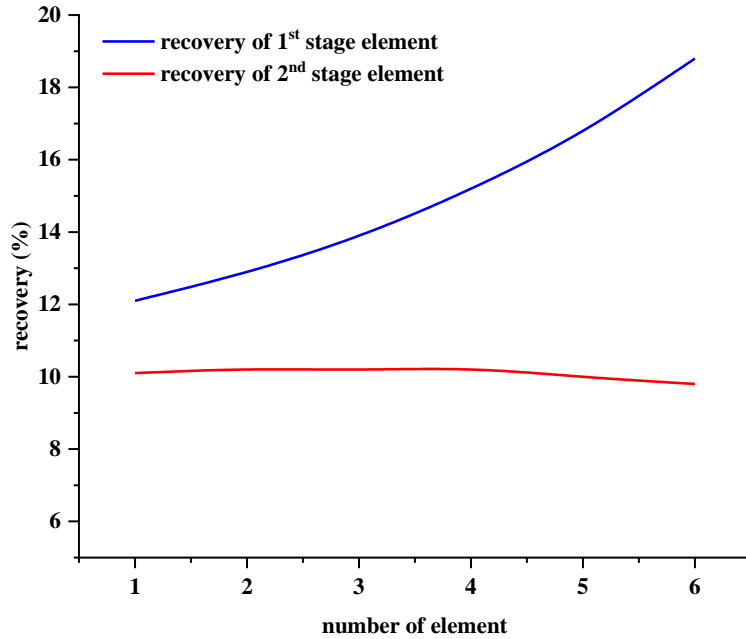


Figure 4.26. Difference of recovery for each element between the two stages.

As shown in Figure 4.26, the recovery of first stage elements is higher than the second stage because of the feed water high concentration for the second stage, and the staging ratio as 1 of 3 parts of the water is recovered by the second stage. (DuPont 2020)

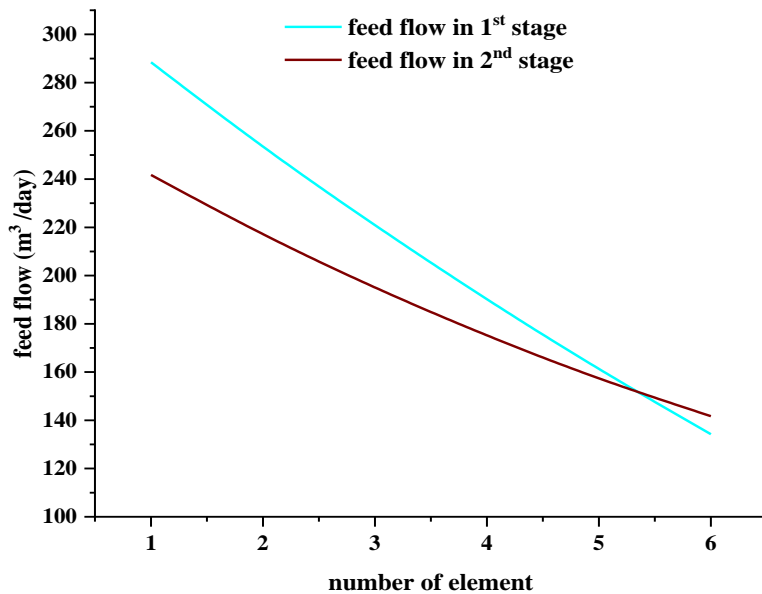


Figure 4.27. Comparison of feed flow between stages given by WAVE

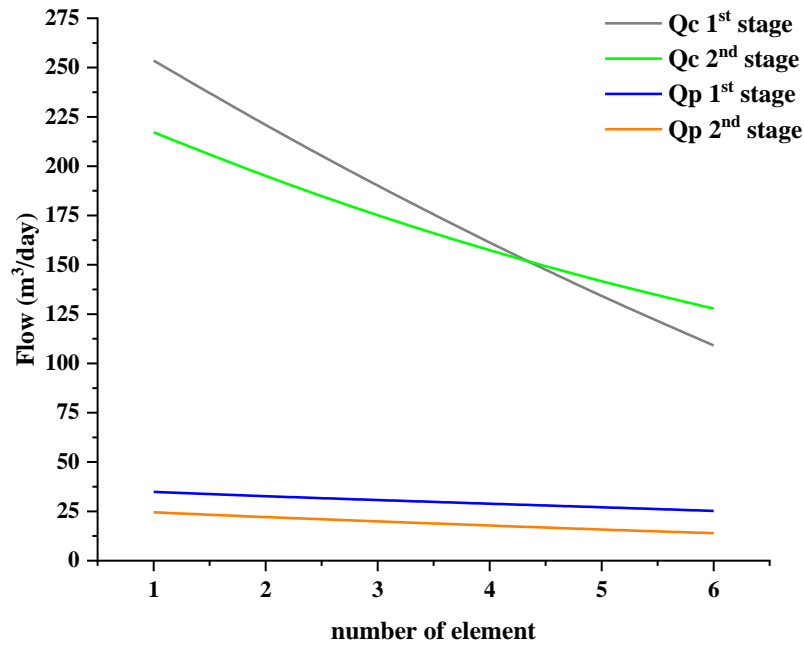


Figure 4.28. Comparison of permeate and concentrate flow of two stages given by WAVE

Figure 4.27 and 4.28 shows the feed, permeate and concentrate flow for each element of both stages. It indicates that feed, permeate and concentrate flow for the second stage is less than the first stage. It is because of low pressure and high concentration of feed water for the second stage, and also the recovery for the second stage is less than the first stage because of the staging ratio and vessel number in the second stage.

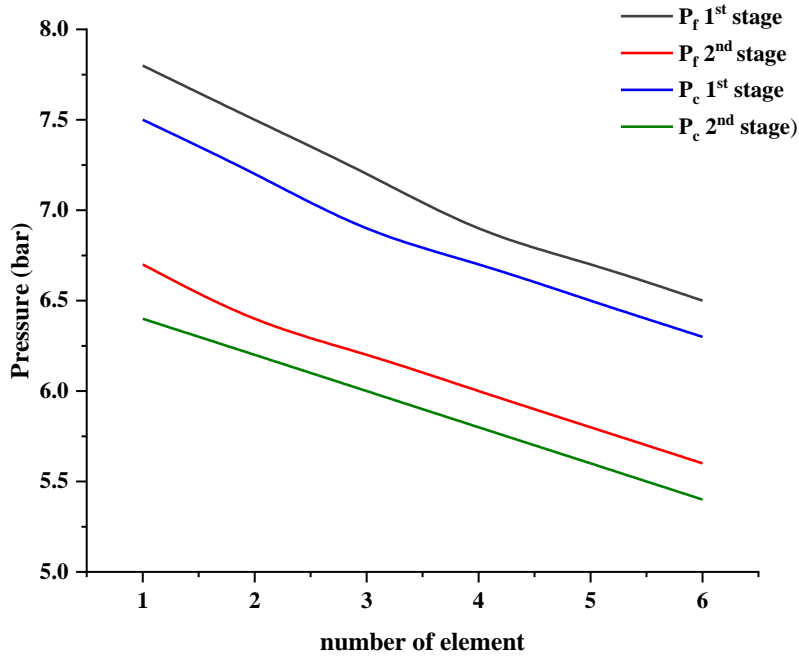


Figure 4.29. Difference of feed and concentrate pressure between the two stages

Figure 4.29 shows the difference in feed and concentrate pressure for the first and second stage of the RO system. The pressure drop for the first stage is 1.3 bar and for the second stage is 1.1 bar which is below the maximum pressure drop value along the pressure vessel for the selected membrane elements (DuPont, 2020).

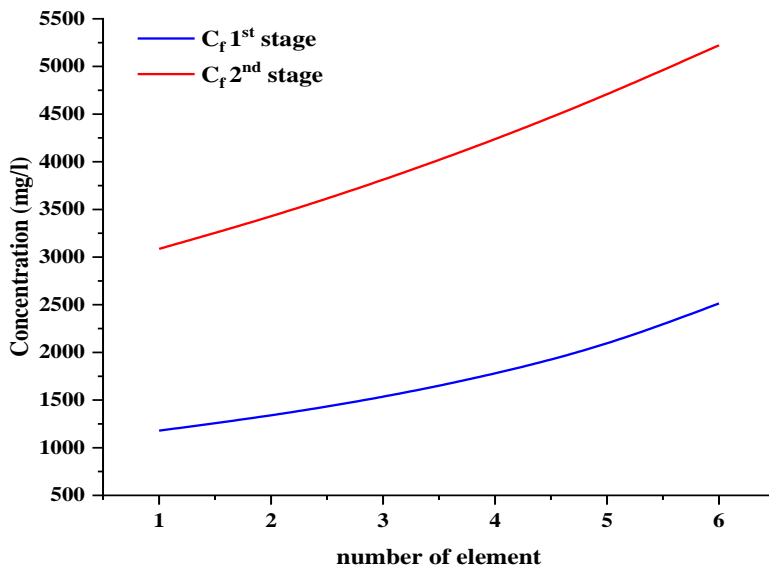


Figure 4.30. Shows the feed concentration for the first and second stage.

As we can see, the concentration for the second is much high than the first stage because the concentrate of the first stage becomes the feed flow for the second stage, and the concentration of the concentrate is high than the raw water concentration; therefore, the recovery for the second stage is less than the first stage.

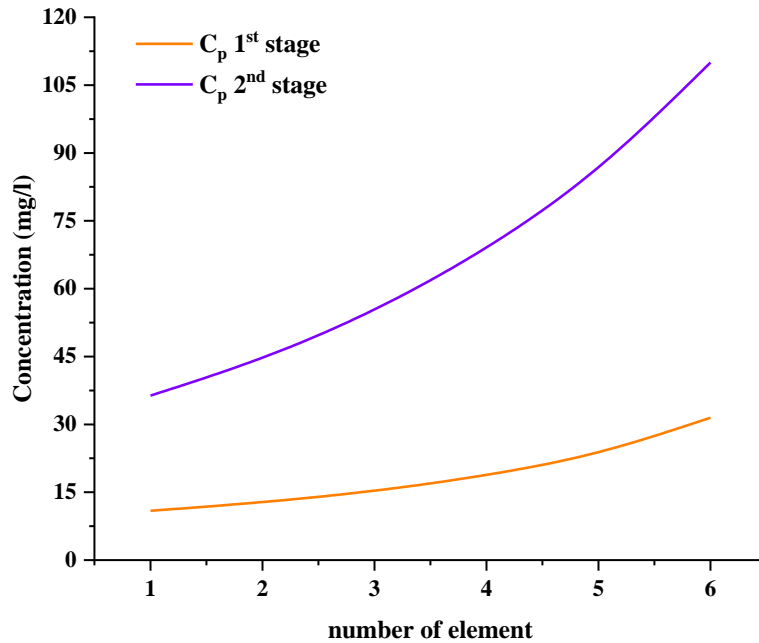


Figure 4.31. Shows the permeate concentration for two stages

As we see in Figure 4.31, the permeate concentration of the second stage is higher than the first stage due to the high concentration of feed for the second stage. The final permeate concentration comes from the average permeate concentration of two stages which is 28.16 mg/l.

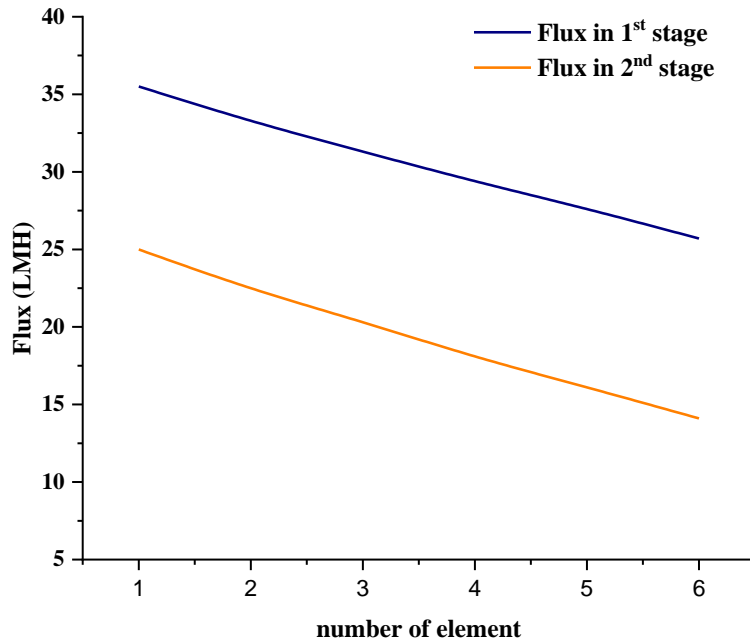


Figure 4.32 Shows the flux for each element for two stages

Flux in the second stage is low than in the first stage it is due to two main reasons

- 1- It is because of the net driving pressure along the pressure vessel.
- 2- The water concentration in the second stage is higher than in the first stage, and because of the high concentration, the pressure drop occurs, and the flux decreases along the elements (AWWA, 2007).

4.2.4.5. Calculation of energy consumption for two stages system

WAVE gave the total energy required for the two stages RO system and the total and per unit energy cost for the system. Table 4.60 shows the energy required by the system.

Table 4.59. Required energy by two stages RO system is given by WAVE.

Peak Power		(kW)		1,359
Energy		(kWh/d)		32,621
Electricity Unit Cost		(₺/kWh)		1.8900
Electricity Cost		(₺/d)		61,653
Specific Energy		(kWh/m ³)		0.36
Pump	Flow Rate	Power	Energy	Cost
	(m ³ /d)	(kW)	(kWh/d)	(₺/d)
Pass 1				
Feed	112,455.52	1,328.36	31,880.61	60,254.36
Stage 2 Boost	42,537.51	30.84	740.14	1,398.87
Pass 1 Total		1,359.20	32,620.75	61,653.28
System Total		1,359.20	32,620.75	61,653.28

As shown in Table 4.59, the power required for the system is 1359 KW, the plant's energy consumption for one day is 32621 KWh/day, and the cost for energy for one day is 61653 Lira for one day of energy consumption. In addition, the energy consumption for producing 1m³ of permeate water is 0.36 Kwh.

4.2.4.6. Wastewater disposal cost

The software gave the total cost of wastewater disposal based on the price given for 1m³ of wastewater disposal, which is 0.3 Turkish Lira, as follows;

Table 4.60. Wastewater disposal cost for two stages RO system

	Flow Rate (m ³ /d)	Unit Cost (₺/m ³)	Hourly Cost (₺/h)	Daily Cost (₺/d)
Waste Water Disposal				
Pass 1	22,498	0.3000	281.97	6767.28
Total Waste Water Disposal	22,498		281.97	6767.28
Total Service Water Cost				6767.28

4.2.4.7. The operation cost of the plant

WAVE calculated the operation cost for the two stages of the RO system, including the energy cost plus wastewater disposal cost, which are as follows.

Utility Cost (Energy + wastewater disposal)	(£/d)	68,420.56
Specific Water Cost	(£/m ³)	0.76

As shown, the total operating cost for 1 m³ of permeate water by two stages RO system is 0.76 Turkish Lira.

Note: chemical adjustment part is the same as one stage RO system, so it does not need to be repeated (see chemical adjustment of the water part).

4.2.5. Design of bypass RO system

When the feed water TDS is low, it is possible to bypass some feed water and combine it to permeate water; it is called single pass bypass RO system. Figure 4.33 shows the general layout of bypass RO system.

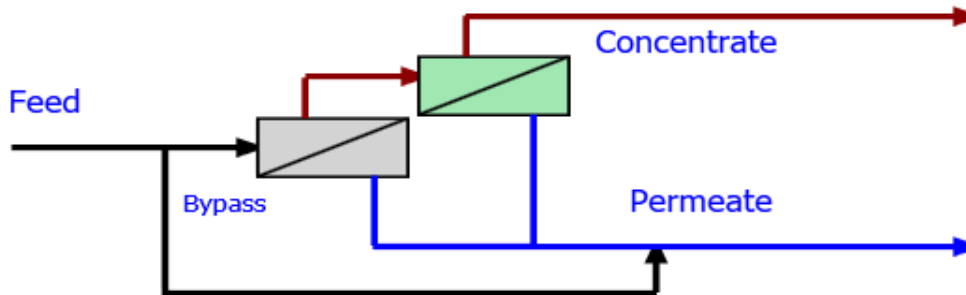


Figure 4.33. The general layout of RO system with bypass of feed water (obtained from WAVE software).

The main aim of this system is to adjust permeate water parameters and increase the concentration of some minerals and salts in permeate water. The main advantage of this system is low energy cost and low capital expenditure (CAPEX) of the process, which

reduces the operation and technology cost of the plant. (DuPont, 2020). In addition, bypassing the filtered water to permeate water means no need to install remineralization part for the permeate water. Furthermore, bypassed RO system reduces the water demand than single stage concentrate recycles RO system. Fig 4.34 shows the general input parameters to WAVE software.

Reverse Osmosis Pass Configuration

Configuration for Pass 1

Number of Stages: 1 2 3 4 5

Flow Factor:

Temperature: Design °C

Pass Permeate Back Pressure: bar

Flows

Feed Flow: m³/d

Recovery: %

Permeate Flow: m³/d

Flux: LMH

Conc. Recycle Flow: m³/d

Bypass Flow: m³/d

Stages		
	Stage 1	Stage 2
# PV per stage	340	155
# Els per PV	6	6
Element Type	BW30HRLE-440i	BW30HRLE-440i
Specs		
Total Els per Stage	2040	930
Pre-stage ΔP (bar)	0.31	0.20
Stage Back Press (bar)	0.00	0.00
Boost Press (bar)	N/A	0
Feed Press (bar)	0	N/A
% Conc to Feed	0.00	0.00
Flow Factor	0.85	0.85

Figure 4.34. Input data for the bypass RO system to WAVE

Following it has been designed the bypass RO system with the same parameters (Flux, permeate water flow, and same membrane element) to compare the result of this system to the systems already designed in the present study.

4.2.5.1. General bypass system output overview

Table 4.61 shows the general information for the bypass RO system.

Table 4.61. Output summary of bypass system by WAVE

Pass		Pass 1**		
Stream Name		Bypass system for Kirikkale city		
Water Type		Surface With DuPont UF, SDI < 2.5		
Number of Elements		2970		
Total Active Area		(m ²)	121406	
Feed Flow per Pass		(m ³ /d)	101,203	
Feed TDS ^a		(mg/L)	1,164	
Feed Pressure		(bar)	8.3	
Flow Factor Per Stage		0.85, 0.85		
Permeate Flow per Pass		(m ³ /d)	78,742	
Pass Average flux		(LMH)	27.0	
Permeate TDS ^a		(mg/L)	24.88	
Pass Recovery		77.8 %		
Average NDP		(bar)	5.2	
Specific Energy		(kWh/m ³)	0.33	
Temperature		(°C)	25.0	
pH		8.1		
Chemical Dose		-		
RO System Recovery		80.0 %		
Net RO System Recovery		80.0%		
#	Description	Flow	TDS	Pressure
		(m ³ /d)	(mg/L)	(bar)
1	Raw Feed to RO System	112,491	1,163	0.0
1A	Feed to Pass 1 after bypass	101,242	1,163	0.0
1B	Bypass from Pass 1 Feed to Pass 1 Permeate	11,249	1,163	0.0
2	Net Feed to Pass 1	101,203	1,164	8.3
4	Total Concentrate from Pass 1	22,494	5,143	4.9
6	Net Product from RO System	78,742	24.88	0.0
8	Blend of Pass 1 Permeate and Bypassed Pass 1 Feed	89,991	167.4	0.0

As can indicate from Table 4.61, the total number of membrane elements are 2970, the average flux for the system is 27LMH, permeate water flow is 90000 m³/day, and the recovery for the system is 80 %. Feed flow for RO system is 112491 m³/day with bypass

water, net feed flow for RO system is 101242 m³/day, bypass flow with 10 % bypassing of feed water is 11249 m³/day, and the permeate flow is 90000 m³/day. The permeate concentration of TDS without bypass water is 24.88 mg/l, but after bypass, it is 167.4mg/l.

4.2.5.2. Description of stages

Table 4.62 include the detailed output information of the stages for the bypass system.

Table 4.62. Feed, permeate, and concentrate pressure and concentration for the bypass system

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow	Recirc Flow	Feed Press	Boost Press	Conc Flow	Conc Press	Press Drop	Perm Flow	Avg Flux	Perm Press	Perm TDS
				(m ³ /d)	(m ³ /d)	(bar)	(bar)	(m ³ /d)	(bar)	(bar)	(m ³ /d)	(LMH)	(bar)	(mg/L)
1	BW30HRLE-440i	340	6	101,204	0.00	8.0	0.0	38,881	6.5	1.5	62,349	31.2	0.0	16.48
2	BW30HRLE-440i	155	6	38,882	0.0	6.3	0.0	22,494	4.9	1.4	16,394	18.0	0.0	56.81

As it can be seen, the total number of pressure vessels for the bypass system is 495 pressure vessels in two stages with 27 LMH average design flux. Feed flow for the first stage is 101204 m³/day, and the concentrate flow is 38881 m³/day, while the feed for the second stage is the concentrate flow of the first stage as 38881 m³/day and the concentrate of the second stage is 22494 m³/day. Feed pressure for the 1st stage is 8 bar and for the 2nd stage is 6.3 bar, and the concentrate pressure for 1st stage is 6.5 bar and for 2nd stage is 4.9 bar in the difference of the pressure is less than 2 bar it shows the correctness of the design.

4.2.5.3. Water parameters for input and output with bypass

WAVE can measure the output parameters of permeate water with or without a bypass system to better understand the real output parameters of permeate water. Table 4.64 shows the difference in feed and permeate water parameters with the bypass system.

Table 4.63. Feed and permeate concentration of two stages bypass system

Concentrations (mg/L as ion)							
		Concentrate		Permeate			
	Feed	Stage1	Stage2	Stage1	Stage2	Total	With Bypass
NH ₄ ⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K ⁺	5.14	13.19	22.44	0.13	0.49	0.20	0.82
Na ⁺	189.5	488.1	834.4	3.27	12.59	5.21	28.24
Mg ⁺²	57.83	150.0	258.4	0.34	1.26	0.53	7.69
Ca ⁺²	104.1	270.1	465.3	0.59	2.23	0.93	13.83
Sr ⁺²	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba ⁺²	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO ₃ ⁻²	1.82	6.99	14.47	0.00	0.01	0.00	0.03
HCO ₃ ⁻	108.9	274.9	463.1	2.89	10.73	4.52	18.00
NO ₃ ⁻	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F ⁻	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl ⁻	286.0	738.3	1,265	4.02	15.64	6.44	41.38
Br ⁻¹	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO ₄ ⁻²	403.5	1,047	1,805	2.01	7.53	3.16	53.21
PO ₄ ⁻³	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Boron	1.11	1.98	2.61	0.57	1.11	0.68	0.73
CO ₂	0.90	1.89	3.12	1.10	2.02	1.29	1.09
TDS ^a	1,163	3,000	5,143	16.48	56.81	24.88	167.4
Cond. μS/cm	2,022	4,846	7,868	24	92	39	309
pH	8.1	8.2	8.1	6.6	6.9	6.7	7.4

As can indicate from Table 4.63, the output parameters of the permeate water are less than permeate with a bypass system. For example, the concentration of TDS in permeate water without a bypass system is 24.88 mg/l, but after a bypass system, it increases to 167.4 mg/l, and for SO₄, the concentration is 3.16 mg/l. However, with the bypass system, it increased to 53.21 mg/l. In addition, we can compare the bypass output parameters concentrations with standard values of different parameters in drinking water in table 3.1, which shows the water is good and can be drinkable.

4.2.5.4. Membrane elements specifications

Table 4.64 shows the feed, permeate, and concentrate flow for each element of the two stages, recovery of each element, concentration of feed, permeate and concentrate, feed, permeate and concentrate pressure of elements, and the flux for each element.

Table 4.64. Feed, permeate, and concentrate flow, pressure, concentration, and flux of each element of bypass RO system

Stage	Element	Element Name	Recovery	Feed Flow	Feed Pressure	Feed TDS	Conc Flow	Perm Flow	Perm Flux	Perm TDS
			(%)	(m ³ /d)	(bar)	(mg/L)	(m ³ /d)	(m ³ /d)	(LMH)	(mg/L)
1	1	BW30HRLE-440i	12.0	297.7	8.0	1,164	262.1	35.6	36.3	9.99
1	2	BW30HRLE-440i	12.7	262.1	7.6	1,320	228.7	33.4	34.0	11.71
1	3	BW30HRLE-440i	13.7	228.7	7.3	1,511	197.4	31.4	32.0	13.96
1	4	BW30HRLE-440i	15.0	197.4	7.0	1,748	167.9	29.5	30.1	17.04
1	5	BW30HRLE-440i	16.5	167.9	6.8	2,052	140.2	27.7	28.3	21.43
1	6	BW30HRLE-440i	18.4	140.2	6.6	2,453	114.4	25.9	26.3	28.02
2	1	BW30HRLE-440i	9.1	250.9	6.3	3,000	228.0	22.9	23.3	34.40
2	2	BW30HRLE-440i	9.0	228.0	6.0	3,298	207.4	20.6	21.0	41.86
2	3	BW30HRLE-440i	8.9	207.4	5.7	3,621	189.0	18.4	18.8	51.12
2	4	BW30HRLE-440i	8.7	189.0	5.5	3,968	172.5	16.4	16.8	62.68
2	5	BW30HRLE-440i	8.5	172.5	5.3	4,340	158.0	14.6	14.9	77.12
2	6	BW30HRLE-440i	8.1	158.0	5.1	4,733	145.1	12.8	13.1	95.23

As it can be seen, all the values for each element are in the range of standard condition, which is given in ESS by the manufacturer. (see BW30 HRLE 440i RO ESS).

4.2.5.5. Calculation of energy consumption for two stages bypasses RO system

The required energy for the operation of the bypass RO system is given by software as follows.

Table 4.65. The required energy for the bypass system

Peak Power	(kW)	1,220
Energy	(kWh/d)	29,279
Electricity Unit Cost	(₺/kWh)	1.8900
Electricity Cost	(₺/d)	55,337
Specific Energy	(kWh/m ³)	0.33

Table 4.65 indicates that the total required power for the bypass RO system is 1220 KW and the total energy for one day is 29279 KWh/day. If the cost for 1 KWh is 1.89 Turkiye Lira, then the total energy cost for the plant is 55337 Turkiye Lira, and the energy required for 1 m³ of permeate water is 0.33 KWh/m³. Table 4.66 shows all operating costs for the pump of feed water.

Table 4.66. Operation cost for the bypass system

Pump	Flow Rate	Power	Energy	Cost
	(m³/d)	(kW)	(kWh/d)	(₺/d)
Pass 1				
Feed	101,202.61	1,219.94	29,278.61	55,336.57
Pass 1 Total		1,219.94	29,278.61	55,336.64
System Total		1,219.94	29,278.61	55,336.64

4.2.5.6. Wastewater disposal cost

RO system produces wastewater to dispose of wastewater, and it needs cost. If we assume the cost of wastewater disposal for 1 m³ is 0.30 Turkiye Lira, then the total cost of wastewater disposal is listed in Table 4.67.

Table 4.67. Wastewater disposal for the bypass system

	Flow Rate	Unit Cost	Hourly Cost	Daily Cost
	(m ³ /d)	(₺/m ³)	(₺/h)	(₺/d)
Waste Water Disposal				
Pass 1	22,494	0.3000	281.93	6766.33
Total Waste Water Disposal	22,494		281.93	6766.33
Total Service Water Cost				6766.33

4.2.5.7. The operation cost of the plant

WAVE calculated the total operation cost for the two stages RO system with bypass of feed water which includes the energy cost plus wastewater disposal cost, which indicate as follows.

Utility and Chemical Cost	(₺/d)	62,103
Specific Water Cost	(₺/m ³)	0.690

As shown, the total operating cost for 1 m³ of permeate water by two stages RO system with bypass of feed water is 0.69 Turkish Lira.

4.3. Comparison of One and Two Stages RO System

As we designed three different layouts for the same raw water data and used the same membrane elements in all three scenarios. The single-stage RO system with concentrate recycled used 566 pressure vessels consisting of 3396 membrane elements, and the energy consumption was 0.44KWh/m³ of permeate water. In two stages RO system it was also used 566 pressure vessels with 27 LMH of design flux and 3396 membrane elements, and the energy consumption was 0.36 KWh/m³ of permeate water. In two stages of the bypass RO system, it used 495 pressure vessels in 27LMH of average design flux with consists of 2970 membrane elements, and the energy consumption was 0.33KWh/m³ of permeate water. Let us compare these three layouts to each other according to energy consumption and the number of membrane elements. It comes out

that the most economical layout is two stages bypass RO system because of low energy consumption and the low number of pressure vessels and membrane elements.

For better understanding it drawn the comparison in graphs as follow;

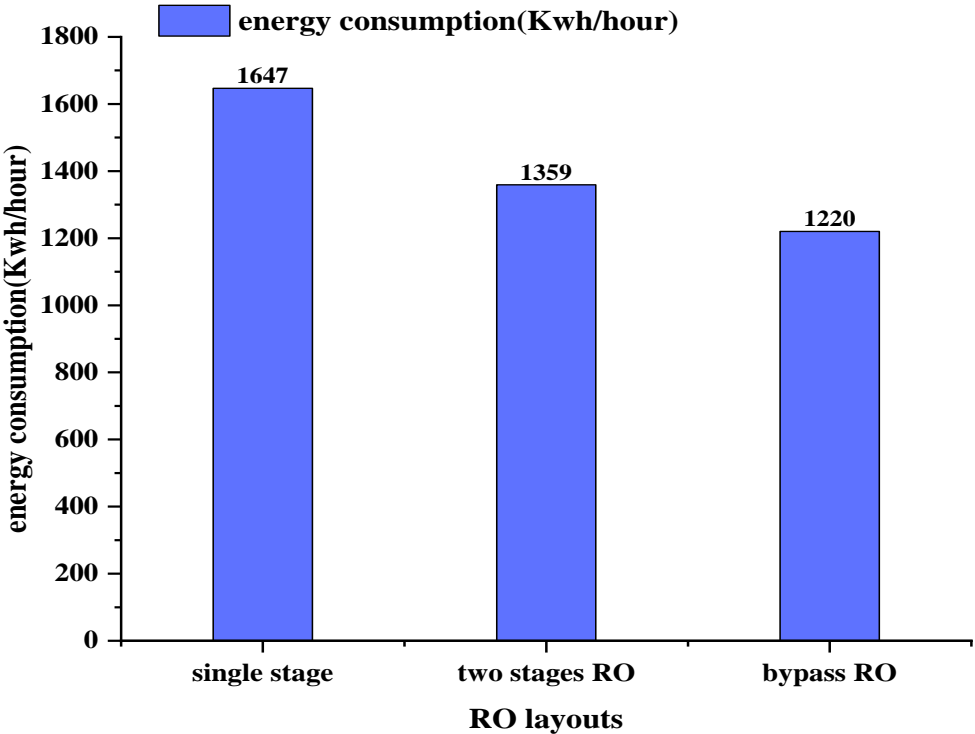


Figure 4.35. comparison of RO layouts for energy consumption

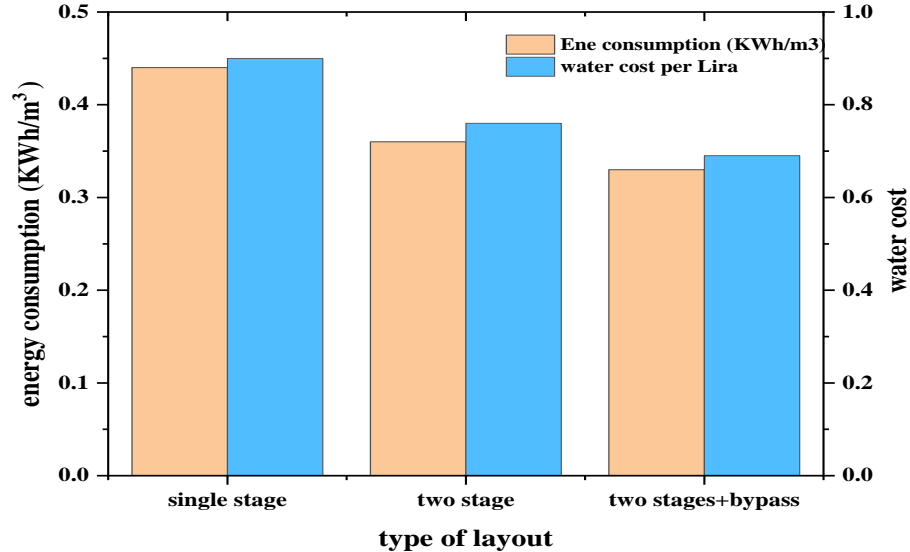


Figure 4.36. comparison of RO layouts for energy consumption and water cost

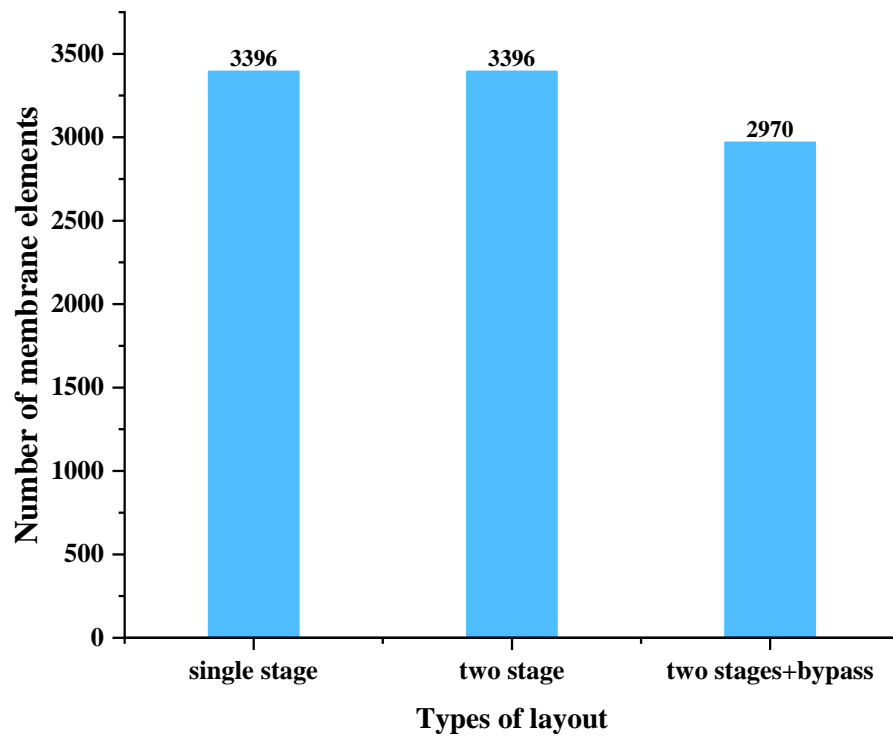


Figure 4.37. comparison of RO layouts for energy consumption and water cost

4.4. Energy Recovery Device Design

ERD devices reduce the energy consumption for RO plant and by installing the ERD devices it reduces the operation cost for the plant, but before installation life cycle cost must be done for the ERD devices and RO plant.

4.4.1. Turbocharger design for RO system

For calculating TC efficiency on the energy demand in two stages RO system, we must calculate the efficiency of the turbine in TC, and the Data which is needed for the calculation is taken from WAVE simulation for two stages RO system and summarized in the following table.

Table 4.68. Feed and concentrate pressure of two stages RO system

#	Description	Flow (m ³ /d)	TDS (mg/L)	Pressure (bar)
2	Feed	112,456	1,179	8.1
	Concentrate 1st stage	42,539	3086	6.4
4	Concentrate 2nd stage	22,498	5,776	5.5
6	Permeate	89,995	28.16	0.0
	Specific energy KWh/m ³		0.36	

The power generated by the turbine is calculated by the following equation;

$$W_t = N_t * K * Q_t * \Delta P_t \quad (\text{Eq. 40})$$

Where W_t is the turbine shaft power, N_t is the turbine efficiency, K is the conversion constant, Q_t is the turbine flow and ΔP_t is the differential pressure across the turbine. The absorbed power by the pump is calculated by the following equation;

$$W_p = K * Q_p * \frac{\Delta P_p}{N_p} \quad (\text{Eq. 41})$$

Where W_p pump absorbed power, K is the conversion constant, Q_p is the pump flow, ΔP_p is the differential pressure across the pump and N_p is the pump efficiency. In a turbocharger, it assumes that generated energy by the turbine is equal to absorbed energy by the pump, so we have $W_t=W_p$

$$N_t * K * Q_t * \Delta P_t = K * Q_p * \frac{\Delta P_p}{N_p} \quad (\text{Eq. 42})$$

$$N_t * N_p = Q_p * \frac{\Delta P_p}{Q_t * \Delta P_t} \quad (\text{Eq. 43})$$

We have as

$$R = \frac{Q_t}{Q_p} \quad (\text{Eq. 44})$$

$$N_t * N_p = \frac{\Delta P_p}{R * \Delta P_t} \quad (\text{Eq. 45})$$

For the finding of the net transfer efficiency of the turbocharger, we have

$$N_{trn} = N_t * N_p \quad (\text{Eq. 44})$$

$$N_{trn} = \frac{\Delta P_p}{R * \Delta P_t} \quad (\text{Eq. 46})$$

For the calculation of the ΔP_t it assumes pressure for concentrate water is 0.5 bar, so we have $\Delta P_t =$ concentrate pressure inlet to turbine minus concentrate outlet pressure from the turbine, which is 1.5 bar

$$\Delta P_t = 5.5 \text{ bar} - 1.5 \text{ bar} = 4 \text{ bar}$$

And for the ΔP_p We have the pressure absorbed from the turbine minus the feed pressure of the pump.

$$\Delta P_p = 6.4 \text{ bar} - 4 \text{ bar} = 2.4 \text{ bar}$$

Assume the boost pressure by TC 2.4 bar.

$$N_{trn} = \frac{\Delta P_p}{R * \Delta P_t} = \frac{2.4 \text{ bar}}{0.8 * 4 \text{ bar}} = 0.75$$

As we can see, the net transfer efficiency of TC is approximately 75%. TC manufacturers published the TC specification sheet and mentioned the efficiency of the TC, and most TC has an efficiency between 50 to 80 %. For the calculation of electricity demand, we have;

$$E = \left[\frac{(0.0275 * P_{feed})}{N_{pump} * R} \right] - \left[\frac{0.0275 * (1 - R) * P_{conc} * N_{turbine}}{R} \right]$$

If we use ERD in our system, then the energy required will decrease. For this purpose, it is used the following equation;

$$E = \left[\frac{(0.0275 * P_{feed})}{N_{pump} * R} \right] - \left[\frac{0.0275 * (1 - R) * P_{conc} * N_{turbine}}{R} \right]$$

We have energy consumption by 1 m³ of two stages RO system which is calculated 0.289 KWh/m³ obtained by hand calculation.

$$E = [0.289 \text{ KWh/m}^3] - \left[\frac{0.0275 * \left(1 - \frac{80}{100}\right) * 4.1 * 0.75}{\frac{80}{100}} \right] = 0.205 \text{ KWh/m}^3$$

$$\text{energy for 1h of plant} = 3750 \frac{\text{m}^3}{\text{h}} * 0.205 \frac{\text{Kwh}}{\text{m}^3} = 768.75 \text{ Kwh} \cong 769 \text{ Kwh}$$

$$\text{energy for 1 day of plant} = \frac{769Kwh}{h} * \frac{24 h}{1 \text{ day}} = 18456 \frac{Kwh}{\text{day}}$$

as we can see, the energy consumption for one day of two stages RO plant is $18456 \frac{Kwh}{\text{day}}$ with ERD devices but without ERD, the energy consumption was $26010 \frac{Kwh}{\text{day}}$ which shows near to 30% of energy recovery by ERD.

As indicated from the calculation, the reduction in energy consumption for 1 m^3 of water is $0.084KWh/m^3$ by using TC in the RO system. Figure 4.38 shows the installation site for TC.

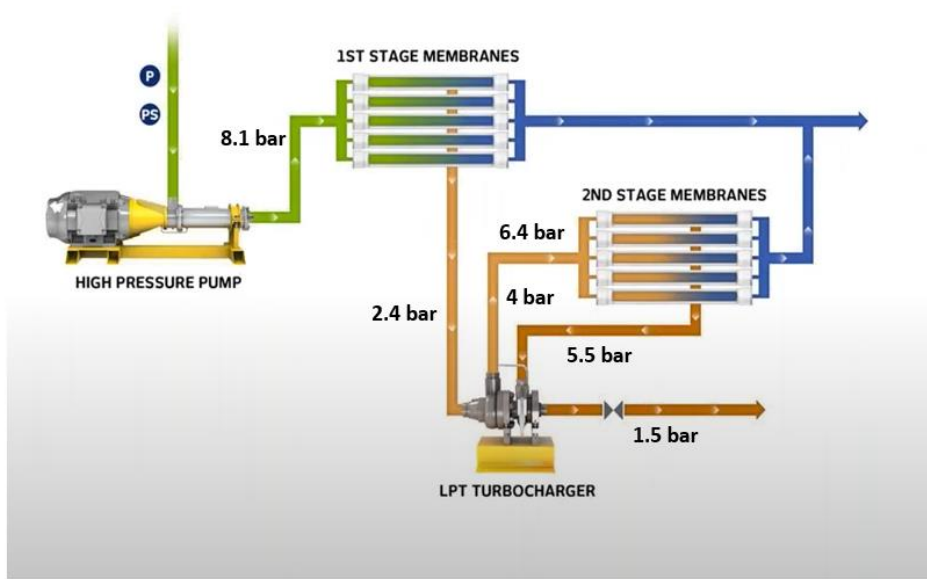


Figure 4.38. Source (Michas, 2013) edited with present study data.

The energy consumption obtained by WAVE for two stages RO system is $0.36KWh/m^3$. If we use ERD device in this system, the energy reduction is calculated as follows;

$$E = [0.36KWh/m^3] - \left[\frac{0.0275 * \left(1 - \frac{80}{100}\right) * 6.4 * 0.75}{\frac{80}{100}} \right] = 0.228KWh/m^3$$

$$\text{energy for 1h of plant} = 3750 \frac{m^3}{h} * 0.228 \frac{Kwh}{m^3} = 855Kwh$$

$$\text{energy for 1 day of plant} = \frac{855Kwh}{h} * \frac{24 h}{1 \text{ day}} = 20520 \frac{Kwh}{\text{day}}$$

as we can see, the energy consumption for one day of two stages RO plant is $20520 \frac{Kwh}{day}$ with ERD devices but without ERD, the energy consumption was $32621 \frac{Kwh}{day}$ which shows near to 36% of energy recovery by ERD.

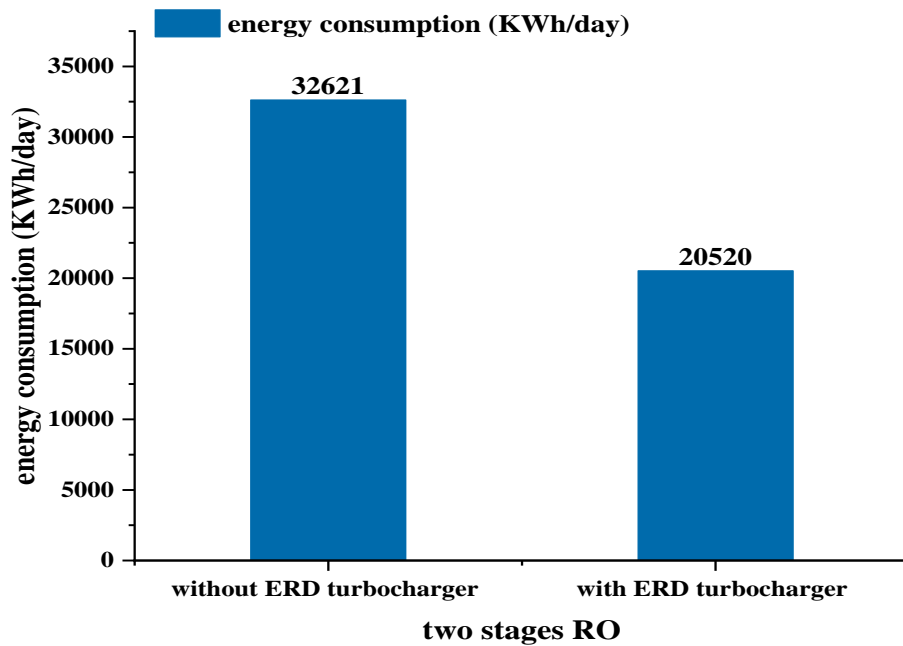


Figure 4.39. Energy consumption for two stages RO plant with and without ERD devices

4.5. RO System Based On Renewable Energy Source

Currently, the RO system uses the available electricity from the grid, produced mainly by fossil fuels. The first part of this study tried to numerically calculate the PV solar panel system and simulate the designed PV system by software. Different softwares are available as commercial and free for assessing and simulating green energy such as HOMER, RETscreen, PV sol, and others (Gökçek, 2018). In the present study it will use RETscreen software for the simulation of PV solar energy production system for the production of energy for the proposed RO water treatment system.

4.5.1. Methods for the PV design

The main problem with the design of this system is that the RO system needs constant energy demand over the day, months, and years but the PV system fluctuates for energy supply to the system during the night, on cloudy days, and so on. Several solutions to this problem are suggested to overcome the problem and supply the required energy to the system (Alsheghri et al., 2015). for example;

A- design PV system with batteries and store the energy and use it during the night and on cloudy days.

B- Producing the demand for night water during the day and storing it in a tank for night uses.

C- Producing extra electricity, selling it to the grid system, and buying the electricity during the solar irradiation is not enough to produce electricity for the RO system.

D- And design a PV system to produce the annual RO required energy and supply the energy to the RO system directly from the grid.

The first solution is not applicable due to the high cost and technology, and the B and C solution required more land and high cost (Alsheghri et al., 2015). The D solution is economical and easy, and we will use it in the present study.

4.5.2. Geographical and Metrological Data of the Site

The designed UF-RO water treatment plant is located in the Kirikkale city of Turkiye and can produce 90000m³/day of drinking water. The present study designed the RO plant by hand and simulated different scenarios for the plant using WAVE software. The energy demand for the UF-RO plant to run and operate all parts, including the UF pretreatment system with RO membrane system, is listed in Table 4.69 for all scenarios.

Table 4.69. Energy consumption for all scenarios of the designed RO plant

Scenario	UF energy demand (KWh)	RO energy demand (KWh)	Total energy demand (KWh)
Single-stage UF-RO design by hand	174	1313	1487
Two stages of UF-RO system design by hand	174	1084	1258
Singe stage with Qc recycled by WAVE	258*	1647	1905
Double stages RO by WAVE	258*	1359	1617
Two stages RO with bypass by WAVE	258*	1220	1478

*It also includes the energy consumption for BW, CEB, and CIP.

As shown in Table 4.69, different scenarios need various energy demands in the present study. It will design the PV system only for one of the designed RO systems for a single-stage Ro system, which needs up to 1500 KWh energy. The plant is located in the area of Hasandede town near Kirikkale city. The geographical data for the site is reported in Table 4.70.

Table 4.70. Geographical data for metrological site of Kirikkale city

Geographical data of site	
Location of the site	17135stationMerkez, Kirikkale,Turkiye
Latitude	39.8433
Longitude	33.5181

In the metrological data, we need to measure the sun's irradiation on the surface of the selected area and wind speed for at least one year. To design a PV system, it is essential to know the average direct radiation for years' months, and days for a specific area.

Figure 4.40 shows the map of direct radiation of solar for Turkiye, which was taken from the Global solar atlas.

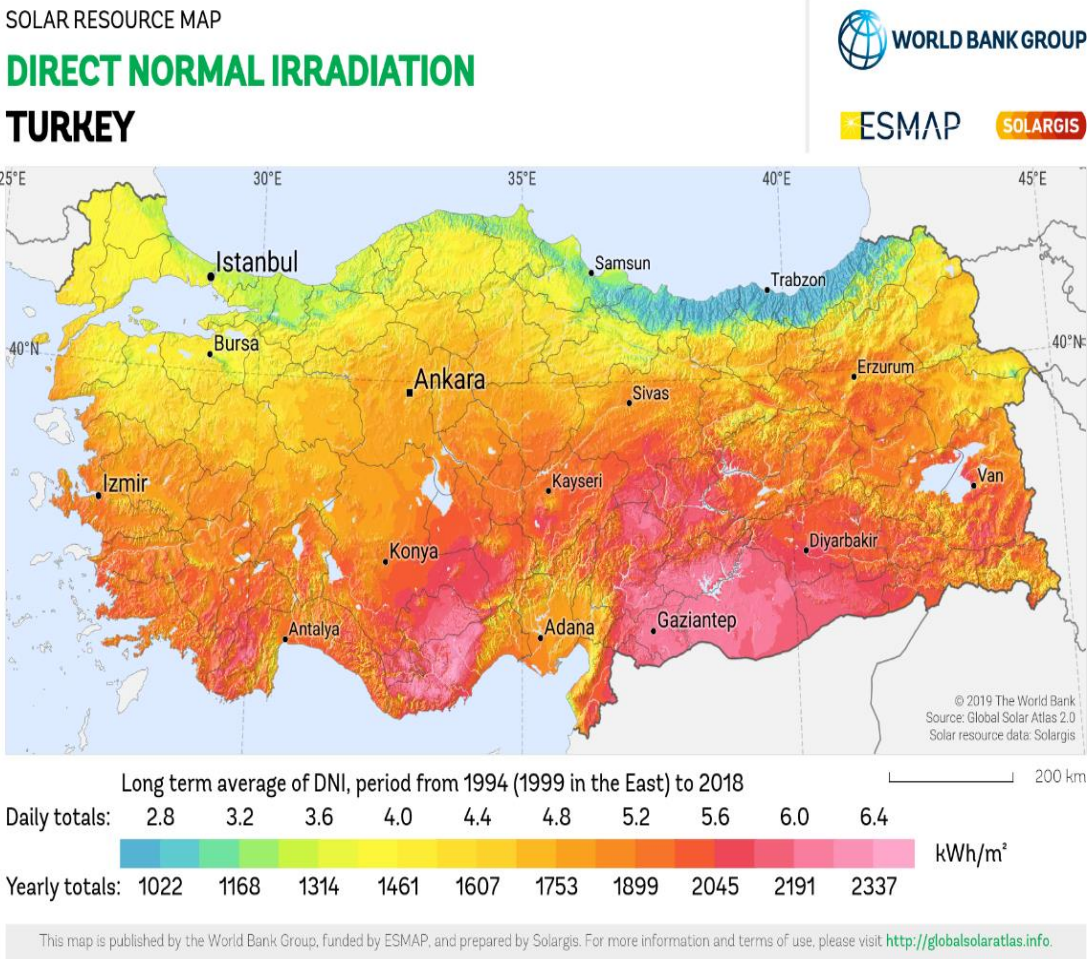


Figure 4.40. DNI for Turkiye (<https://globalsolaratlas.info/download/turkey>)

Figure 4.40 indicates that the southern side of turkey has high direct radiation up to 6.4 KWh/m² daily, which means the south part of the country is more suitable for producing energy with PV systems. Furthermore, the global horizontal irradiation for turkey has been shown in Figure 4.41.

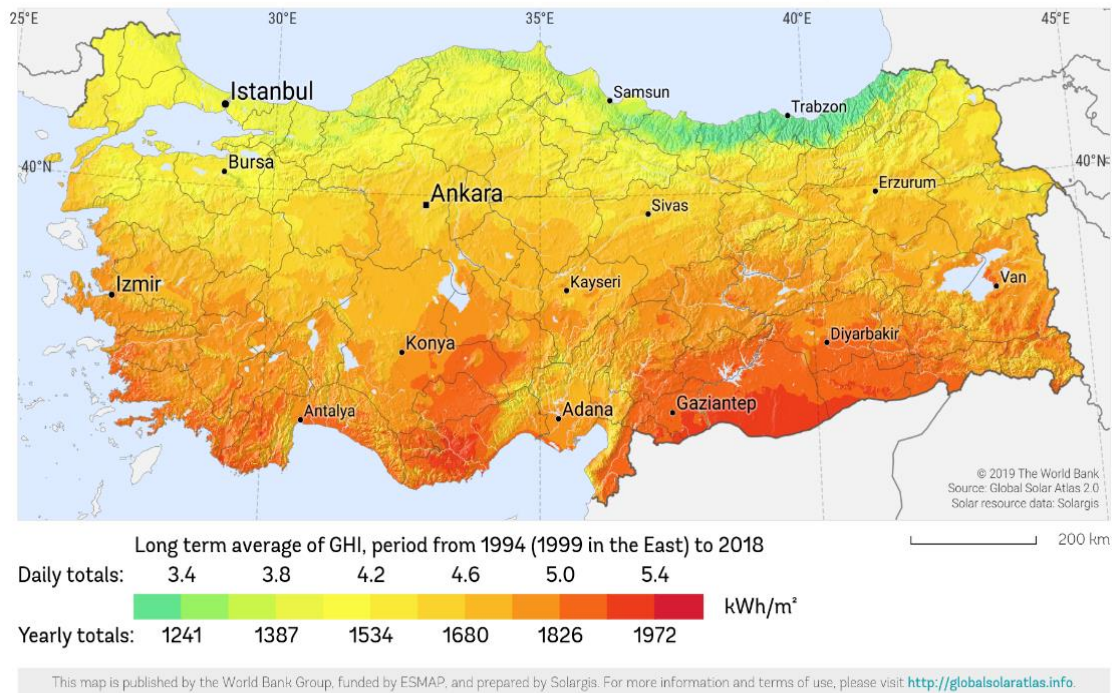


Figure 4.41. Shows the global horizontal irradiation(GHI) for Turkiye.

(<https://globalsolaratlas.info/download/turkey>)

GHI is the amount of solar energy integrated in a time that is attenuated by all constituents of the atmosphere and falling on a horizontal surface of the earth. GHI integrates direct, diffuse, and reflected components of solar energy. (European Commission). As shown in Figure 65, the GHI is less than DNI for Turkiye.

In addition, the global solar atlas represents the PV power output(PVOUT) worldwide. PVOUT is used to illustrate the potential of PV systems and represent the amount of power generated per unit of the installed PV capacity over a long time and measured in kilowatt-hours per installed kilowatt-peak of the system capacity (kWh/kWp). (<https://globalsolaratlas.info/global-pv-potential-study>). Figure 4.42 shows the PVOUT of Turkiye taken from the global solar atlas.

**PHOTOVOLTAIC POWER POTENTIAL
TURKEY**

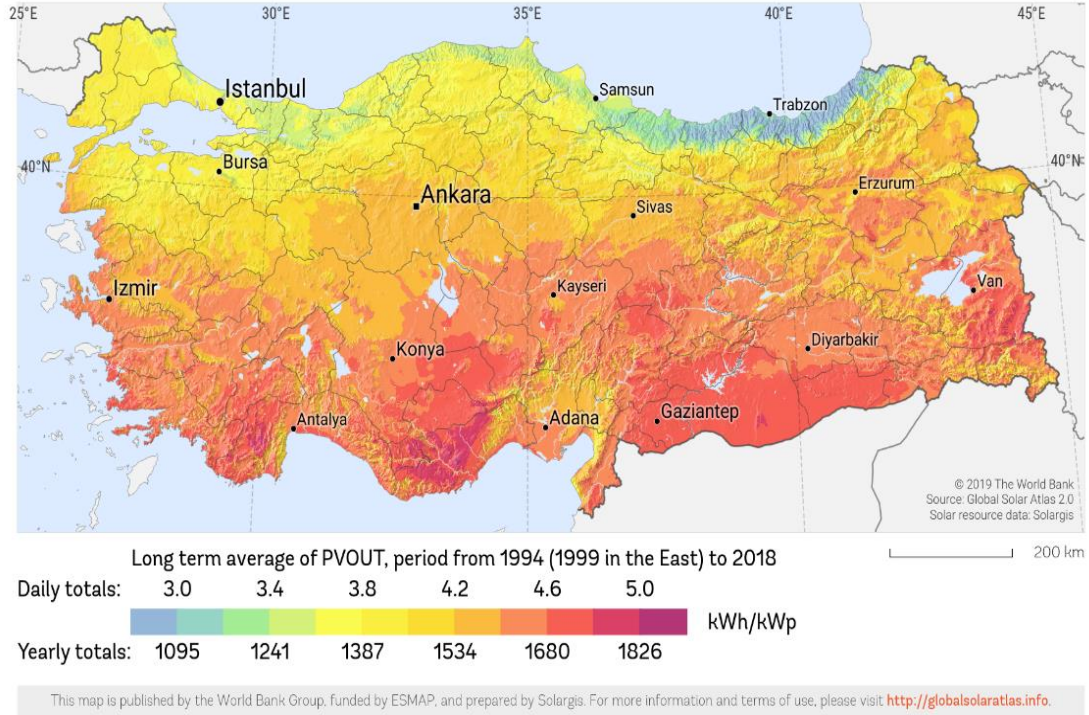


Figure 4.42. PVOUT for Turkiye (<https://globalsolaratlas.info/download/turkey>)

As we can see in Figure 4.41, the PVOUT in the southern areas of the country has enormous potential for solar energy production. The global solar atlas used data from 1994 to 2018 in these maps. The present study is planned to calculate a PV energy production system for the Kirikkale city RO water treatment system. The DNI, GHI, and PVOUT maps for Kirikkale city are shown in Figure 4.43, 4.44, and 4.45.

SOLAR RESOURCE MAP
DIRECT NORMAL IRRADIATION
 Kirikkale, Turkiye

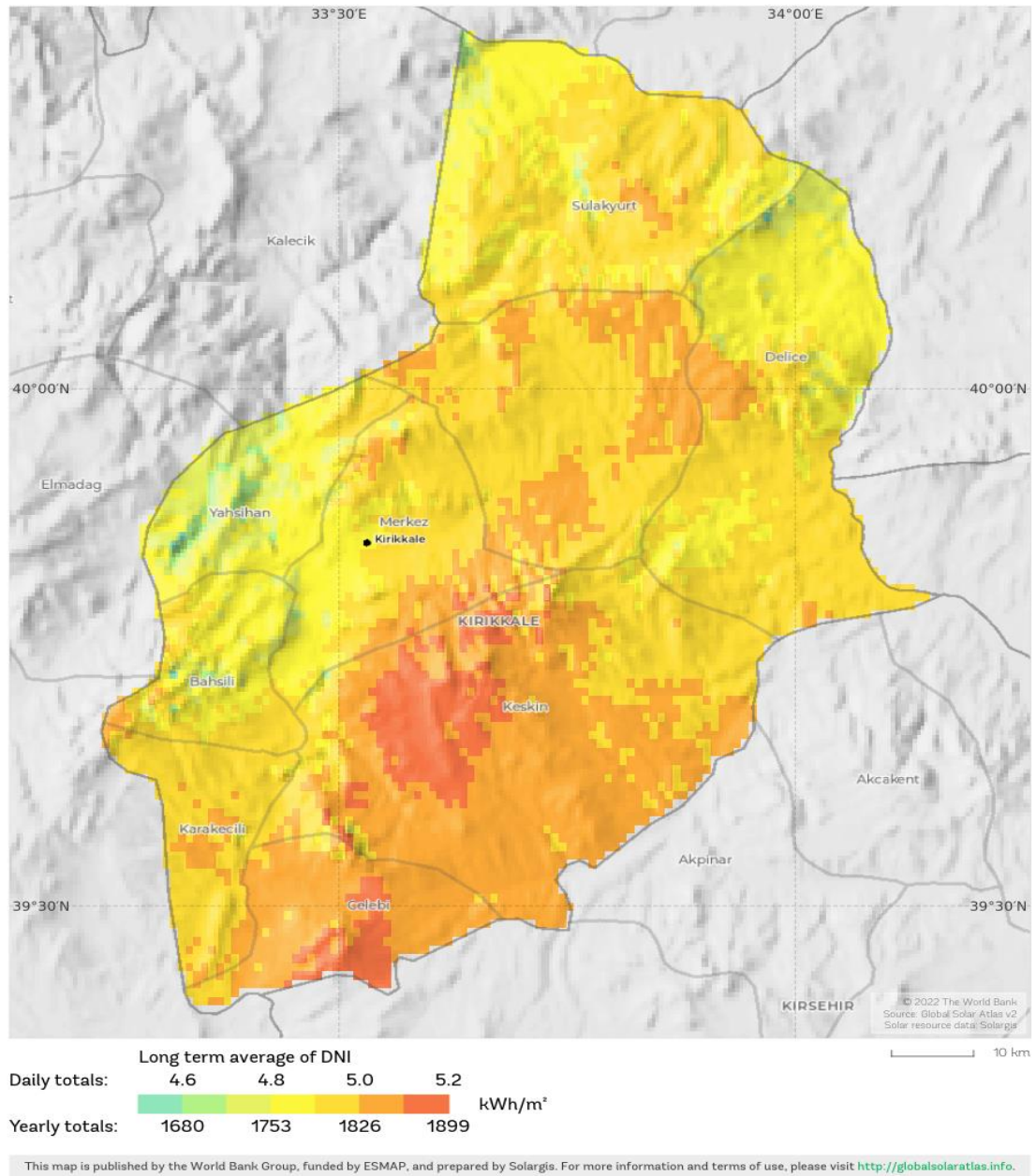
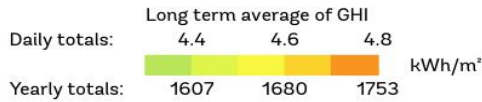
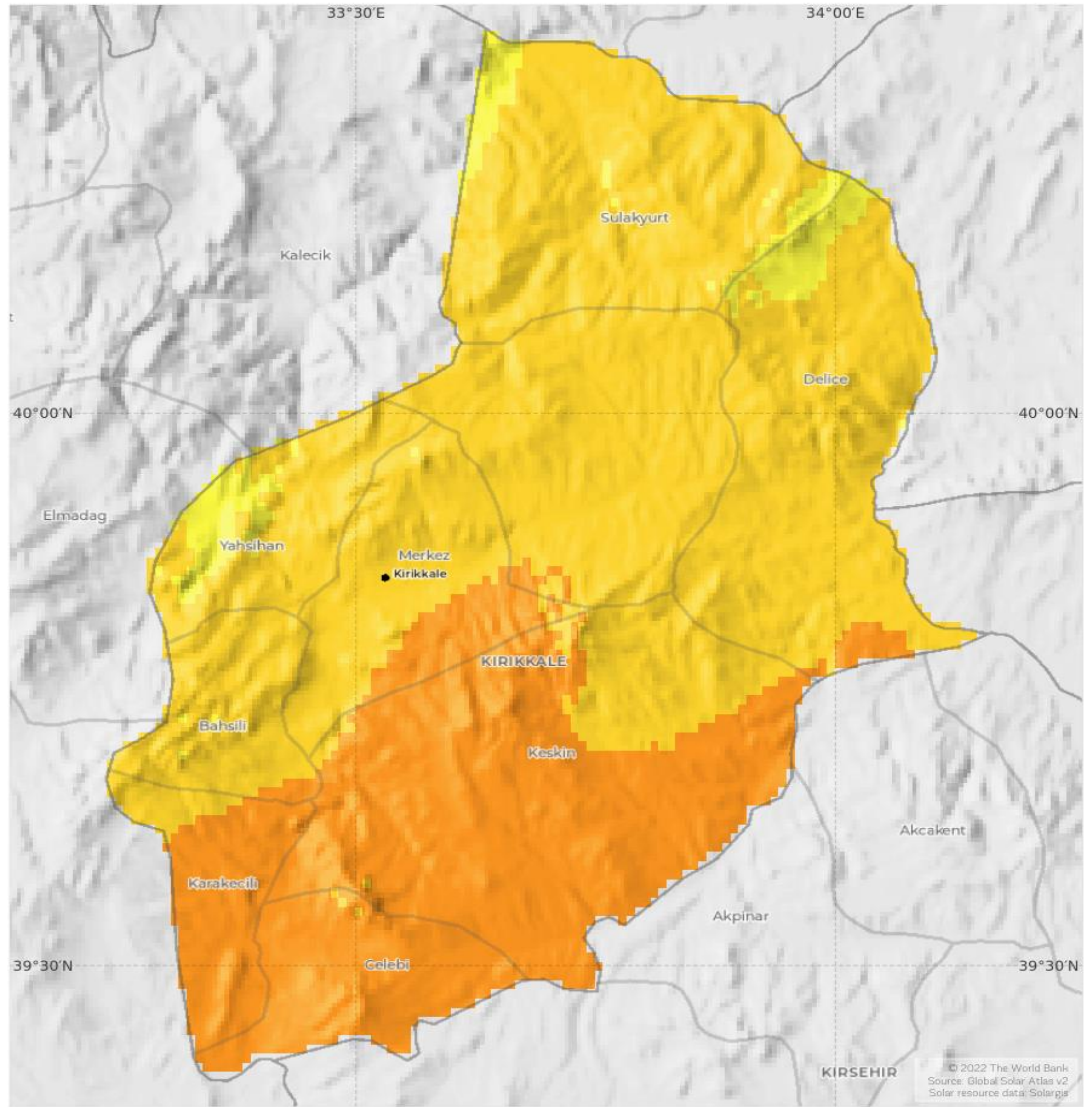


Figure 4.43. DNI for Kirikkale city (<https://globalsolaratlas.info/map>)

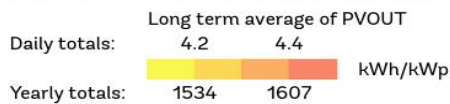
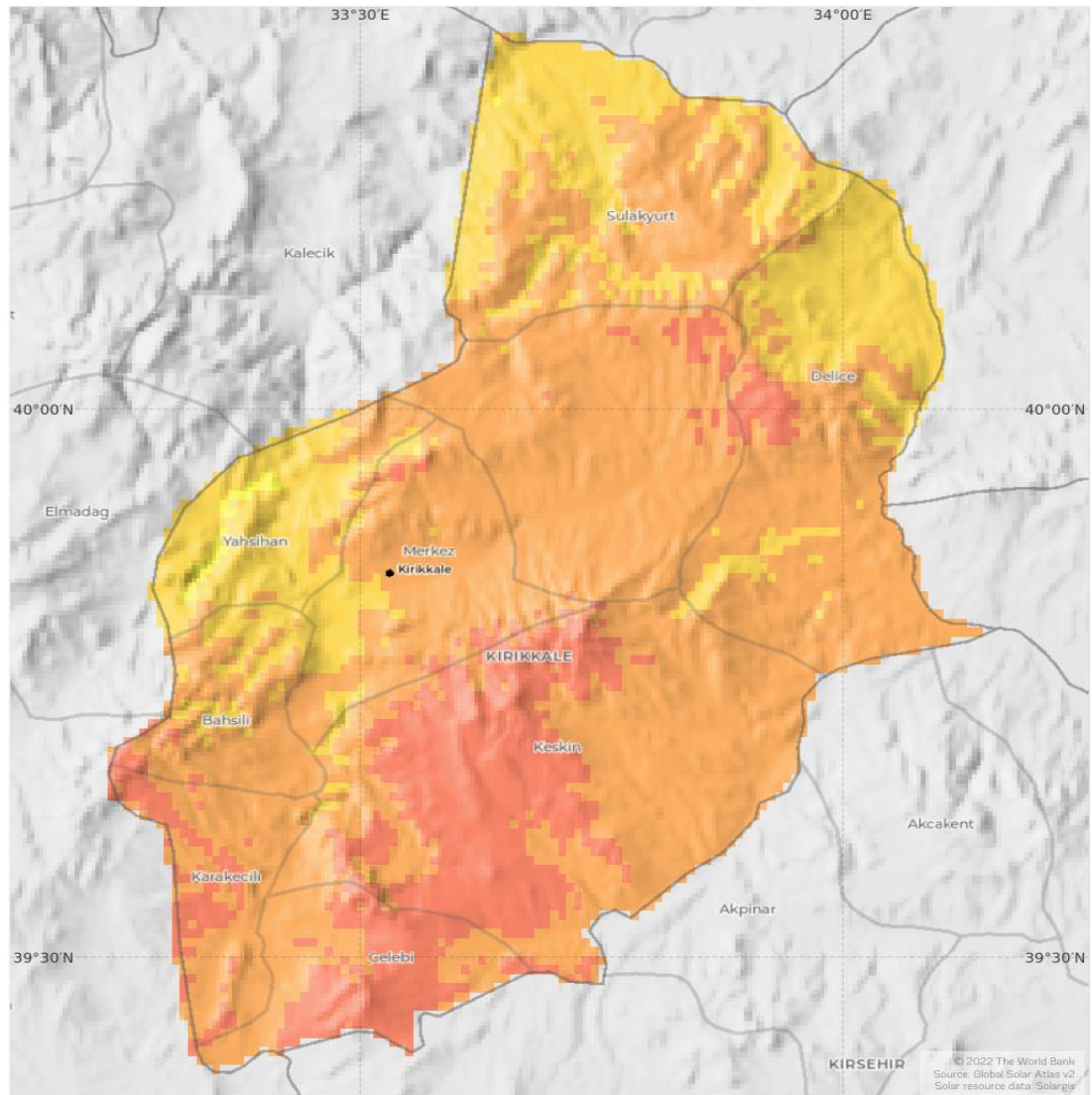
Figure 4.43 shows the direct normal irradiation for Kirikkale city, where the plant is located near the city of Kirikkale at Hasandede Mahalle. It indicated from Figure 4.43 that the southeast part of Kirikkale, where the plant is located, has an average of 5 KWh/m² of DNI.



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Figure 4.44. GHI for Kirikkale city (<https://globalsolaratlas.info/map>)

Figure 4.45 shows the GHI for Kirikkale city the selected area has up to 4.8 KWh/m² GHI.



This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit <http://globalsolaratlas.info>.

Figure 4.45. PVOUT for Kirikkale city (<https://globalsolaratlas.info/map>)

Figure 4.45 shows the PVOUT potential for Kirikkale city; for the selected area, the PVOUT is 4.4 KWh/KWP.

For the selected area, it has also taken the above mentioned data from Turkiye metrology department for five years. Table 4.71 shows the average GHI data for Kirikkale city for five years.

Table 4.71. Average global horizontal irradiation for 5 years

Average global horizontal irradiation(GHI) for Kirikkale city				
2017	2018	2019	2020	2021
4.273198	4.314798	4.241813	4.496546	6.631848

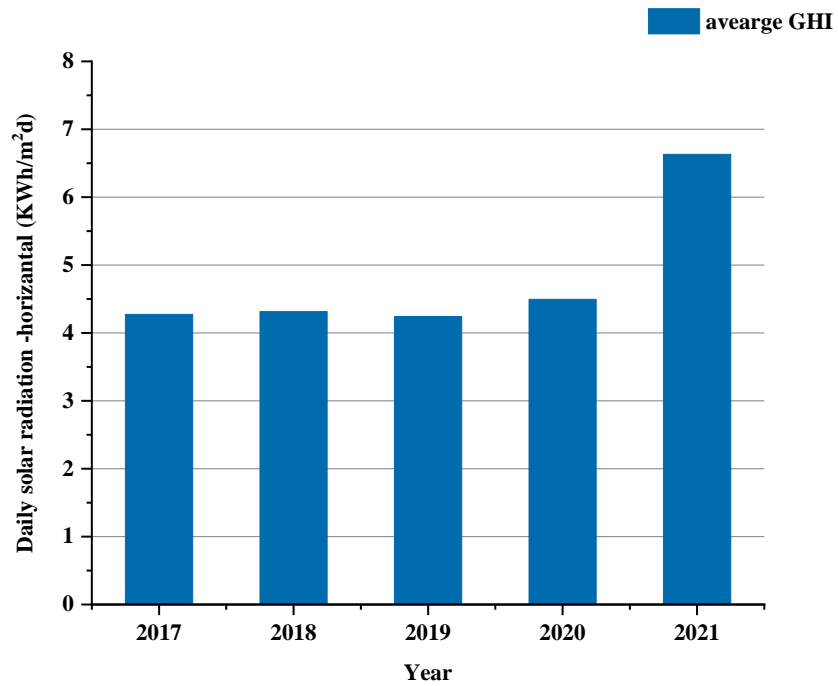


Figure 4.46. Average daily solar radiation for 5 years of Kirikkale

Figure 4.46 shows the average daily solar radiation horizontally on the surface of Kirikkale city from 2017 to 2021, which shows rapid increases in 2021 as the average GHI for 2021 is 6.63 KWh/m² d. Table 4.72 shows the average daily GHI for each month of the five years.

Table 4.72. Average daily irradiation for months of the 5 years

Average daily GHI for each month of 5 years					
	2017	2018	2019	2020	2021
January	3.977	1.429032	1.435	1.903	1.639
February	4.911	2.304348	2.471	2.393	3.221
March	3.784	3.326	4.416	4.029	3.429
April	5.000	6.120	4.907	5.503	4.700
May	5.262	5.684	5.913	6.248	6.684
June	6.180	7.183	6.540	6.700	7.657
July	6.429	7.145	6.823	7.542	11.900
August	5.423	6.626	6.077	6.539	10.987
September	4.397	5.093	5.267	5.223	9.083
October	2.297	3.590	3.626	3.752	8.023
November	2.213	2.173	2.387	2.510	6.443
December	1.406	1.103	1.040	1.616	5.816

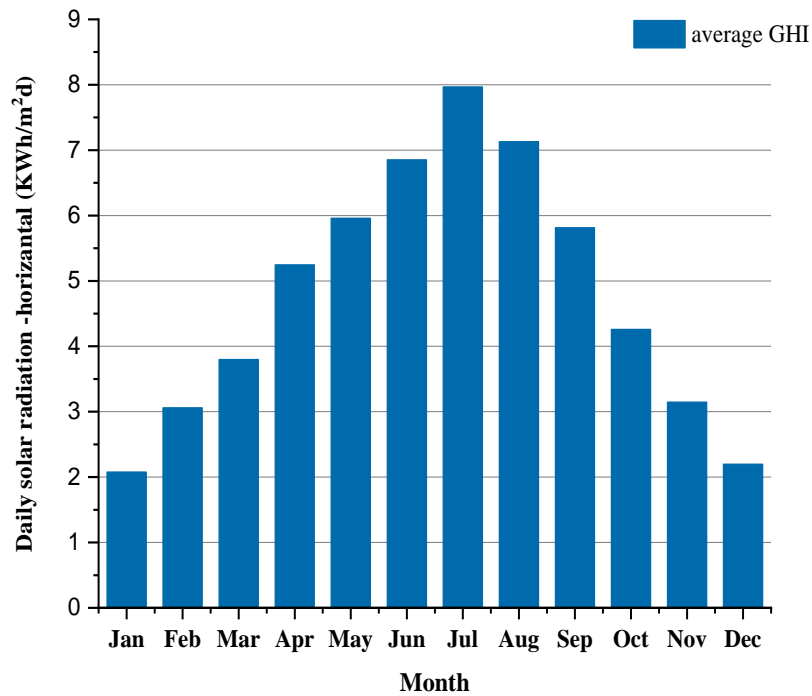


Figure 4.47. Daily solar radiation for each month of the year for Kirikkale city

Table 4.72 and Figure 4.47 show the daily solar radiation of each month for five years as it can be seen that the highest value is in July and August months which are more than 7 KWh/m² d.

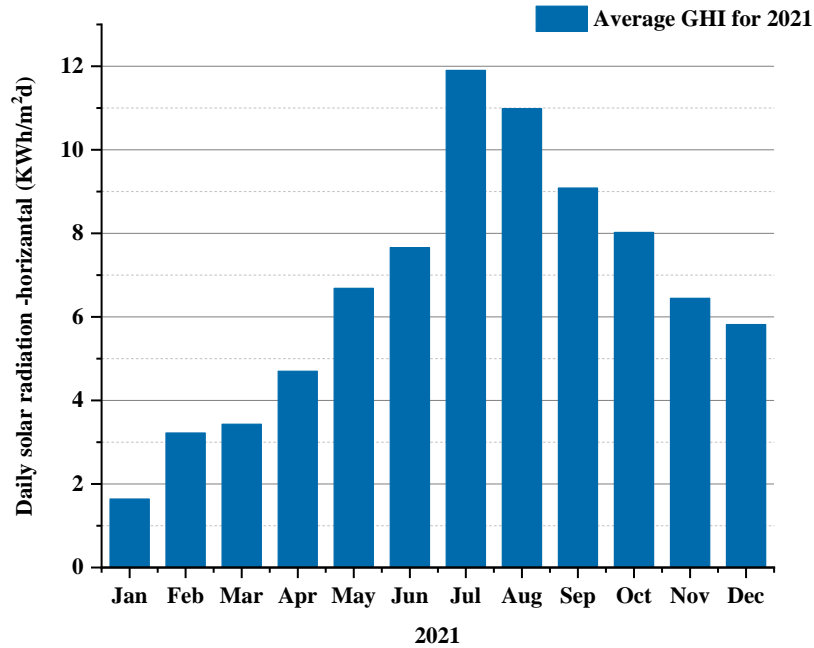


Figure 4.48. Shows the average daily GHI for each month of 2021.

As indicated in Figure 4.48 in 2021, the daily solar irradiation increased for every month of the year but the highest GHI is in July and August, which is more than 10 KWh/m² d. As it can be seen, the GHI is different over months and years. Suppose it finds the average of each month for five years. In that case, it is equal to 4.79 KWh/m² d, which is near the value taken from the global solar atlas for Kirikkale, so we assumed it was 4.8 KWh/m² d of daily solar irradiation for the selected area. According to climate data, the annual sun hours for Kirikkale city is 2345 hours average daily sunshine is 6.42 hours.

4.5.3. Photovoltaic System

A photovoltaic system converts solar irradiation to electricity, called the photovoltaic conversion effect. When semiconductor materials are exposed to light, photons of light beams excite the electrons in the semiconductor material and produce a significant number of free electrons. The current of these electrons generates electricity.

In this way, the photovoltaic effect produces electricity. The photovoltaic cell is the system's main unit in which the photovoltaic effect is used to generate electricity from light. Figure 4.48 shows the process behavior.

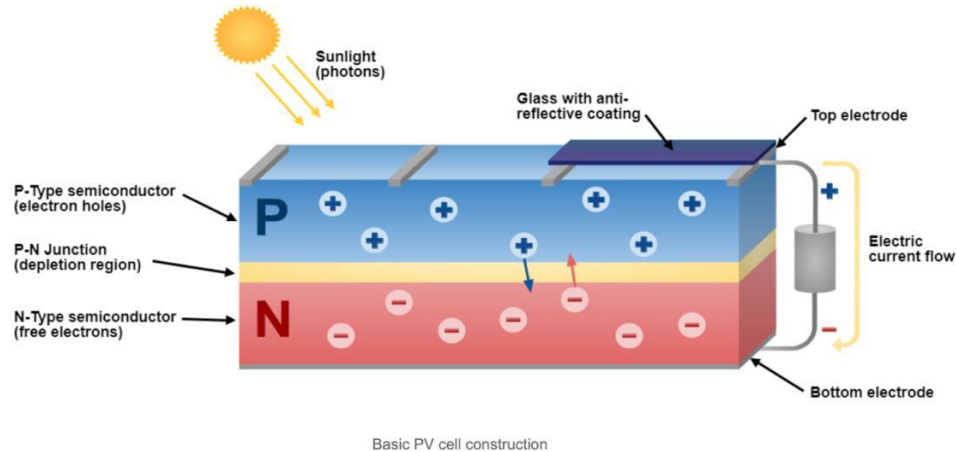


Figure 4.49. Photovoltaic Cell Schematic (Subedi, 2021)

Different materials are used as semiconductor materials for the production of photovoltaic cells. One of the most used materials is silicone (Subedi, 2021). Generally, the PV system has two types off-grid and grid-tied systems. The Off-Grid system has no power backup system, while a grid system is connected to the grid. In a grid-connected system, the PV system converts solar energy into DC electricity, which is converted to AC power via an inverter and connected to the grid system (Subedi, 2021).

In the present study, we will design and calculate the tied grid system for the demand of our designed RO system. It must design the PV system to supply the energy which needs by the RO system, and for the design of the PV system, we use daily solar irradiation of Kirikkale city, where the plant is located. It obtained GHI for Kirikkale from metrology data collected from the site, and the daily irradiation is $4.8\text{KWh/m}^2 \text{ d}$. This section is expected to calculate the annual solar energy in the site and then convert it to electricity. Several PV manufacturers produce PV panels in the Turkiye with different specifications and capacities. The present study will use the Ankara solar manufacturer production (AS-M72 380-405W Mono Perc) Solar Panel. The specifications of this panel are given in the panel specification sheet(PSS) as follows;

AS-M72 380-405W

ELECTRICAL CHARACTERISTICS AT (STC)

Nominal Power (Pmax)	380W	385W	390W	395W	400W	405W
Open Circuit Voltage (Voc)	48.4V	48.6V	48.8V	49.0V	49.2V	49.4V
Short Circuit Current (Isc)	9.99A	10.06A	10.13A	10.20A	10.27A	10.34A
Voltage at Nominal Power (Vmpp)	39.8V	40.0V	40.2V	40.4V	40.6V	40.8V
Current at Nominal Power (Imp)	9.55A	9.63A	9.71A	9.78A	9.86A	9.93A
Module Efficiency %	19,15	19,41	19,66	19,91	20,16	20,37
Operating Temperature	-40 °C to +85 °C					
Maximum System Voltage	1000V / 1500V					
Maximum Series Fuse Rating	20A					

STC : Irradiance 1000W/m2 Cell temperature 25C AM 1.5

ELECTRICAL CHARACTERISTICS AT (NOTC)

Nominal Power (Pmax)	283W	287W	291W	295W	299W	303W
Open Circuit Voltage (Voc)	44.9V	45.1V	45.3V	45.5V	45.7V	45.9V
Short Circuit Current (Loc)	8.09A	8.15A	8.21A	8.27A	8.33A	8.39A
Voltage At Nominal Power (Vmpp)	36.7V	36.9V	37.1V	37.3V	37.5V	37.7V
Current At Nominal Power (Impp)	7.72A	7.78A	7.85A	7.91A	7.98A	8.05A

NOCT, Irradiance 800w/m2 Ambient Temperature 20C Wind Speed 1m/s

STC : Irradiance 1000W/m2 Cell temperature 25C AM 1.5

ELECTRICAL CHARACTERISTICS AT (NOTC)

Nominal Power (Pmax)	283W	287W	291W	295W	299W	303W
Open Circuit Voltage (Voc)	44.9V	45.1V	45.3V	45.5V	45.7V	45.9V
Short Circuit Current (Loc)	8.09A	8.15A	8.21A	8.27A	8.33A	8.39A
Voltage At Nominal Power (Vmpp)	36.7V	36.9V	37.1V	37.3V	37.5V	37.7V
Current At Nominal Power (Impp)	7.72A	7.78A	7.85A	7.91A	7.98A	8.05A

NOCT, Irradiance 800w/m2 Ambient Temperature 20C Wind Speed 1m/s

MECHANICAL CHARACTERISTICS

Cell Type	Monocrystalline PERC
Number of Cells	72 (6x12)
Module Dimensions	1980x1004x42mm
Weight	22.5 kg
Front Cover	3.2 Tempered Glass EN12150
Frame	Anodize Aluminium Alloy
Junction Box	Ip67, 3 dodes
Cable	4mm2 900 - 1200mm
Connector	MC4 or MC4 compatible IP67
Cell Encapsulation	EVA (Ethylene - Vinly - Acetate)

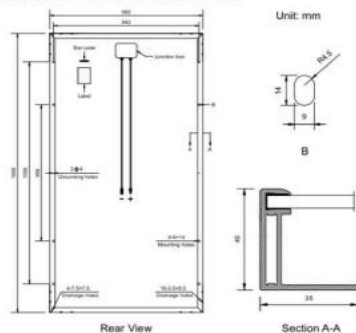
TEMPERATURE CHARACTERISTIC

Nominal Operating Cell Temperature	45°C±2°C
Tempereature Coefficients of Pmax	-0.38%/°C
Tempereature Coefficients of Voc	-0.29%/°C
Tempereature Coefficients of Voc Isc	0.052%/°C

PACKING

Standart Packaking	27 Pieces / Palet
Module quantity per 20'container	270 Pieces
Module quantity per 40'container	594 ieces

ENGINEERING DRAWINGS IV



IV CURVES

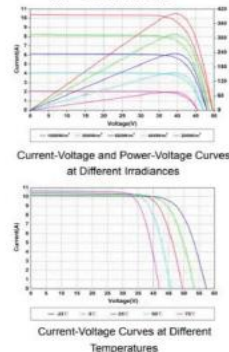


Figure 4.50. Panel specification sheet (<http://www.ankarasolar.com.tr/>)

The required energy for the RO plant is obtained at 1500 KWh this energy demand is only for the running of UF-RO operation. It does not include the energy for the supply of treated water.

$$\text{energy consumption for 1 hour of plant} = 1500\text{KWh}$$

$$\text{energy consumption for 1 day of plant} = 1500\text{KWh} * \frac{24\text{h}}{\text{day}} = 36000\text{KWh/day}$$

The average daily irradiation for the selected area is 4.8KWh/m² d

$$\text{Area of solar panel} = 1.98\text{m}^2$$

The efficiency of solar panels = 20.37%

$$\text{energy product by single panel} = \frac{4.8\text{KWh}}{\text{m}^2\text{d}} * 1.98\text{m}^2 * 0.2037 = 1.93 \frac{\text{KWh}}{\text{day}}$$

The system loses due presence of dirt and snow on the panels = 14%

Invertor losses= 1%

$$\text{energy product by single panel} = 1.93 \frac{\text{KWh}}{\text{day}} * 0.86 * 0.99 = \frac{1.64\text{KWh}}{\text{day}}$$

$$\text{number of panel} = \frac{\text{energy demand for 1 day}}{\text{energy produced by 1 panel}} = \frac{36000\text{KWh/day}}{1.65\text{KWh/day}} = 21819$$

For the supply of RO plant, it needs to install 21819 solar panels in the area and convert the produced energy by convertor and supply to the main grid system.

The solar collected area is calculated as follows;

$$\text{net area for panel arrays} = 21819 * 1.98\text{m}^2 = 43200\text{m}^2$$

Furthermore, it can find the site's monthly electricity production, summarized in Figure 4.51.

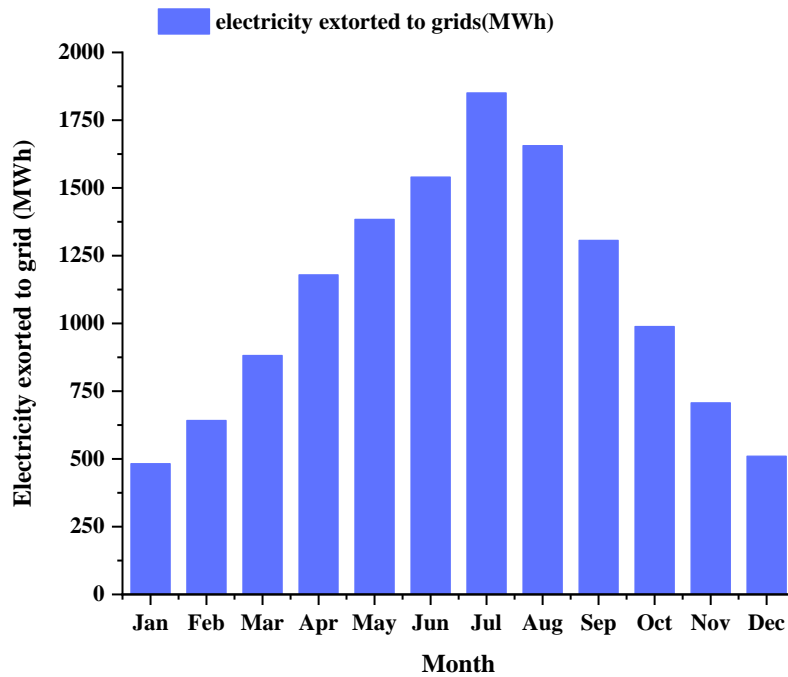


Figure 4.51. Produced and reported energy to the main grid system by PV

As it can be seen, the most electricity produced in July is 1850.63 MWh, and the annual produced energy by the PV system is about 13128.7 MWh which is equal to the energy consumption of the RO system. The produced DC energy is converted to AC energy by converter and then by transformers sent to the main grid system.

4.5.4. Inverters installation

The PV system is designed to install panels in 20 subfields. Each subfield is connected to a converter with a capacity of 500 KW, which changes the direct current to alternating current and sends it to a transformer that connects to the main grid system. An inverter is an electronic device that converts DC electricity to AC and can accept maximum current from the PV side (Bentouba et al., 2021). The efficiency of the inventor is up to 98.5% (Bentouba et al., 2021). Moreover, the project totals 26 invertors installed, and 10 transformers will transfer the electricity to the grid. Table 4.74 shows the description of invertors and transformers.

Table 4.73. Inverter and transformer specifications

Equipment	Numbers
380-405Wp panels	21819
1 MW subfield	10
invertors	26
1250 kVA/630 kVA transformers	10

For the economic issues, it is essential to evaluate the designed PV project and see the results according to the selling of the energy and the price of the project construction. Furthermore, it will evaluate the reduction of greenhouse gas emissions (GHG) by implementing the project.

4.6. Simulation of The PV System by RETscreen

Different simulation softwares are available for the PV system, such as HOMER, RETscreen, PVsys, and others. In the present study, the selected PV system will investigate by RETscreen. The RETscreen is clean energy project analysis software that is published by the government of Canada and can simulate financial and emission analysis of the project (Salehin et al., 2016). The main focus of analysis for a PV system is for emissions analysis and reduction of emissions by implementing the PV system. In addition, RETscreen can analyze different scenarios for financial details for the PV project. However, the present study doesn't include the financial analysis and scenarios due to the lack of financial data for the next 20 of Turkey. Following it discuss the study area, metrological data for the area, and selection of the PV system for the study.

4.6.1. Selection of the area for the PV system

RETscreen can select the project area and can calculate the daily average horizontal irradiation for the area. For the present study, it selected Kirikkale city for the plant. Figure 4.52 shows the location for the climate data and plant implementation area.

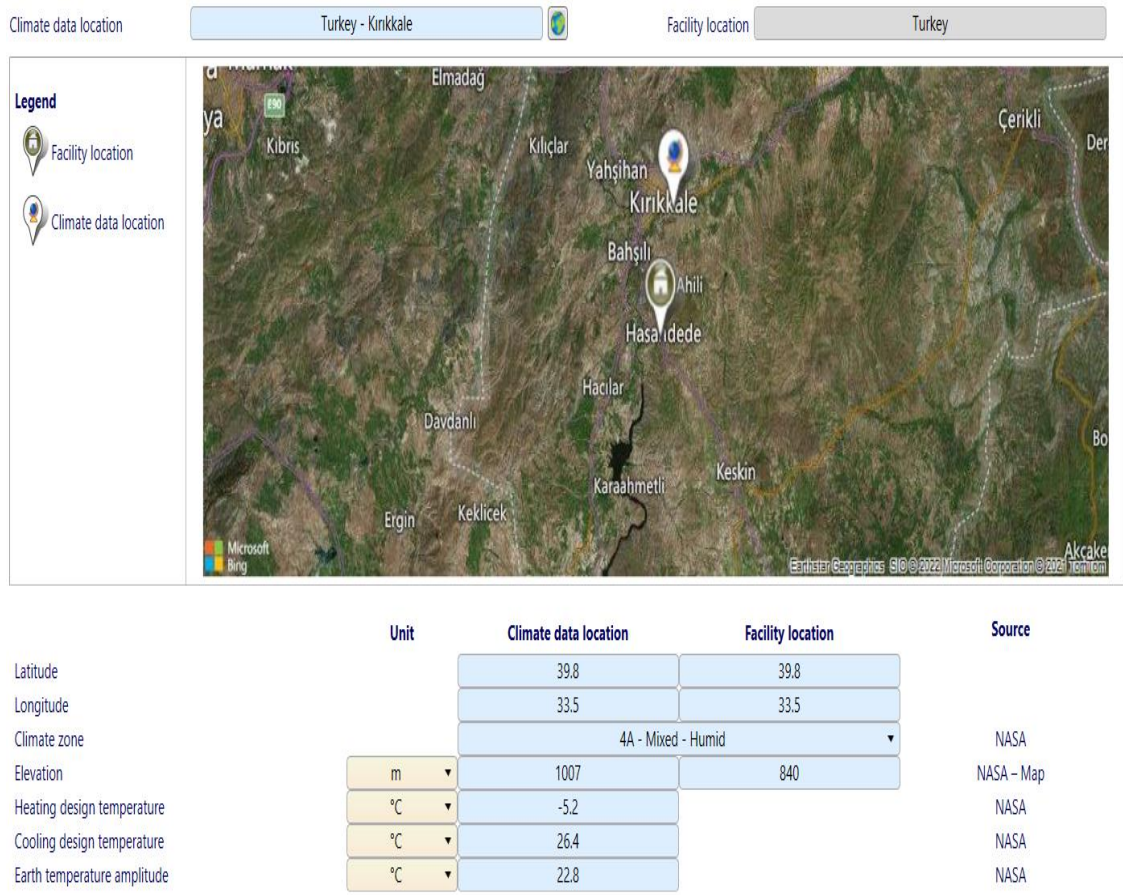


Figure 4.52 Shows the climate data location, which has been taken from the NASA station, which is in Kirikkale city.

The data consists of the latitude, longitude, climate zone, elevation, high and low temperature, and earth temperature amplitude. Furthermore, the software gave the climate metrological data for the site as follows;

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days 18 °C	Cooling degree-days 10 °C
	°C	%	mm	kWh/m ² /d	kPa	m/s	°C	°C-d	°C-d
January	-1.0	82.9%	40.92	2.04	90.2	3.4	-1.6	589	0
February	0.3	76.9%	32.20	2.84	90.0	3.8	-0.1	496	0
March	4.1	69.7%	36.89	4.06	89.9	3.7	4.2	431	0
April	9.7	64.7%	47.70	4.82	89.9	3.3	10.1	249	0
May	14.8	58.9%	44.64	6.04	90.0	3.0	15.5	99	149
June	19.2	50.7%	35.40	6.90	89.9	3.2	20.7	0	276
July	22.6	42.1%	14.26	7.14	89.9	3.8	24.8	0	391
August	22.7	40.0%	9.92	6.32	89.9	3.6	25.0	0	394
September	18.2	44.3%	16.20	5.15	90.1	3.2	19.7	0	246
October	12.2	57.3%	33.79	3.53	90.3	3.1	12.5	180	68
November	5.4	72.1%	37.20	2.30	90.3	3.2	4.7	378	0
December	0.6	82.3%	45.88	1.71	90.2	3.3	-0.1	539	0
Annual	10.8	61.7%	395.00	4.41	90.1	3.4	11.4	2,961	1,523
Source	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA	NASA
Measured at					m	10	0		

Figure 4.53. Metrological data for Kirikkale site by RETScreen

Figure 4.53 shows the site's air temperature, humidity, precipitation, daily solar irradiation, atmospheric pressure, wind speed, earth temperature, and the highest and coolest degree for the site all months of the year and annual average values for each parameter of the Kirikkale city.

As indicated in Figure 4.53, the annual average daily solar irradiation- horizontal for the site is 4.41 KWh/m²/d, taken from NASA. If it compares to the value taken from the site metrological station and the value taken from the global solar atlas, the difference is less (4.79KWh/m²/d). It can say the system is accurate and acceptable. Figure 4.54 shows the daily solar irradiation of the site for all months of the year.

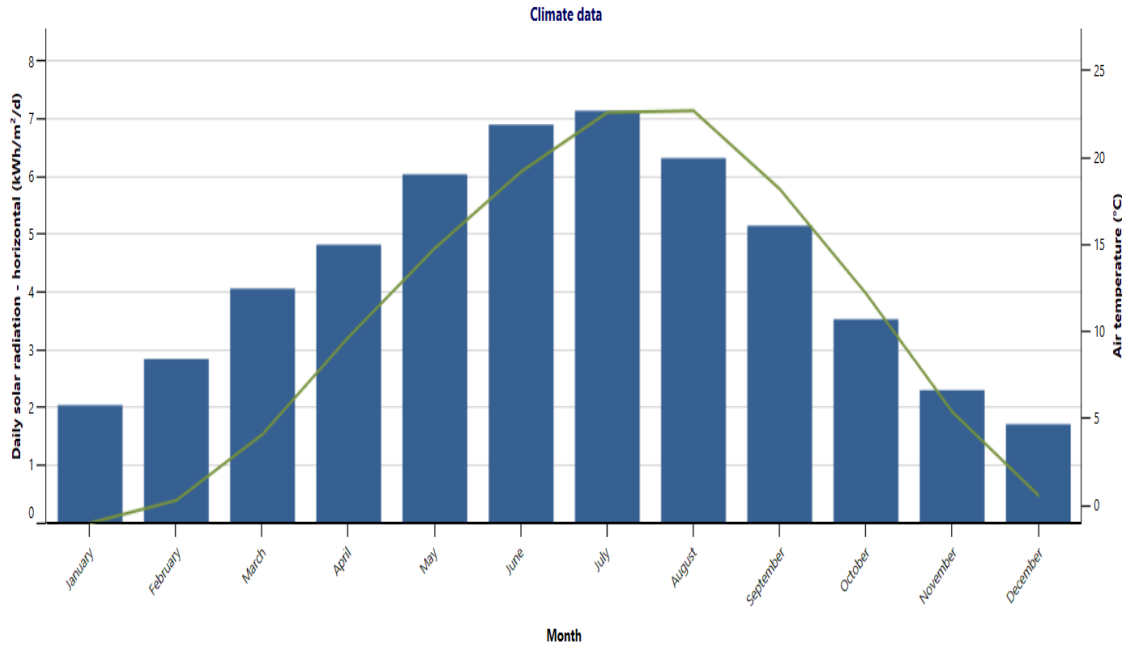


Figure 4.54. DSI with air temperature for the site by RETScreen

Figure 4.54 indicates that the highest daily irradiation for Kirikkale city is in July, which is 7.14 kWh.m²/day, the lowest in December, which is 1.71 kWh.m²/d.

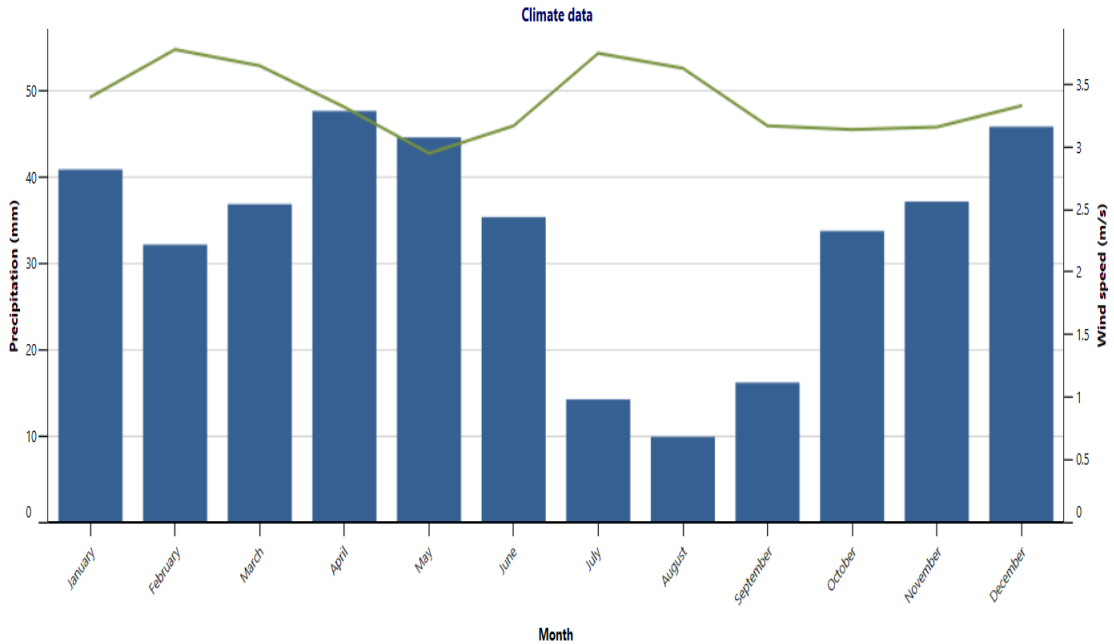


Figure 4.55. Monthly average precipitation in the site by RETScreen

shows the monthly average precipitation and wind speed for Kirikkale city, which is given by the RETScreen software.

4.6.2. Annual energy production with the PV system

RETScreen can calculate the annual energy production for the selected area as we input the climate data which discussed before. For the calculation of annual energy production analysis, it needs to import energy type, PV panel type, power capacity, model manufacturer, solar tracking mode, slope, miscellaneous losses, inverter efficiency, and the capacity of the inverter, and miscellaneous losses of the inverter. Table 4.74 shows the summary of input parameters to RETScreen PV system simulation.

Table 4.74. Input parameters in RETScreen for PV system

Model information	
PV panel type	Mono-silicon PV panel
PV panel numbers	25000
Model manufacturer	Vikran solar
Power capacity	9125KW
Solar tracking mode	Fixed
Slope	40°
The efficiency of PV panel	18.81%
Area of Panel	1.94m ²
miscellaneous losses	15%
Efficiency	95%
Capacity	9000KW
Miscellaneous losses of the inverter	1%

According to the parameters mentioned above, RETScreen gave the monthly and annually produced energy for the selected area as follows;

Month	Daily solar radiation - horizontal	Daily solar radiation - tilted	Electricity export rate USD/kWh	Electricity exported to grid
	kWh/m ² /d	kWh/m ² /d		MWh
January	2.04	3.41	0.10	795.632
February	2.84	4.01	0.10	836.220
March	4.06	4.86	0.10	1,099.783
April	4.82	4.92	0.10	1,059.047
May	6.04	5.56	0.10	1,206.476
June	6.90	6.03	0.10	1,239.379
July	7.14	6.37	0.10	1,327.025
August	6.32	6.23	0.10	1,294.717
September	5.15	5.92	0.10	1,212.066
October	3.53	4.76	0.10	1,039.320
November	2.30	3.70	0.10	810.642
December	1.71	2.91	0.10	676.836
Annual	4.41	4.89	0.10	12,597.144
Annual solar radiation - horizontal	MWh/m ²	1.61		
Annual solar radiation - tilted	MWh/m ²	1.79		

Figure 4.56. Monthly and annually produced energy by the PV system

As indicated in Figure 4.55, the annual electricity exported to the grid system is 12597.14 MWh by the 25000 PV solar models of Mono-Si - 72-SOM GRAND ULTIMA Silver-1500V - 365W from Vikran solar manufacturer. In addition, the software gave the monthly extorted energy to the grid system as the lowest exported energy is in December (676.83 MWh) and the highest is in July, which is 1327.02 MWh.

4.6.3. Greenhouse gases(GHG) reduction by implementation of PV system

Conventional energy systems use Fossil fuels to produce electricity, which is the main cause of emissions of Greenhouse gases to the atmosphere, which increase the Air temperature (Adam and Apaydin, 2016). The main production sources of CO₂ are burning fossil fuels, wood, solid waste, and so on. In the past century, different GHG gases have been increased in atmospheric concentration, such as carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), as well as halogenated compounds such as Chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs) and perfluorocarbon (PFCs). For the reduction of GHG emissions to the air, it is important to change the conventional energy production sources to clean energy sources such as solar, wind and hydraulic energy. The present study designed a PV system for electricity production for the RO

water treatment plant in Kirikkale. By implementing this PV system project, it is expected to reduce the GHG emission to the atmosphere, which is emitted by the production of electricity from fossil fuels. Using the RETscreen software, it evaluated the PV system, which was designed to produce more than 12000 MWh of electricity for the RO plant. RETscreen compares the PV system energy production to the annual CO₂ emissions by producing the same energy as the conventional system. It can simply compare the GHG emissions for producing 1 MWh from fossil fuels with the 1 MWh of energy produced by the PV system.

Table 4.75. GHG emission factor for oil gas and coal

Fuel type	CO2 emission factor(Kg/GJ)	CH4 emission factor(Kg/GJ)	N2O emission factor (Kg/GJ)	Electricity generation efficiency(%)	T and D losses(%)	GHG emission factor (tCO2/MWh)
Oil	74.12	0.0029	0.0019	28.57149	7.0%	1.0121
Coal	92.66	0.0145	0.0029	33.83833	7	1.0734
Natural gas	49.5617	0.001	0.0009	40.78559	7	0.4729

As can indicate in Table 4.75, the production of 1 MWh electricity from oil emitted 1.012 tCO₂ equivalent CO₂ to the air with a 28.57% efficiency. The electricity generation efficiency is the efficiency of energy conversion from primary heat potential to actual power plant output. For example, if a plant burns the oil with 28.57% efficiency, it indicates that 28.57 % of the heat content of the oil is transmitted to the electricity. Transmission and distribution (T and D) is the loss percentage of the base case electricity system, which includes all energy losses between the power plant and the end-user. In addition, the production of 1MWh from natural gas produced 0.473 tCO₂ equivalents and emitted to the atmosphere, which consists of CO₂, N₂O, and NH₄ in the calculation. As mentioned before, the proposed PV system can produce 12597 MWh of electricity annually. For the calculation of GHG emission reduction for annual energy, we have;

Table 4.76. Annually total GHG emission by conventional sources for the production of electricity

	Fuel consumption for electricity (MWh)	GHG emission factor (tCO ₂ /MWh)	Total GHG emission (tCO ₂)
Oil	12597	1.0121	12750
Coal	12597	1.0734	13522
Natural gas	12597	0.473	5958

Table 4.76 indicates that for producing 12597 MWh of electricity from oil, it is caused to produce and emit 12750 tCO₂ into the air. From natural gas 5958, tCO₂ will be emitted to the atmosphere annually.

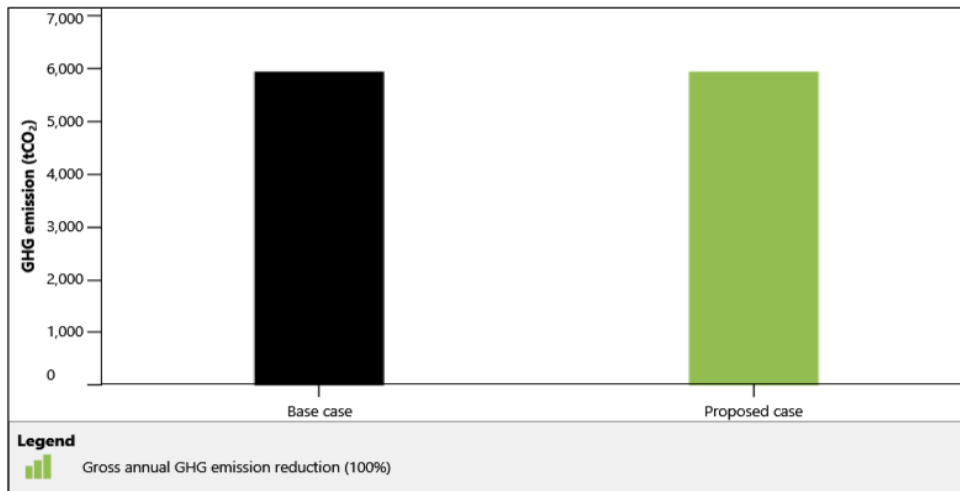


Figure 4.57. Comparison of conventional and PV system GHG emissions

RETScreen calculates the gross annual reduction in GHG emissions estimated to occur if the proposed PV system is implemented. The calculation is based on emissions of both the energy production by conventional cases and the energy production by PV case systems annually. The comparative GHG emission reduction to different fossil fuel consumption is listed in Table 4.77.

Table 4.77 Comparative GHG emissions reduction

	Total GHG emission (tCO₂)	Liters of gasoline not consumed	Barrels of crude oil not consumed
Oil	12750	5478281	29651
Coal	13522	5810096	31447
Natural gas	5958	2559903	13855

As can see in table 4.77, if we produce 12597 MWh electricity from the proposed PV system instead of oil consumption, it means that we did not consume 5478281 liters of gasoline and 29651 barrels of crude oil which shows significant amounts of GHG emission reduction. As it analyzes the PV power system for the Kirikkale city RO plant with the RETscreen software, this project can produce annually 12597 MWh electricity. By inverter, it can change to AC and transfer to the main grid system. As in conclusion if we produce the same value of energy by oil, natural gas or coal it will produce thousands of tons of CO₂ and release it to the atmosphere, and we can say by the implementation of PV system we can reduce the emission of GHG to the air therefore we can say to PV energy system as a green energy system which produce 0 % CO₂.

Note: for the implementation of a large-scale PV system, it's necessary to employ lifecycle cost analysis for the system to examine the operation, construction, maintenance, energy production, saving flow (saving cost), average energy income, and GHG reduction cost during the lifecycle of the project. Furthermore, the PV financial analysis should be compared to the RO system lifecycle operation, energy consumption and implementation cost to specify the net return and annual saving and revenue for the RO system which is currently running by the electricity produced from conventional material (natural gas and coal).

5. CONCLUSION

With the increasing world population, the demand for clean drinking water is increasing and the limited availability of clean water has increased the desalination process. Different desalination processes are designed and implemented for water treatment purposes. Among them, the RO water treatment process is the most using and cost-effective process. On the other hand, the RO water treatment process is more expensive than the conventional one, and the RO technology is an energy-intensive process and needs more energy for the operation of the plant. The present study focused on designing and evaluating an RO plant based on real-site raw water data.

For the source water, it designed different types of RO systems and evaluated each system layout according to energy consumption. It designed two types of RO systems by hand: single stage RO system with concentrate recycling with 80% recovery and 50% concentrate water recycled. This system can remove all contaminants from raw water from source water from 190 mg/l TDS to 28.35 mg/l of TDS in permeate water which shows more than 97 % removal, and the energy consumption for this system is calculated 0.35 KWh/m³ of produced water. Two stages RO system with 80 % recovery was designed and evaluated by hand. The result for this system is also good, as the permeate TDS concentration was 21.35 mg/l which shows high removal percentage, and the energy consumption for the two stages RO system was 0.289 KWh/m³. In addition, it evaluated these proposed, designed systems by WAVE design software to know the accuracy and correction of the design. It applied different scenarios to WAVE software for the source water data as it designed and evaluated the single-stage RO system with 80 % recovery and 53.5 % concentrate recycled and discussed the output of the WAVE software, the permeate concentration for the treated water was 37.74 mg/l. The energy consumption was 0.44 KWh/m³ of treated water. Two stages RO system was evaluated with 80 % recovery. The result was accurate. The permeate water concentration was 28.16 mg/l, and the energy consumption for this system was 0.36 KWh/m³.

In addition, it was evaluated the two stages of RO with bypass of feed water and the concentration of different parameters were checked and compared to the water standards. The result was accepted for the drinking water quality, and this system's energy consumption was given as 0.33 KWh/m³ of treated water. Among these designed systems,

the best-proposed system was two stages RO with bypass system, and it was due to low energy consumption, and by bypass of filtered feed water. It increased the permeate water parameters such as TDS, SO₄, Na, Cl, Mg, Ca, K and others. There is no need to apply a remineralization unit to increase the value of different parameters.

In the rest of the study, it evaluated the RO system for the risk of fouling and scaling formation by WAVE software according to LSI and Stiff and Davis Stability Index to decrease the risk. The acid and alkali (HCl and NaOH) were added to adjust the water and pH chemicals.

At the same time, it was calculated the pressure vessels for all scenarios for single and two stages RO systems. The number of PV was 566 pressure vessels in 27 LMH average design flux. In comparison, for the two stages of RO with a bypass system, the number of pressure vessels was 495 in 27 LMH average design flux, which shows this system is more economical than the other two RO systems by using fewer pressure vessels. Different feed pressure was applied for each RO system to push feed water through the membrane surface and remove all contaminants from the water, and the feed pressure for all systems was in the range of 6 to 9 bar. As pretreatment is needed for the RO system to remove particles and organics from water and reduce the risk and forming of different fouling and scaling, the ultrafiltration unit was designed as a pretreatment for the RO system. The results for the filtered water were good for the RO feed water as the UF system reduced the SDI from 5 to 2.5 and removed all TOC from feed water and TSS from source water.

To reduce the energy consumption of the RO system, the ERD device was designed for the two stages of the RO system as the device converted the concentrate pressure to feed pressure. The value of the feed pressure got decreased. As calculated, this device reduced the energy consumption from 0.289 KWh/m³ to 0.205 KWh/m³ of treated water and shows the system's 30 % of energy recovery.

To find clean energy sources for the supply of energy to the RO system, the RO plant location site (Kirikkale city) was investigated for the PV solar energy production system by the metrological data of the city and found that Kirikkale city has an enormous potential for the production of energy from solar as it was obtained the daily solar irradiation for the selected area is 4.8 KWh/m²/d. The PVOUT potential for the investigated area is 4.4

KWh/KWp. The PV system was evaluated to supply clean energy for the RO system. It designed the PV power system with 21819 PV models, producing up to 13000 MWh of electricity annually. The proposed system was designed as the generated electricity converted by 26 invertors with 500KW capacity to the transformers and connected to the main grid system. The RO system will use energy from the main grid system.

In the end, the designed PV system was evaluated by RETscreen software according to the reduction of GHG emissions to the atmosphere. The results have shown that implementing the PV system reduces the emissions of thousands of tons of CO₂ equivalent GHG to the air.

Furthermore, the software made a comparison of the energy production from oil, natural gas, and coal to the PV system as for the production of 12597 MWh electricity annually from oil emits 12750 tCO₂ equivalents GHG to the atmosphere. In contrast, by implementing the PV system, it reduces to zero. In addition, the software compared emitted GHG to fossil fuel consumption, such as to prevent the emissions of 12750 tCO₂ to the atmosphere, which means that 29651 Barrels of oil were not consumed or 5478281 liters of gasoline were not consumed. The existing RO system in the area uses conventional energy produced from fossil fuel sources, which negatively impacts the environment and climate change in the area. Moreover, by implementing the PV system, the risk will illuminate and the emission of GHG will reach zero percent.

6. RECOMMENDATION

RO membranes are changing their performance over time. It needs a detailed study of membrane fouling and sailing in different temperatures and seasons. It is recommended to use two stages of RO with a bypass system due to low energy consumption, and minimum pressure vessels are required than other RO systems.

Use the membrane elements from the DuPont manufacturer, which can apply high feed pressure and high average design flux, and the WAVE software can calculate and evaluate the DuPont manufacturer products. The reduce the energy consumption, it is recommended to install the designed ERD system in the present study; it will reduce the energy consumption by up to 30 % for two stages RO system.

To supply the RO system energy demand, it recommends implementing the PV system on the site, which connects to the main grid system and uses the energy from the main grid system. However, before implementation detailed financial and lifecycle cost study must investigate to examine and compare the design, operation, and maintenance cost of the PV project with the RO system.

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Hayatullah AHMADZAI graduated from Abdulhai Gardizi High School. In 2015, he graduated from the Engineering faculty department of Civil Engineering of Paktia university. He entered the Ondokuz Mayıs University of Master's program in the environmental engineering department in 2020 and finished it in 2022. He has an upper intermediate level of English and a good level of Turkish. Key areas of interest for AHMDZAI's are water treatment, membranes, desalination, modeling for water and wastewater, and water management.

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Publications:

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Professional experience:

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1- Working at SCORE project as a data collector and making models to know the risk of flood in Samsun coastal city, Samsun University

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2- Project planner, ministry of urban development and lands, Gardiz, Paktia, Afghanistan