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Opportunities of Variable Speed Drives in Desalination

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The purpose of this Bachelor's thesis was to study the structure of the reverse osmosis (RO) desalination process and to explain the role of variable speed drives (VSDs) in the system. This thesis is a good starting point for those wanting to understand the RO process, the different parts of a RO plant and the role of VSDs in the different plant applications. RO is currently the most used desalination technology globally.

This thesis was carried out through extensive desk research. The results of this study are collected from academic journal articles and books, case studies and company documents.

This thesis showed that VSDs have a role in ensuring energy efficiency, precise operations and equipment protection. These factors improve the RO plant's performance and decrease operational and capital costs. In RO, energy consumption is a major factor that influences the total cost of producing fresh water. Increasing the energy efficiency of plants, so that fresh water can be produced at lower costs, is one of the biggest challenges facing RO plants in the future. VSDs will continue to be used as an essential part of these systems.

Keywords	desalination, reverse osmosis, variable speed drives

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Tässä insinöörityössä esiteltiin kattavasti käänteisosmoosilaitoksen rakenne sekä erilaisia käyttökohteita taajuusmuuttajille prosessissa. Tätä opinnäytetyötä voidaan hyödyntää, kun halutaan tutustua käänteisosmoosiprosessin kulkuun, laitoksen välineistöön ja taajuusmuuttajien rooleihin laitoksen erilaisissa pumppukäytöissä.

Insinöörityö oli luonteeltaan kirjallisuustutkimus. Lähteinä on käytetty tieteellisiä artikkeleita ja kirjoja, sekä yritysten julkaisemia asiakirjoja.

Energiatehokkuus on RO laitoksissa hyvin tärkeä tekijä, koska sähkönkulutus käsittää ison osan kokonaiskustannuksista. RO laitosten energiatehokkuuden kehittäminen on yksi isoimmista haasteista, jotta tulevaisuudessa puhtaan veden tuottaminen saataisiin halvemmaksi. Taajuusmuuttajat tulevat olemaan jatkossakin olennaisena osana näitä järjestelmiä.

Avainsanat	suolanpoisto, käänteisosmoosi, taajuusmuuttaja

Contents

Appendix 1 Centrifugal and Isobaric ERDs

Abbreviations

BWRO	Brackish water reverse osmosis.
CA	Cellulose acetate.
CIP	Clean in place.
CSI	Current source inverter.
DTC	Direct torque control.
DWEER	Dual work exchanger energy recovery system.
ERD	Energy recovery device.
HDD	Horizontally directed drain well.
HTC	Hydraulic turbocharger.
IGBT	Insulated gate bipolar transistor.
MED	Multiple-effect distillation.
MF	Microfiltration.
MSF	Multi-stage flash.
NDP	Net driving pressure.
PA	Aromatic polyamide.
PLC	Programmable logic controller
PWM	Pulse Width Modulation.

PX	Pressure exchanger.
RO	Reverse osmosis.
SEC	Specific energy consumption.
SWRO	Seawater reverse osmosis.
TDS	Total dissolved solids.
TMP	Transmembrane pressure.
UF	Ultrafiltration.
VSD	Variable speed drive.
VSI	Voltage source inverter.

1 Introduction

Approximately 97% of the world's water supplies are seawater. Of the remaining fresh water, a mere 1% is actually available for us to use for drinking and irrigation. As global fresh water resources are also very unevenly distributed, over 40% of the world's population lives in areas with limited access to water supplies. Moreover, it is estimated that access to water will only become more difficult, as the global population will continue to grow and the global demand for water will continue to grow even faster. Both developed and developing countries are facing water scarcity issues. For these reasons, it is vital to search for methods that can be used to turn seawater into fresh water. [1, 2318.]

Desalination is a general term used to describe the process that removes salt from seawater. Desalinating seawater makes the water suitable for drinking and irrigation. Several desalination technologies exist. The focus of this thesis will, however, be on reverse osmosis (RO). Today RO is the leading technology used in new desalination plant installations because it has strong separation capabilities and is cost efficient. The technology used in the process has improved significantly over the past three decades and has been driving substantial decreases in capital and operation costs. [1, 2317-2318.]

Even though seawater RO processes currently require 10 times less electricity than thermal desalination processes, energy costs are still often over 50 percent of total operating and maintenance costs. [1, 2340; 2, 2]. In practice, all of the required energy is used for running the motors driving various pumps in the plant [3, 243]. Therefore, the energy efficiency of these applications is an important factor in the RO process.

Variable speed drives (VSDs) play an important role in optimizing the energy use of the pumps, because the pump output pressures and flow rates can be constantly matched to the varying requirements of the process. In addition, precise control over motor and pump applications is often essential in order to maintain good performance and to avoid any equipment damage [4, 10].

The purpose of this thesis is to introduce the RO process and to discuss the variable speed drives that are used in the RO process. More specifically, the objective is to objectively describe how VSDs can be used in the process. RO plants contain many pump applications in which VSDs can be used. Since the use of RO as a desalination technology is only projected to increase in the future, new plant installations are of interest for VSD manufacturers.

The division of the thesis is as follows: chapter 2 outlines the principles of a VSD; chapter 3 discusses water; and chapter 4 introduces desalination and the reverse osmosis process. Chapters 5 to 8 describe the different components of the RO plant. Each chapter ends with an overview of how VSDs can be used in each component. Chapter 5 presents the plant intake; chapter 6 outlines the pretreatment systems; chapter 7 provides an overview of the RO separation system; and chapter 8 discusses the post-treatment. Chapter 9 finally summarizes and concludes the thesis.

2 Principles of a Variable Speed Drive

In this section the basics of variable speed drive (VSD) are explained. As the thesis focuses on desalination from a VSD point of view, it is beneficial to understand their basics.

A variable speed drive (VSD), also known as a frequency converter, is an electrical device that changes the frequency of the alternating current and voltage that supply e.g. an AC motor. By using a VSD, it is possible to control the speed, torque or position of an AC motor in an accurate and energy-efficient way. In water treatment technology, for example, motors are used to power up pumps. VSDs play an important role in water systems, as they are nowadays used to control the motors, which in turn power up the pumps that produce the water flow. Without VSDs, the flow is throttled by valves or dampers, while the motors are always running at full speed. A pump’s energy consumption can be reduced by as much as 60% when it is paired with a VSD instead of a throttling device. Other remarkable benefits of using VSDs are reduced wear on machines and large cost savings. [5, 3; 6, 5; 7.]

The two main types of frequency converters are indirect frequency converters with a DC link (see Chapter 2.1) and direct frequency converters without a DC link. Indirect frequency converters convert the input AC power first to a DC power and then back to AC power, whereas direct frequency converters chop the input AC power straight to an AC power with a different frequency and voltage. Indirect frequency converters include voltage source inverters (VSI) and current source inverters (CSI), whereas direct frequency converters are either matrix converters or cycloconverters. Section 2 will focus on VSI drives, because they are the most commonly used VSD type. [8, 48-50.]

For RO plants, most of the electricity consumption goes into running the high pressure pumps [9, 16]. In this pump application, a specific pressurization of the membrane system is required to ensure ideal conditions for water production and to prevent any damage to the elements [10, 8]. In general, this means that either the pressure or flow has to be throttled by valves, or that the pump motor speed needs to be adjusted directly with a VSD. A VSD would lower the energy used for pumping.

2.1 The Main Components of a VSD

This section describes the main parts of a variable speed drive. As illustrated in figure 1, a VSD (VSI) can be divided into three main components: a rectifier, a DC voltage intermediate circuit and an inverter. They are run by a control unit that sends signals to the three components. [11, 14.]

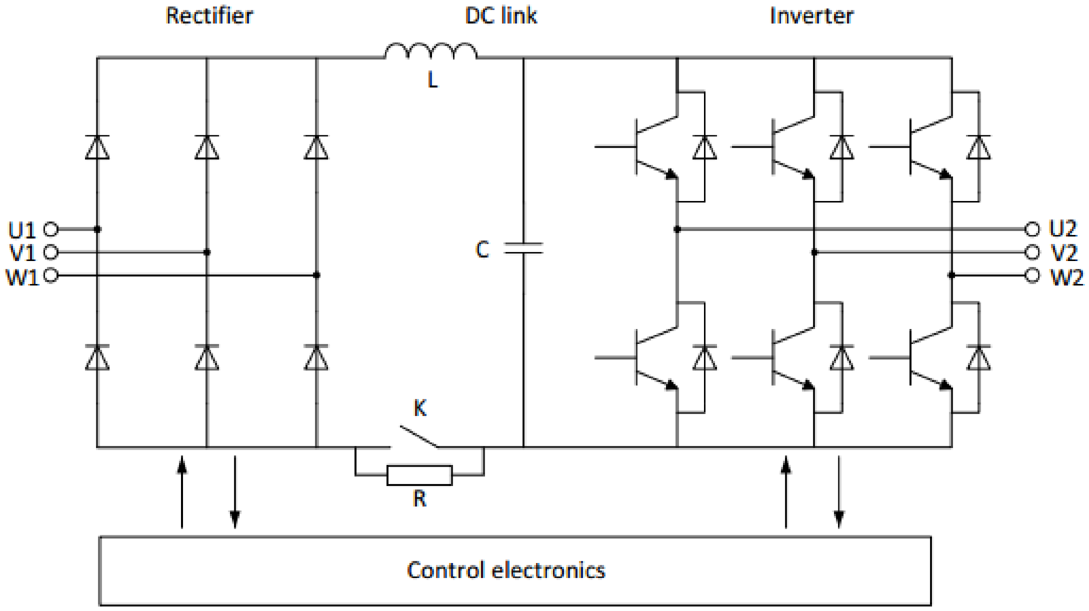

Figure 1 The main components of a VSD. Copied from [12].

The rectifier's terminals U1, V1 and W1 are connected to the network. The rectifier converts the input AC power to DC power. Then, the DC circuit filters the waveform and acts as a power supply for the next component, which is the inverter. The inverter converts the DC power to AC power with a different frequency and amplitude. This is then directed to the motor via terminals U2, V2 and W2. The rectifier, DC circuit and inverter are introduced in the following sections. [11, 14.]

2.1.1 Rectifier

The rectifier converts the mains AC voltage into a DC voltage. Rectification is done by using semi-conductors, which can be e.g. diodes, thyristors, insulated gate bipolar transistors (IGBTs) or a combination of these. The most common rectifiers and the semi-conductors used to assemble them will be presented next. A diode rectifier is the simplest and the most used solution. It most commonly consists of a 6-pulse diode bridge, as shown in figure 2. [5, 6.]

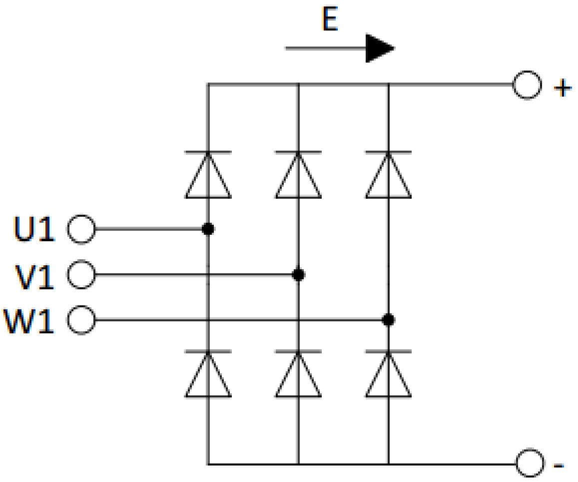

Figure 2 Schematics of a 6-pulse diode bridge rectifier. Copied from [12].

The figure above illustrates how a 6-pulse diode bridge is formed by six diodes in a 3-phase supply. 12-pulse rectifiers, which consist of 12 diodes, also exist. The bridge rectifier produces a DC voltage, allowing the energy (E) to flow from the network in the DC circuit, where it is stored in a capacitor. [5, 6.]

Diodes only allow the energy to flow in one direction. Therefore a diode rectifier is called an uncontrollable rectifier. An example of a fully controllable rectifier is the thyristor rectifier. A thyristor rectifier typically consists of two thyristor bridges: one is a motoring bridge and the other is a regenerative bridge. Both of these are made up of six thyristors. Figure 3 illustrates the thyristor rectifier. [5, 7.]

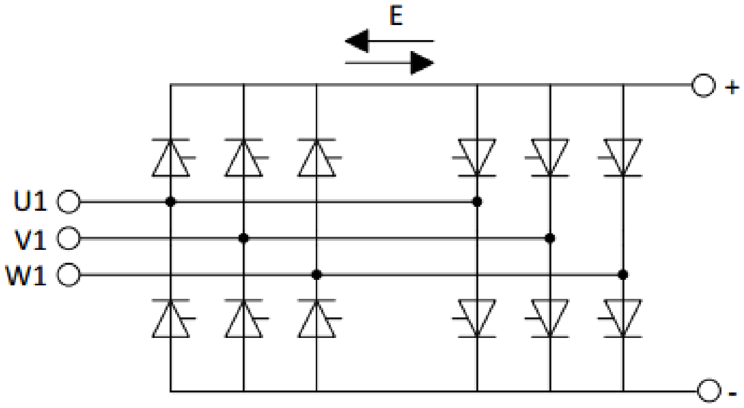

Figure 3 Thyristor rectifier with a motoring bridge and a regenerative bridge. Copied from [12].

As seen in Figure X thyristors allow the energy (E) to flow in two directions. This method enables, for example, the transfer of braking energy back into the supply network via terminals U1, V1 and W1. Another example of a fully controllable rectifier is an IGBT rectifier, which is made of six insulated gate bipolar transistors and six flyback diodes. A schematic of the IGBT rectifier is shown in figure 4. [5, 7-8.]

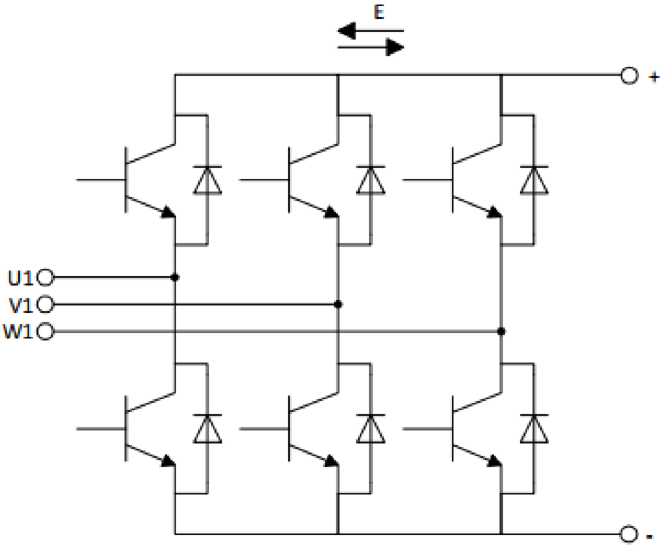

Figure 4 IGBT rectifier. Copied from [12].

As with the thyristor rectifier, the energy can flow in two directions. The switching is regulated by a control program and control electronics. The IGBT rectifier needs a filter in front of it to function correctly. [5, 8.]

2.1.2 DC Voltage Intermediate Circuit

The most commonly used VSD type is the voltage source inverter (VSI), which has a DC voltage intermediate circuit (or DC link) between the rectifier and the inverter. The DC voltage intermediate circuit levels the pulsating DC voltage coming from the rectifier. The DC circuit acts as an energy storage and a DC power supply for the inverter, as well as a reactive power supply for the motor. A simplified schematic of a typical DC voltage intermediate circuit is illustrated in figure 5. [8, 50; 5, 9.]

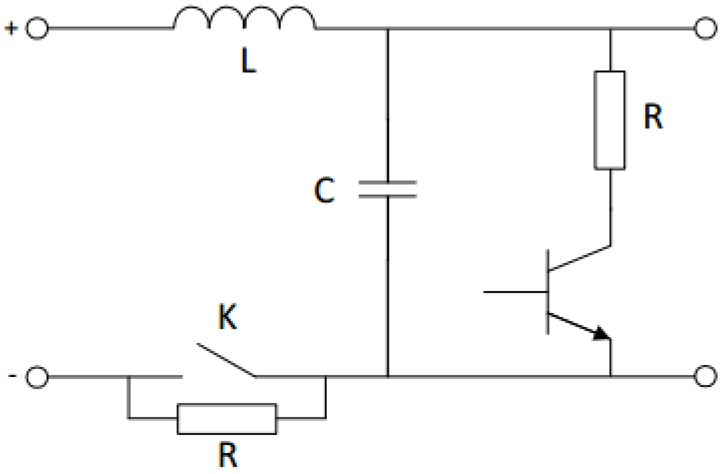

Figure 5 DC voltage intermediate circuit. Copied from [12].

Typically, a DC voltage intermediate circuit contains a capacitor (C), a choke (L), and a charging circuit. The charging circuit can be made up of, for example, a switch (K) and a resistor (R). With the capacitor, the DC circuit can store energy for the inverter. The choke levels the pulsating DC voltage. The DC circuit may also include a braking unit (or braking chopper), which is shown on the right in figure 5. The chopper controls the voltage in situations where the system feeds energy back into the network. [5, 10; 13, 32.]

2.1.3 Inverter

The inverter is the last component of the VSD and it is connected to the load. The purpose of the inverter is to transform the DC voltage into an AC voltage suitable for the motor. Inverters most commonly consist of six IGBTs and six flyback diodes, but they can also be made up of thyristors or other semi-conductors. A schematic of the IGBT inverter is illustrated in figure 6.

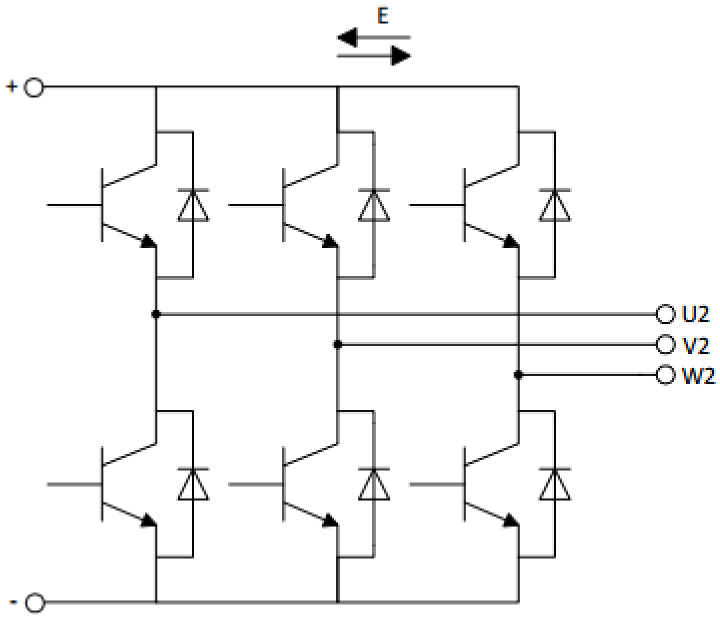

Figure 6 IGBT inverter. Copied from [12].

The required output waveform for the motor is formed by switching the IGBTs either to an open or closed position, in a certain order. This is controlled by the control electronics unit. By altering the width and the amount of voltage pulses, a specific amplitude and frequency of the AC voltage can be achieved. This AC voltage is supplied to the motor through terminals U2, V2 and W2. The objective is to connect each motor phase, constantly in a certain order, either to the negative or the positive pole of the DC circuit. As a result, an AC power is produced, which causes the rotation of the motor. [5, 11; 11, 15.]

2.2 Control

A VSD controls an electric motor's speed, torque and flux position. Different motor applications set different requirements for the aforementioned quantities. The control can be performed by using frequency, flux vector or direct torque control (DTC). [13, 3.]

The frequency and vector controls are based on Pulse Width Modulation (PWM), which is a method used to adjust the output frequency and voltage. The frequency and voltage references are fed to a modulator, which simulates an alternating current's sinewave and directs it to the stator windings of the motor. Figure 7 illustrates PWM. [14, 11-13.]

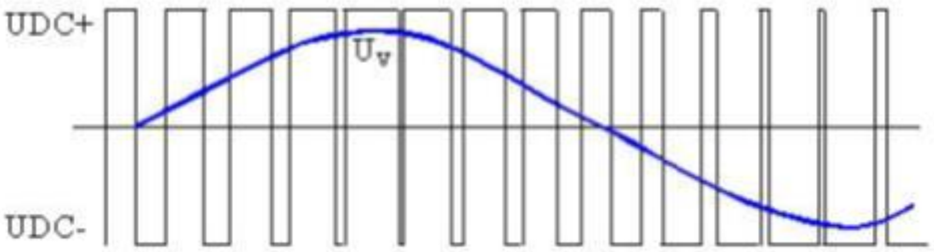

Figure 7 Producing a phase voltage by PWM. Copied from [15].

As seen in figure 7 the semi-conductors of the inverter are controlled in a way that they form an AC voltage. The semi-conductors switch DC voltage on and off very fast. The result is a phase voltage that on average resembles a sinewave.

In frequency control, a VSD commands the motor to rotate at a certain speed by adjusting the drive's output frequency and voltage. The motor speed value is determined by the frequency and the load torque. When operating at speeds up to the nominal speed, the output voltage increases (and decreases) linearly with the output frequency. [13, 5.]

In the flux vector control, the actual position and speed of the motor's rotor needs to be accounted for. To perform this, the VSD uses a motion sensor as a feedback. The sensor measures the rotor's speed and angular position relative to the stator field and feeds the data to a microprocessor, which contains a mathematical model of the motor. With flux vector control, the VSD can produce any accurate speed or torque that the motor is capable of handling. For example, maximum torque can be achieved at zero speed. [14, 12-13.]

In DTC, the controlling variables are torque and the magnetizing flux of the motor. DTC does not use modulation and does not need feedback, as the drive can calculate the status data of the motor itself by using the mathematical models off the AC motor principles. Thus, DTC drives adjust the variables that directly affect the motor's torque. The changes in speed and torque are performed faster than in PWM. [14, 14-16.]

3 Water Resources

In this section, the current global water situation will first be discussed, as this has a large impact on the need for and interest in desalination. Then, different properties of water will be outlined, as these need to be accounted for in the design of a desalination plant.

The importance of fresh water to life and the global ecosystem is undisputed; it is one of our basic needs [16, 10]. To satisfy our basic needs, however, the quality of water is just as important as the quantity of water [16, 10]. Over 96% of the world's water is saline and thus unsuitable for public supply and irrigation [17, 12]. However, these saline water supplies provide a virtually unlimited source for desalination. Desalination thus has the potential to increase fresh water availability globally over the coming decades [18, 270].

3.1 Global Need for Fresh Water

70% of Earth's surface is covered in water. In total, this amounts to 1386 million km^3 of water [17, 12]. Figure 8 illustrates the division of Earth's water resources by water type.

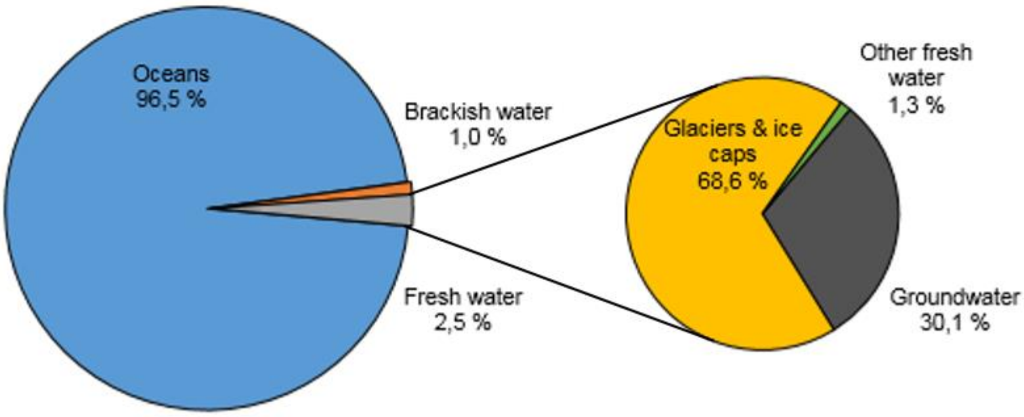

Figure 8 The world's water sources and fresh water division. Data gathered from [17; 19].

As shown in figure 8, 96.5% of Earth’s water resources are in the oceans and seas, 2.5% is fresh water and 1% is brackish water. Brackish water is slightly salty water that can be found as surface water and as groundwater. Almost 70% of the Earth’s total fresh water is in the form of glaciers and ice caps, while 30% is groundwater.

Today, over 40% of the world’s population lives in areas under water stress, i.e. areas where the use of water exceeds its supply [20]. Over one billion people do not have access to safe drinking water at all [21, 1]. Indeed, fresh water resources are globally very unevenly distributed. Both developing and developed countries face water shortage issues. Figure 9 shows the degree of water exploitation globally. The areas with water stress indicators higher than 0.5 could make use of technologies like desalination to produce fresh water.

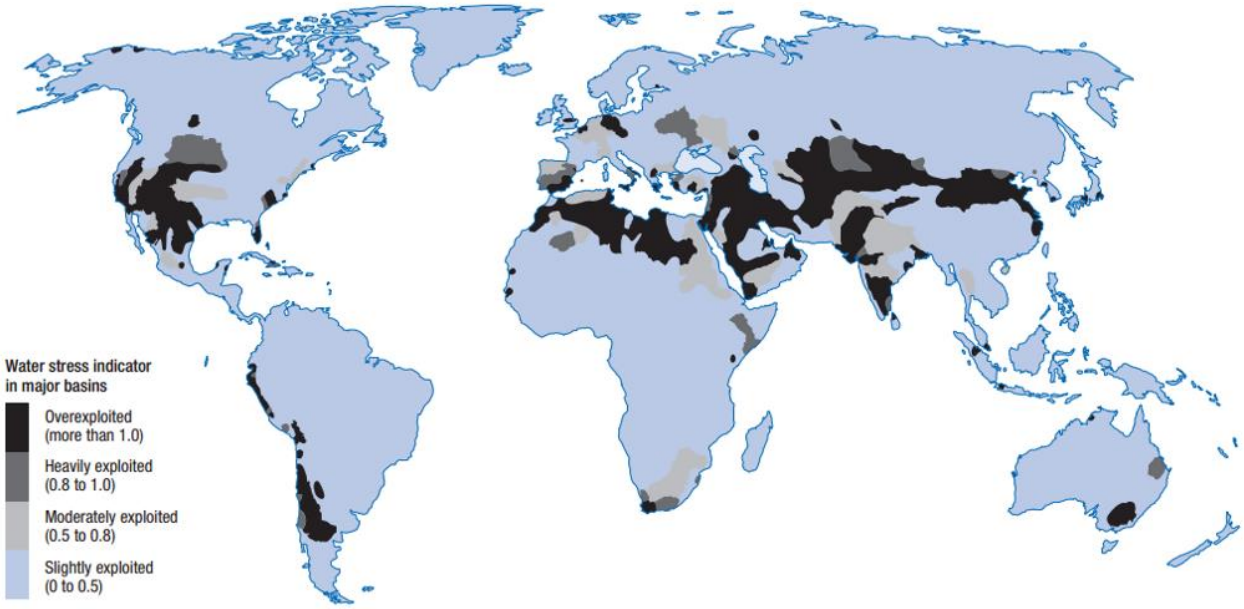

Figure 9 Global water stress. Modified from [22, 140].

Globally, water shortages are only projected to increase, as the world’s population continues to grow at a rate of 85 per million per year. Because of these continuous increases in demand, fresh water sources are under immense pressure. [21; 4.]

3.2 Quality of Source Water and Its Significance in RO

Several design choices for a desalination plant, such as desalination method, pretreatment steps, brine disposal method and product recovery are often determined by the type of water source. In addition, source water salinity and temperature values have an effect on the RO process control, as they vary over time. [1, 2319-2333.]

3.2.1 Water Salinity

The term salinity is used to describe the amount of salt in water. Salinity levels are usually defined in terms of total dissolved solids (TDS) and is measured in milligrams of solids per liter (mg/l) [23].

Fresh water is defined as water that contains less than 1,000 mg/L of salts or total dissolved solids (TDS). Water with TDS levels less than 600 mg/l is typically considered to taste good, while TDS levels higher than 1000 mg/l water becomes less pleasant. Seawater and brackish water are the two feed water types categorized in desalination plants. Generally, the feed water salinities vary between 1000 mg/L TDS to 60,000 mg/L TDS. Desalination plants are usually designed to produce drinking water that contains TDS of 500 mg/L or less. [24, 228; 1, 2319-2333.]

3.2.2 Seawater

Seawater contains TDS levels higher than 25,000 mg/L. The worldwide average for seawater is 35,000 mg/L TDS. Membranes that are used in SWRO processes are capable of processing water up to 60,000 mg/L TDS. However, typical feed water in SWRO contains between 30,000 and 45,000 mg/L TDS. Seawater wells (beach wells) can also be used as sources. The benefit from using beach wells is that the water has less organic material, which is often present in surface water, as it has been naturally filtered through sand. However, beach wells have limited resources of water and may not provide enough feed water for the bigger SWRO plants that are designed nowadays. Therefore, large SWRO plants must often take their feed water from open seas. [1, 2319-2326.]

The salinity and temperature of open oceans do not fluctuate much over time. However, large variability occurs in partially isolated seawater bodies, such as bays and estuaries [25, 15]. As RO plants typically treat such waters, the source water quality must be monitored constantly.

3.2.3 Brackish Water

Brackish water contains TDS levels between 1000 mg/L and 25,000 mg/L. The feed water for brackish water RO is often groundwater. These can be either naturally saline aquifers or groundwater sources, that have formerly been fresh water, but have become brackish due to seawater intrusion or activities caused by humans, such as irrigation or overuse. Brackish water exists also in coastal areas, i.e. places where fresh water combines with salt water, such as estuaries in coastal areas. Salt marshes also contain brackish water. [23.]

In brackish water RO, feed water salinity is usually between 1000 to 10,000 mg/L TDS. The range of TDS is relatively high. Moreover, while brackish waters normally have low organic carbon content and low particulate or colloidal contaminants, the concentration of some elements, including boron and silica, can differ greatly depending on the source. The precise identification of the source water of BWRO systems is thus important for efficient optimization. [1, 2319-2326.]

4 Desalination

This section will first define desalination and present an overview of its uses globally. Then, reverse osmosis is introduced. The RO process, major process parameters, RO plant components, RO plant control and energy efficiency will be briefly outlined.

4.1 Overview

After decades of development, seawater and brackish water desalination have become important methods for the production of drinking water. For instance, many cities or major industries in the Middle East or in remote areas, such as the Canary Islands or the Caribbean, would not have been able to develop without desalination because of scarce fresh water sources. Likewise, frequent droughts and increased uncertainty about water supplies in many areas have increased interest in desalination technologies. For example, seawater and brackish water desalination are expected to grow 10 to 20 percent in California during the next 10 years. [9, 2; 26.]

All major desalination technologies use a desalting device to separate saline water into fresh water (permeate) and brine (concentrate). A simplified demonstration of the desalting device is shown in figure 10. The fresh water product contains a low level of TDS whereas brine contains a high level of TDS. Brine is a by-product of the desalination process. The energy needed to desalinate water can be thermal, mechanical, electrical or a mix of these. This depends on the type of separation technology that is used in the process. [9, 5.]

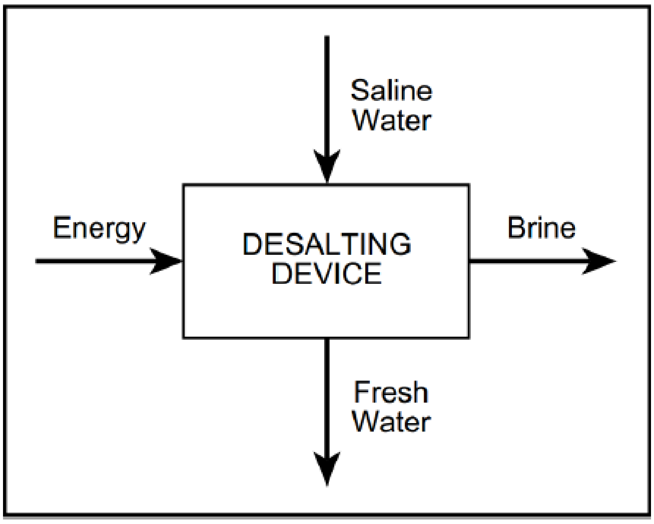

Figure 10 A basic demonstration of a desalting device. Copied from [9, 5].

Desalination technologies can be divided into thermal processes and membrane processes. Thermal processes mainly use Multi-stage flash (MSF) and multiple-effect distillation (MED) methods, and membrane processes mainly use Reverse osmosis (RO). Figure 11 below shows the share of different technologies in the total global installed capacity.

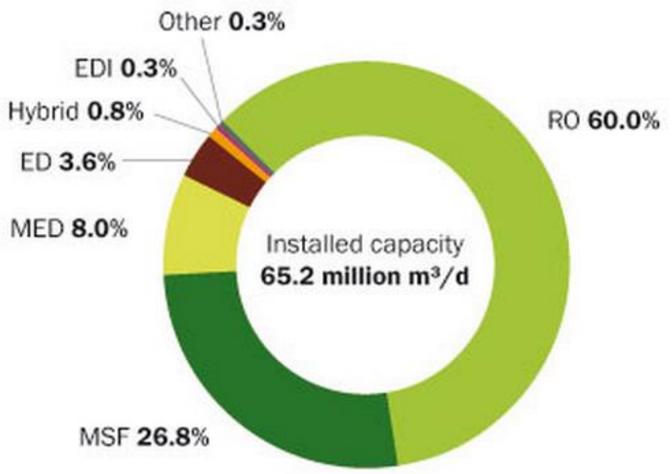

Figure 11 Global installed desalination capacity by technology. Copied from [27].

As seen from figure 11, RO is currently by far the most used technology, accounting for about 60% of total installed capacity. The second and third most used technologies, MSF and MED, account for 26.8% and 8% of total installed capacity respectively.

There are over 17,000 desalination plants in the world, comprising a total capacity of over 80 million cubic meters of desalination water per day. In the 150 countries that use desalination methods, over 300 million people rely on desalination for a large part of their daily water needs. The United States has traditionally been the leader of brackish water desalination, while most of the seawater desalination capacity has been in the Gulf States. United States use mainly RO technologies while Gulf States rely mostly on MSF processes. Historically, the Middle East has used desalination technologies on the largest scale. In Europe, most of the desalination capacity is in Spain and Italy. [28; 1, 2321.]

4.2 Reverse Osmosis

The RO process is a desalination process in which brackish water or seawater is forced through a semi-permeable membrane by using high-pressure pumps. As a result, salt and other contaminants remain on one side of the membrane while water molecules pass through. The following sections explain the process in more detail.

4.2.1 Osmotic Pressure and Major RO Process Parameters

Osmosis is a natural phenomenon, which occurs when two solutions of different concentrations of ions are in contact with each other through a semipermeable membrane. The semipermeable membrane does not allow salt or other types of ions to pass. The difference in the concentrations generates an osmotic pressure, which forces the solutions into a chemical balance: the water molecules of the solution with less ions flow through the membrane to the other side. [25, 3.]

Reverse osmosis is based on overcoming the osmotic pressure. This means that an external hydraulic force, which is greater than the osmotic pressure, is applied to the system. This reverses the flow of water and water molecules pass through the membrane to the permeate side. This in turn increases the concentration of salts on the feed water side. Figure 12 demonstrates the difference between osmosis and reverse osmosis. [25, 3.]

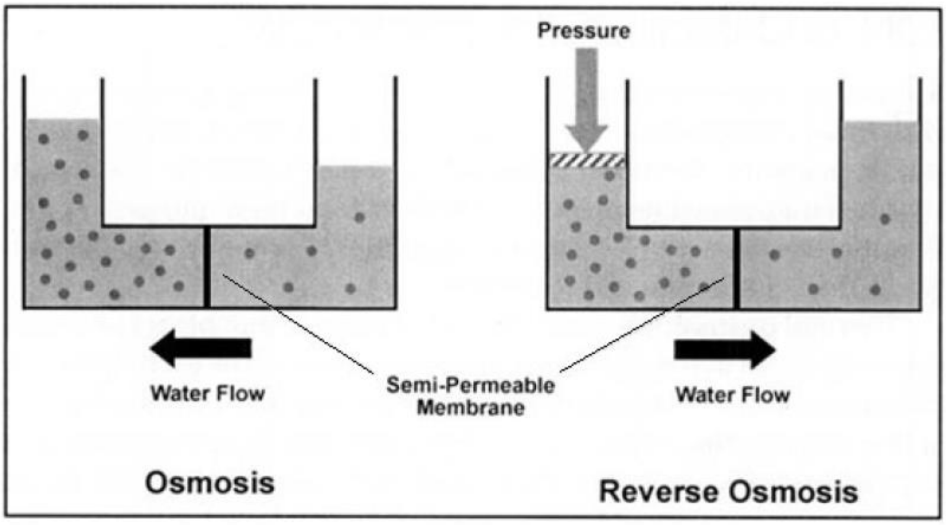

Figure 12 Demonstration of osmosis & reverse osmosis. Copied from [25, 4].

As a result of the RO process, two separate streams exit the membrane vessel: one permeate stream and one concentrate stream. Although semi-permeable RO membranes hold all suspended solids, a small amount of dissolved solids (e.g. minerals) will pass through with the fresh water. RO membranes will be discussed later on. [29, 44.]

Source water quality and temperature are key factors in defining the magnitude of the osmotic pressure. A higher feed water salinity results in a higher required feed pressure. Likewise, a higher water temperature increases the osmotic pressure. However, a higher temperature also lowers the viscosity of water, resulting in increased membrane permeability. Because the impact of higher temperatures on osmotic pressure is relatively lower than the impact of lower viscosity on membrane permeability, warmer source water is usually beneficial in RO. Treating warmer source water up to 30°C allows using lower feed pressures, thus lowering energy consumption. Higher water passage, however, increases also salt passage, which in turn lowers product water quality. [29, 58-74.]

In general, the process parameters, shown in table 1, determine the RO membrane's performance. The process parameters determine the permeate salinity and the required feed pressure. Table 1 shows the consequences when the parameter values are changed.

Table 1 Process parameters' impact on permeate salinity and feed pressure. Modified from [30, 501].

Parameter	**Parameter Value Change**	**Permeate Salinity Value Change**	**Feed Pressure Value Change**
Feed salinity	Increase Decrease	Increase Decrease	Increase Decrease
Permeate recovery rate	Increase Decrease	Increase Decrease	Increase Decrease
Feed water temperature	Increase Decrease	Increase Decrease	Decrease Increase
Permeate flux rate	Increase Decrease	Decrease Increase	Increase Decrease
Membrane fouling (age)	Increase	Increase	Increase

The permeate recovery rate is the percentage of the source water that is converted into fresh water. The remaining feed water becomes the concentrate. SWRO systems usually operate at recovery rates between 40 to 65 percent, whereas BWRO plant recoveries are typically between 65 to 85 percent. For example, a SWRO plant with 40 percent recovery will produce 40 m^3 of fresh water and 60 m^3 of brine out of every 100 m^3 of seawater. [29, 60; 30, 500.]

The majority of SWRO plants have a constant permeate flow. When recovery increases, the needed feed flow decreases as a higher amount of feed flow passes through the membranes as fresh water. As a result, all of the system equipment (e.g. piping, pumps, storage tanks, pretreatment equipment etc.) can be smaller. This in turn decreases costs. However, as shown in table 1, an increase in recovery results in an increase in the required feed pressure. Therefore, the advantage of lower feed flow is lost when recovery rises above 55-60%, which is thus considered to be the optimum recovery rate. [1, 2340.]

The feed flow rate is usually determined by source water pump station and pretreatment production rates. Therefore, a decrease of recovery rate will lower product water flow, if operating at constant feed flow. Increasing the recovery rate (if possible due to the pretreatment system) at constant feed water temperature requires higher feed pressure, in order to maintain the same permeate flow. The feed pressure is adjusted by controlling the speed of the high-pressure pump (or booster pump) with a VSD. In addition, for adjusting the recovery rate, the concentrate stream needs to be throttled with a valve in parallel with the feed pressure control. [30, 501.]

Permeate flux is the rate of fresh water transported per unit of membrane area. The permeate flux of a complete RO system can be calculated by dividing the flow rate of permeate produced by all membranes by the total surface area of the membranes. The selection of system permeate flux depends on the quality of the source water and the type of RO membranes. A higher feed water quality implies a higher acceptable design flux. On the other hand, when treating poor quality source water, the RO system should be operated at a lower flux because operating the RO system at a high flux would result in membrane fouling and would require cleaning too often. In general, the more permeable a membrane is, the higher the flux it can be designed for at the same feed water quality. For example, BWRO membranes are more permeable and can thus be used at higher fluxes than SWRO membranes. [29, 63.]

Membrane condition typically refers to the fouling of the membranes. Membrane fouling is the build-up of foreign substances on the membrane surface [31, 27]. Fouling is one of the biggest threats to the functioning of the membrane desalination process, as it will decrease the membrane's efficiency [25, 5]. Higher operating pressures will be needed to maintain the permeate flux and quality [31, 27]. RO membranes are primarily subject to surface fouling. Fouling can also occur inside the membrane module and between the membrane sheets, where spacers are located to make way for the concentrate stream [1, 2327]. The pretreatment process is used to minimize membrane fouling. Pretreatment systems are discussed in chapter 6.

4.2.2 Basic RO Plant Components

A simplified plant structure consists of the following basic components:

- Saltwater intake system
- Pretreatment facility
- RO separation system
- Post-treatment facility

Every RO plant construct is based on these basic units. The intake pumping station collects the saline source water and delivers it to the pretreatment facility. In RO pretreatment, chemicals are added and the suspended solids are filtered, in order to protect and ensure the functionality of the RO membranes. Next, the pretreated feed water is delivered to the actual RO separation system, which in general includes high-pressure pumps, RO membranes and often an energy recovery system. The pumps apply various pressures depending on the feed water conditions. The saline solution is directed to the membrane vessels, which block the salts while a portion of fresh water flows through (permeate). Meanwhile, the concentrated solution (brine) is discharged from the system. If the plant uses energy recovery system, the brine flows through it. The post-treatment unit processes the permeate e.g. by adjusting the pH to a level suitable for distribution. Figure 13 illustrates flow of water through the different parts of a basic RO plant.

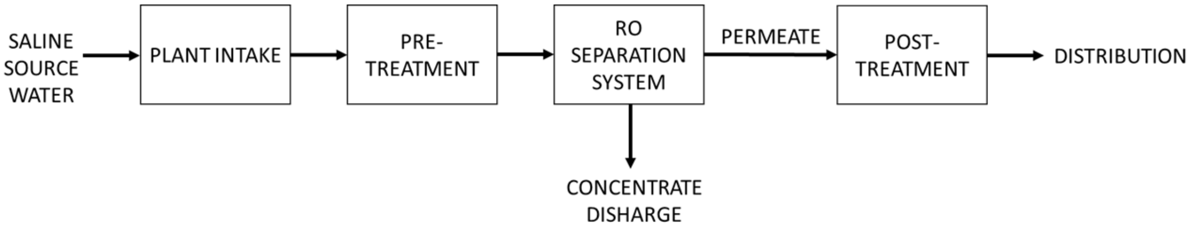

Figure 13 Simplified structure of a RO plant. Modified from [9, 17].

Each of these units use various pumps which need VSDs. The main parts of a RO plant are discussed in more detail in later chapters in this thesis. Sections 5, 6, 7 and 8 look at the plant intake, pretreatment, RO salt separation process, and post treatment respectively. In addition, the role of VSDs in different applications is referenced.

4.2.3 Plant Control and Energy Efficiency

Specific energy consumption (SEC) is the energy cost per volume of permeate product. In the late 1970s, the SEC for SWRO systems was 20 kWh/m^3. Since then continuous developments have occurred in RO systems: the membranes are more permeable and require lower pressures, the pumping systems are more efficient and energy recovery systems were developed. As a result of these technologies, the membrane's net transfer efficiency has increased up to 93 to 97 percent. Some modern SWRO plants have managed to decrease the SEC to 2 kWh/m^3. [32, 241.]

Generally, between 50 and 75 percent of the energy used by SWRO plants is used to control the motors of high pressure feed pumps of the first pass. The pumping power required is directly in relation to the feed pressure and flow rate. Higher salt concentrations require higher pressures and pumping power, in order to produce a target permeate flux. The energy cost in SWRO is normally 40 to 50 percent of the total production costs and may be up to 75 percent of the plant’s operating costs. The biggest cost difference between SWRO and BWRO plants is the required electrical power. BWRO plants need lower hydrostatic pressures for permeate production because of lower source water salinity levels and more permeable membranes. Therefore, BWRO plants’ power costs account for only 11% of total costs. [32, 241; 33, 1; 1, 2332-2341.]

Another key factor that determines a RO plant’s energy consumption is the efficiency of the actual RO separation system, generally consisting of high-pressure pumping combined with membrane vessels and the energy recovery system. For a designed recovery rate, the required feed pressure is generally determined by source water characteristics (temperature/salinity). These features in saline source water may have substantial fluctuations during a year. As a result, a RO plant operation is very much based on responding to variations in feed water conditions. Optimal energy efficiency requires precise adjustments in flow rate and pressure values. In order to control the actions on the feed side of the membranes properly, a proper controller has to be applied to the desalting system. This can be either a throttling valve or a VSD. [2, 2.]

The most energy-efficient way to control flow and pressure is by controlling the pump speed with a VSD [4, 1]. When using a VSD, the pump will use only the amount of energy needed by process. If a throttling valve is used, it might, for example cancel out the benefit of the energy recovery device altogether, because its operating principle is to dissipate energy [2, 2]. RO facilities typically contain many pumps and motors. As an example, the Hadera SWRO plant in Israel is currently the second largest SWRO plant in the world (production capacity of 525,000 m^3/day) [34]. This plant contains almost one hundred electric motors with powers ranging from 11 to 6000 kW that are used to drive pumps of various sizes [35].

It is clear that VSDs have an important role in improving the energy efficiency of various pump applications in RO plants. However, membrane performance and the efficiency of the energy recovery system have the largest impacts on the total energy consumption or energy efficiency of a RO plant [32, 241].

One of the main challenges for RO plants in the future is how to further increase energy efficiency so that fresh water can be produced at even lower costs [32, 257]. It can be assumed that here energy recovery systems will play a key role. In modern RO systems, control is typically achieved through VSDs that control the high pressure pump and the energy recovery system's booster pump. High pressure pumps, energy recovery systems and VSDs are discussed in more detail in chapter 7.

5 Plant Intake

The main purpose of the plant's intake system is to collect source water from the saline water body and convey it to the pretreatment facilities. Plant intake type and configuration are highly site specific. The intake structure and operation also determine the design and performance of downstream processes, especially pretreatment systems. Desalination plant intakes are either open (surface) or groundwater (subsurface) intakes. Open intakes collect water directly from the sea through an underwater structure, whereas subsurface intakes pump brackish water from aquifers e.g. via beach wells. [29, 193; 36, 1-2.]

Intake facilities can also be recognized as the first treatment step of the desalination plant. While the source water for subsurface intakes is already filtered by subsurface soil, open intake systems normally contain coarse bar screens followed by fine screens, which together block larger debris and marine organisms, thus protecting downstream facilities (e.g. intake pumps and pretreatment systems) from equipment damage. If the plant is using membrane pretreatment, an additional microscreening system is needed to retain smaller solid debris, such as plankton and shell particles, which may cause damage to the membranes. Careful investigation of the environment surrounding the intake site and a well-designed system structure will not only protect the downstream equipment, but will also help decrease the negative impact on marine life, improve system efficiency and decrease operation costs. [29, 235; 36, 2.]

5.1 Open Intakes

The inlet structures of open intakes can be located either onshore or offshore. Onshore open intakes are mainly used only for thermal desalination plants, as the source water quality near the shores is usually too poor for membrane desalination. [29, 194-198.]

An example of a SWRO plant with onshore open intake is the Tampa Bay desalination plant (95,000 m^3/day), which is located near a power plant. The cooling water discharged by the power plant provides most of the source water to the nearby desalination plant, while the rest of the source water is pumped from an onshore intake canal. These types of applications, known as co-located intakes, may offer several benefits, e.g. cost savings by having a shared intake structure, including intake pipeline and pre-screening of the source water. [29, 194-198.]

Offshore open intakes are the most popular source water collection systems for medium and large desalination plants. The inlet structure is located typically 300 to 2000 meters from the shore, 8 to 20 meters below the water surface and is normally either a vertical well, made of concrete or metal, or a wedgewire screen. [29, 194.]

The intake water conduit configuration mainly depends on the plant fresh water production capacity and on the structure of the sea bottom. Large RO plants usually have tunnel intake conduits made of concrete. These are installed between 5 to 20 meters below the bottom of the sea and linked to the inlet screen structure by a vertical riser shaft. The intake tunnel can either have a single inlet structure located at the end, or several inlets throughout it. [29, 205-206.]

5.2 Subsurface Intakes

Subsurface intakes are the most used source water collection systems for brackish water desalination plants. Typically, these systems are wells that collect water from deep brackish aquifers. The salinity of the aquifers is normally 600 to 3000 mg/L of TDS. This type of source water often only needs minimal pretreatment for RO system (e.g. cartridge filtration). [29, 210.]

Subsurface intake systems in SWRO collect water from coastal aquifers or offshore aquifers beneath the ocean floor. Coastal aquifers often have lower TDS concentrations than open waters. Currently, less than 10% of SWRO plants in the world use well intakes. [29, 210-211.]

Commonly used subsurface intakes include vertical and radial beach wells, horizontally directed drain wells (HDD) and infiltration galleries. Vertical wells are the most popular subsurface intake systems, being used in both seawater and brackish water desalination facilities. Horizontal wells, HDD wells and infiltration galleries are mostly used in seawater desalination only. Figure 14 illustrates the construct of these wells. [29, 210; 30, 93-94.]

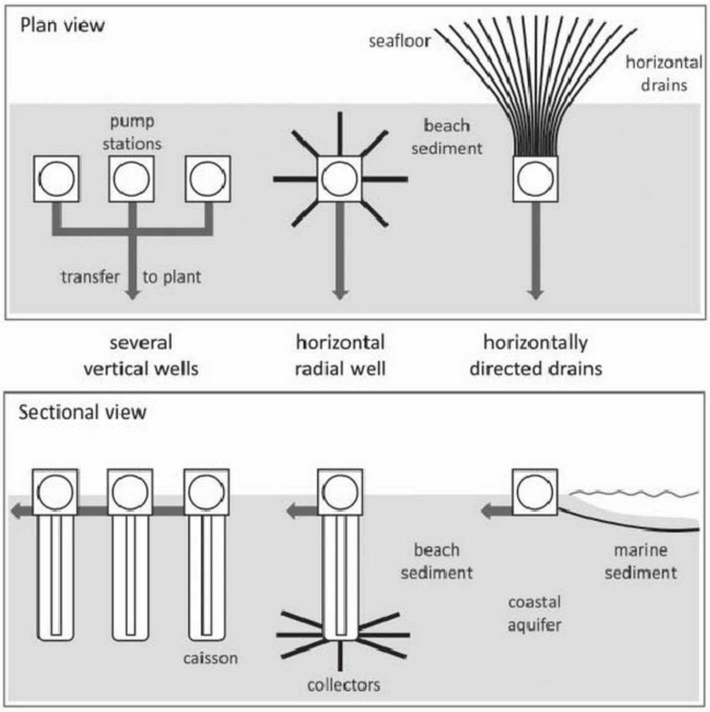

Figure 14 Different subsurface wells. Copied from [37, 22].

The presence of faults along the coast in parallel to the ocean may break the hydraulic connection between the aquifer and the sea. This situation requires the use of horizontal wells instead of vertical wells [29, 221]. If the permeability of the natural sediments is not adequate, infiltration galleries can be used. In these applications, the natural sediment is replaced by a more permeable medium and the perforated pipes are installed underneath them [30, 92]. The construct is usually simpler for vertical wells than horizontal wells, thus lowering the costs for vertical wells [29, 223]. However, horizontal wells and drains collect source water more efficiently (compared to vertical wells), allowing the same amount of water to be collected with less wells [29, 215].

Vertical wells are equipped with a submersible or vertical turbine pump, which is installed inside a steel or fiberglass pipe (well casing) that lines the well borehole. The pipe is used to prevent the well from caving in. The well screen acts as the intake section of the well while filtering sand and other particulates. Currently, one of the largest plants operating with vertical intake wells in the world is the Sur SWRO plant in Oman (production capacity of 80,200 m^3/day). The plant intake area contains 25 duty and 8 standby beach wells, each producing 70 to 100 L/s of source water. Each well is between 80 and 100 meters deep and has a diameter of 14 inches. The wells are equipped with submerged pumps. [29, 212-213.]

5.3 Intake Pump Station

The groundwater wells are often operated either by submersible end suction centrifugal pumps that are placed directly inside the well with the motor, or vertical turbine pumps, which can be line-shaft or submersible. Vertical turbine pumps are specialized centrifugal pumps with a vertical shaft and a series of impellers (stages). Line-shaft vertical turbine pumps have the motor mounted on the top of the pump and above the water. Submersible vertical turbine pumps have the motor on the bottom of the pump. [29, 225; 38.]

Open intake facilities use wet-well, dry-well or canned pump stations. Currently, wet-well pump stations are the most popular type of an intake pump station, due to simplicity and lower costs. The application usually uses vertical turbine pumps which are placed in a wet well. Thus, a separate structure for the pumps is not needed, resulting in a more compact well. One downside to the wet-well configuration is that the pumps are always under water and thus exposed to corrosion. The maintenance of the pumps is also often more challenging. [29, 225.]

Dry-well pump stations typically use split-case horizontal mixed-flow centrifugal pumps, which are located in a separate structure. This decreases the need for maintenance and also makes the maintenance of the pumps easier. However, dry-well pump stations have higher construction costs and risk of interruption of operations caused by flooding. [29, 226-228.]

Canned pump stations use specially designed vertical turbine pump configurations, in which a canned motor is integrated inside the pump. These canned pumps need a 25 to 30 percent smaller footprint than conventional wet-well pump configurations and over 50 percent smaller footprints than dry-well designs. Moreover, canned pump stations have the lowest construction costs. [29, 226-227.]

5.4 VSDs in RO Plant Intake

The type, size and number of pumps, pump motors, and the motor speed controls (i.e. constant or variable speed controls) usually depend on the source water delivery system. Intake pump stations usually have at least two duty pumps and one standby pump. Plants with higher production capacities require more duty and standby pumps. For instance, a plant with a design availability factor of at least 96% (i.e. that 96% of the time the plant will produce at its full production capacity) would usually require at least five duty pumps and two standby units. Installing a VSD on at least one of the pumps is usually advised in order to achieve higher efficiency and flexibility. [29, 228.]

5.4.1 Water Monitoring and Controls

The intake pump station control system is typically integrated into the plant’s main control system. Intake pump stations are monitored and controlled with sonic level sensors, wet-well level indicators, pump controllers, flow meters and flow recorders, control valves, temperature sensors and indicators, as well as oil and grease sensors. Typically, source water intake pumps are controlled by flow, because this will determine the output flow of the pretreatment processes. By using pumps with VSDs, the flow is controlled with pump speed, thus allowing the output to match a selected flow set point. The intake flow is normally measured and recorded continuously, as the intake pumps can thus be shut down automatically (e.g. by VSDs) if, for example, flow malfunctions occur. [29, 230; 39, 490].]

Another option is that the pumps are controlled by the water level height in the well storage. An analog signal will inform the VSD if the water level reaches preset minimum or maximum threshold values and the VSD in turn adjusts the pump speed to maintain the water level within the demanded values. Without VSDs, the water level is controlled by starting up or shutting down secondary pumps. However, it is normally preferred that the flow rates through the treatment processes are kept constant to achieve better performance. For this reason, the flow rate from the intake pumps should only be varied gradually when needed. [39, 490-491.]

However, even if the pumps are not controlled by the well water level height, the height is typically still monitored in order to prevent dry running, which causes the overheating of the pumps [29, 230]. VSDs designed for water treatment often have integrated functions that can detect dry running. If needed, they will automatically slow down or shut down the pump, in order to prevent pump damage.

Temperature sensors are constantly monitoring the temperature of intake water in order to detect any temperature fluctuations. In addition, continuous measurement of intake water salinity, turbidity and other quality conditions are usually included. When these values are outside preset limits, the pumping system is alarmed. For example, UF/MF (pretreatment) and RO membranes warranties usually have limitations concerning water temperatures. [29, 231.]

5.4.2 Water Hammer Protection

A water hammer (also known as a pressure surge) is a pressure spike which occurs in the pipeline if the flow is abruptly closed by a pump or valve. The risk of harmful pressure spikes typically exists when the distance between the intake pumps and pretreatment facilities is higher than 300 meters, or if the flow rate generated by the intake pumps exceeds 5500 m^3/day. Recurring surges put stress on the source water delivery piping, pumps and other equipment, and will eventually cause damage to the system. Pumps can be damaged if suddenly stopped, due to the water colliding into the pump on the suction side. During normal operation, VSDs can control the surges by ramping the pump start-ups and shut downs. However, the system is also equipped with surge tanks and different types of valves that control the surges e.g. during pump failures. [29, 229; 40, 22.]

5.4.3 Submersible Pump Applications

VSDs have a worthy role in submersible pump applications. Submersible pumps are equipped with thrust bearings which will be damaged if the pump operates at below minimum speed (usually 30 Hz). This challenge occurs during the pump start and stop situations. To eliminate the risk of damaging the thrust bearings, the pump speed has to be adjusted from zero speed to minimum speed (30 Hz) as fast as possible. Submersible pump manufacturers often recommend that this ramp time takes a maximum of 2-3 seconds. After the minimum speed is achieved, the pump speed can be gradually increased to the desired operating speed normally. The acceleration ramps are illustrated in figure 15. [41.]

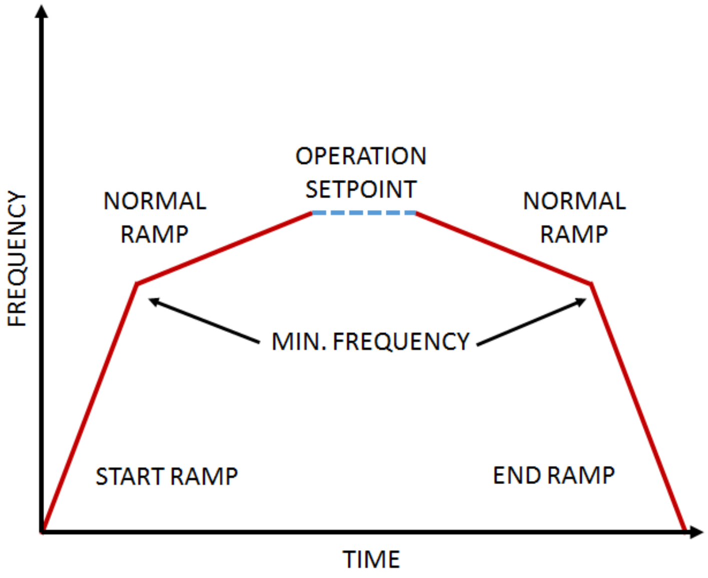

Figure 15 Ramps for submersible pumps. Modified from [42, 33].

Likewise, when the pump is being taken out of operation and the minimum speed is reached again, the speed has to be decelerated to stop as quickly as possible, as seen in figure 15 [41].

5.4.4 Environment

Two key environmental issues with open intakes are that algae, fish and other aquatic organisms can get trapped in intake screens (referred to as impingement), and that pumps and filters can cause damage to marine life (referred to as entrainment). One solution to reduce impingement and entrainment is to reduce the plant intake flow. In situations where the plant production needs daily changes, installing VSDs on the intake pumps can help reduce issues caused by impingement and entrainment, as the amount of source water can be better matched to production needs. [29, 134-137.]

6 RO Pretreatment Systems

The main objective for a pretreatment system is to decrease the fouling propensity of the water that flows through the RO membranes. Membrane fouling weakens the functionality of the membranes and therefore must be taken in account, especially in seawater and brackish water RO plants using surface water sources. Spiral-wound elements, which are the most used RO membranes nowadays, contain a feed spacer, which can get blocked by suspended solids. The plugging of the feed spacers results in a pressure drop, which has to be compensated by an increased feed pressure, in order to keep the permeate flow rate. Groundwater sources usually require less extensive pretreatment systems, e.g. cartridge filtration combined with the addition of acid and/or scale inhibitors. [1, 2329; 31, 27.]

Since surface water membrane plant intake systems have equipment that can filter large debris, floating matter, most large aquatic organisms, sand and stringy materials from the source water, the pretreatment system needs to focus on removing the following contaminants:

- colloidal and particulate contaminants (suspended solids and silt)
- inorganic compounds that can precipitate and scale the membranes (including iron and manganese, calcium carbonate, calcium sulfate)
- organic contaminants (including organics, micro-organisms and soluble organic compounds that micro-organisms use as food in the source water)

RO pretreatment systems can be divided roughly into two types: conventional pretreatment and membrane pretreatment. These processes are explained in the following sections. [31, 79.]

6.1 Conventional Pretreatment

6.1.1 Coagulation and Flocculation

Conventional pretreatment systems usually begin with chemical additions, followed by a disinfection phase, media filtration and cartridge filtration [1, 2329]. Source water particles, including colloids, suspended materials, bacteria and other organisms, can be eliminated by conventional pretreatment [43, 107].

The chemicals, including acids, coagulants and flocculants make the saline solution more compatible with granular media filtration. Adding acid lowers the feed water pH rates. Coagulation and flocculation are important steps in conventional pretreatment. Saline source water contains particles and colloids which are in a stable condition. By dosing various coagulants, such as aluminium salts, lime or polyamines, the particles will be destabilized. This enables the subsequent flocculation phase, in which the particles become attached to each other, so that they can be removed (filtered) effectively in later phases. Flocculation uses mostly anionic or nonionic polymers to form larger particles. [43, 107-108.]

6.1.2 Disinfection

Disinfection is accomplished by adding a strong oxidant, like chlorine. A high concentration of the oxidant is used so that the residual disinfectant can be allowed to pass through the rest of the pretreatment system stopping any biological growth. Most RO membranes today are made of aromatic polyamides, which are sensitive to chlorine. For this reason, all chlorine must be removed before the feed water enters the actual RO unit. Extended chlorine use will deteriorate the RO membranes and weaken the ability to reject salt. [1, 2330.]

6.1.3 Granular Media

Conventional pretreatment finishes with granular media filtration and cartridge filtration. Media filtration “beds” consist of a combination of granular materials such as sand, pumice and gravel and the permeate flow can be caused either by using gravity or pressure. Cartridge filtration takes out the larger particles that pass through media filtration. These particles (larger than 5–10 µm) must be removed from the water before RO treatment, as they can foul the channels that are used for brine disposal. [1, 2330.]

Granular media filters typically operate at constant flow. This means that the feed pressure of these filters will increase as solids accumulate on the filter bed. At a certain threshold, a process called filter media backwash is activated (typically once or twice every 48 hours). The backwash function uses either filtered source water or brine from the RO system. During the operation, the backwash water flows in the opposite direction, removing and transporting solids out of the system. Some backwash systems also use pressurized air to enhance particle removal. This type of backwash typically uses a combination of air scour and low-rate backwash, followed by high-rate backwash without adding air. [29, 286; 39, 500.]

A successful backwash is an essential phase in filtration, because poorly performed backwashing will result in problems in the filtration process. The backwash water is typically pumped from a treated water storage or supplied directly from the plants concentrate transmission main. [29, 286; 39, 500.]

6.2 Considerations for VSDs in Conventional Pretreatment

6.2.1 Coagulation and Flocculation

Source water chemical processing facilities consist of three main parts: coagulation tanks, flocculation tanks and chemical feeding equipment. Flocculation is a much slower process than coagulation, as it needs longer time for retention and mixing. As a result, the two processes require different types of designs. [29, 256.]

In these processes, the source water’s condition has to be taken into consideration. For example, the temperature of source water is an important factor, as it determines the water viscosity [43, 112]. In coagulation, it is essential that the chemicals are introduced quickly and uniformly with the source water [43, 780]. Therefore, the flow rate of chemical feeding should match the flow rate of the treated water [39, 493].

Generally, chemicals are added by positive displacement chemical metering pumps. Coagulant dosing, for example, can be controlled by monitoring turbidity or coagulant flow and adjusting the feed pump speed based on this information. The main goal for coagulation tanks is to mix the added coagulant and source water into a homogeneous mixture. The mixing facilitates efficient coagulation. The most popular types of coagulant mixing systems in desalination plants are static in-line mixers and mechanical (flash) mixers. [43, 657; 29, 256.]

In flocculation, the chemical dosage is typically very low, as overdosing causes fouling. The most popular type of flocculation system is a mechanical flocculator equipped with vertical mixers. Overdosing and/or poor mixing of the chemicals with the source water can cause fouling of the downstream cartridge filters and RO membranes. [29, 258-261.]

It is recommended that the mixers in coagulation and flocculation tanks are equipped with VSDs, which can be used to alter the intensity of mixing. This facilitates process control when the quality, temperature or flow rate of the source water changes [39, 780]. VSDs can be used to control the mixing speed manually, based on past operating experience, or in proportion to the flow rate [39, 495].

6.2.2 Media Backwash

The granular media backwash process can be based on using water or water and air. It is essential to control the flow rate of the wash water, in order to ensure successful cleaning and to prevent media loss. Flow rate requirements vary because of temperature changes between the seasons (e.g. denser cold water needs a lower flow rate). Backwash flows have to be adjusted gradually. As a result, systems with no air scour are typically controlled by valves. Systems using an air-water combination include two backwash flow rates, which can be adjusted by a VSD installed on the backwash pump. [39, 500.]

6.3 Membrane Pretreatment

MF and UF systems equipped with hollow-fiber membrane elements are the most typical membrane pretreatment methods for removing particulate, colloidal and organic foulants from the source water. MF (typically pores of 0.04 µm) and UF (pores of 0.02 µm) membranes are effective especially against turbidity and silt. [31, 84; 29, 311.]

The filtration in these systems is either driven by pressure or by vacuum. In pressure driven systems, the feed water is pumped through membrane modules, which are enclosed in a pressure vessel. In vacuum driven systems, on the other hand, the feed water is vacuumed through membrane modules which are packed inside cassettes, which in turn are submerged in feed water. [29, 321.]

The structure of pressure driven MF or UF system resembles the general structure of a RO system. In general, the source water is transported into a wet well (feed tank) through a microscreen. The water is pumped into the membrane filtration system from the feed tank and collected into a filtrate tank after the membrane process. In vacuum driven systems, the structure of the system is somewhat different. The membrane modules are typically installed in concrete or metal tanks which are often open to atmospheric pressure. The vacuum pumps on the permeate side create the driving force to the feed water. Filtered water is typically collected into a filtrate tank. [29, 320-321.]

All membrane pretreatment systems consist of four operational modes, which are normally monitored and managed by a programmable logic controller (PLC):

1. Filtration Processing
2. Backwash
3. Cleaning
4. Integrity testing

These operational modes are explained in the following sections.

6.3.1 Filtration Processing

Depending on the filtration method, MF and UF systems can be operated in three different configurations. The filtration can be driven by vacuum, as mentioned previously, or pressure, which can have two different filtration modes. The feed water in pressurized systems is filtered in either direct-flow or cross-flow mode. In direct-flow mode, all of the source water flows through the membranes, whereas in cross-flow mode, only a part of the water (90-95 percent) passes through the membrane. The remaining reject flows along the membrane feed side. While moving along the membrane surface, the rejected water produces a shearing velocity that clears the feed side of the membrane from solids. [29, 314.]

The reject water in the cross-flow mode is redirected back to the feed system and blended with the feed stream. Concentrate waste is discharged from the system once in a while. The energy consumption is higher in the cross-flow than in the direct-flow mode, because the concentrate circulation requires additional pumping (recirculation pump). Thus, most UF and MF membrane elements on the market are designed to be used in the direct-flow mode. However, the cross-flow mode is usually more suitable than the direct-flow operation mode if the source water quality is poor (i.e. contains high turbidity). [29, 314.]

6.3.2 Membrane Backwash

Backwash is needed to remove the solids from the feed side of the membranes. The operation is initiated by a timer and occurs every 30 to 120 minutes for about 30 to 60 seconds. Backwash is triggered when the transmembrane pressure (TMP), which is the difference between the feed pressure and the pressure of the filtrate, reaches a certain maximum threshold. Usually the pretreatment system production capacity (flux) is reduced if the threshold TMP is exceeded. Membranes have a considerably weaker capacity to store solids within the system, compared to granular media filters. As a result backwashing occurs 30 to 50 times as often for membrane systems as it does for granular media filters. Either filtered feed water or RO concentrate is used for backwashing. Some systems also use gas (air) in the process. In addition, the membranes are treated with chlorine and other chemicals before backwashing once or twice per day, in order to prevent organic deposits and biofilm. [29, 315-316.]

6.3.3 Membrane Cleaning

Despite of the backwash operations, membranes used in the pretreatment system foul over time. Membrane fouling causes the TMP required to filter saline water of a specific target volume (flux) and quality to rise over time. Cleaning of the membrane is normally required every 1 to 3 months, when the TMP reaches a preset level. During membrane cleaning, the modules are offline and a low-pH solution followed by a high-pH solution is recirculated through them. After 8 to 24 hours of recirculation, the cleaning chemicals are flushed off and the membrane modules are returned to normal operation. [29, 316.]

6.3.4 Integrity Testing

Membrane system integrity testing includes features or tests that help identify occasional damage, e.g. punctures, in the membrane equipment. The most common integrity test is a pressure hold and visual test, which require the system to be offline while the water is dismissed from the system. The pressure hold test involves applying air under a pressure of 0.3 to 1 bar to the system and monitoring the decay of air pressure over time. The pressure hold tests vary depending on the membrane system configuration. [29, 317.]

6.4 Considerations for VSDs in Membrane Pretreatment

UF and MF membrane systems are often equipped with several pumps, depending on the configuration: feed or permeate (vacuum) pump, recirculation pump, backwash pump, cleaning pump and chemical dosing pump [43, 427].

Variations in source water quality and temperature, along with degree of membrane fouling, determine the operating pressure required for filtration. For example, lower temperatures require higher TMP in order to provide a constant production rate [43, 426]. To account for these variations, flow and pressure rates have to be controlled. These can be controlled e.g. by throttling valves. However, the most efficient way to control flow and pressure is by adjusting pump speeds with VSDs. Significant amounts of energy can be saved when the pump operates directly as the process requires. [4, 1.]

6.4.1 Feed/Permeate Pumps

The source water is normally delivered to pressurized membranes by centrifugal feed pumps equipped with VSDs, in operating pressures between 1.4 and 2.0 bar. Vacuum type systems usually operate at a maximum of -0.8 bar. Large pressure driven membrane systems may have a pump station with multiple feed pumps, delivering feed water to multiple pressure vessel groups (membrane banks). This decreases the amount of feed pumps needed. In submerged and small-scale pressurized systems, on the other hand, each membrane bank is typically operating with an individual vacuum or feed pump. [44, 58; 43, 427.]

MF and UF systems can operate under two primary concepts: constant pressure or constant flow. Constant pressure operation means that the feed pressure is kept at a certain value regardless of the system permeate flow rate alteration. With this concept, the treated water flow rate decreases over time, because the accumulation of solids from the source water raises the TMP. As the treated water flow produced by UF/MF drops over time, the output of the plant drops as well. [44, 56.]

A constant flow operational concept means that the filtered water flow through the membranes is kept steady, and the feed pressure increases over time. The feed pressure needs to be increased because of membrane fouling, which develops between backwash and cleaning cycles. The centrifugal feed pumps have to be sized to meet the demand for higher pressures. This results in a declining energy efficiency and higher power use, when the TMP gets higher. These efficiency issues can be eliminated by using VSDs on the feed pumps. [44, 56-57.]

Generally, in systems where each membrane unit has an individual feed pump, the pumps are operating at a constant flow rate. A VSD controls the pump to operate at the flow and pressure range required by the membrane unit. Constant pressure, on the other hand, is used in systems where the pumps are arranged in a single pumping unit to feed multiple membrane banks via common header. With this setup, VSDs can be used to adjust the general pressure required to operate the dirtiest membrane unit. Meanwhile, on each membrane unit’s feed or permeate piping there is a throttling valve controlling the flow through the unit. More efficient energy consumption can be achieved by cleaning every unit at approximately the same time and by setting the pumps’ pressure outputs to values slightly higher than needed. [44, 190.]

6.4.2 Recirculation Pump

If the filtration is cross-flow type, the system usually includes a recirculation pump, which redirects some of the reject water back to the feed system. This pump should be able to compensate pressure loss along the membrane modules and provide a designed flow rate. Depending on the source water quality, the recirculation flow rate should be 3 to 6 times higher than the flow rate of source water. Recirculation pumps are usually not used continuously, thus the output flow is typically adjusted by an effluent valve. [43, 427; 44, 58-183.]

6.4.3 Filter Backwash

A backwash pump is employed for delivering washing liquid typically from a tank containing previously filtered water. The wash water pressure is between 0.5 to 2 bars. For small capacity membrane systems, an individual backwash pump is installed for each membrane bank. Large-scale systems may use a backwash pump station, which operates for all membrane banks. Because the backwash pump has to start and stop repeatedly, it is recommended that the pump motor is controlled by a VSD or a soft-start device. These can both be used to soften the frequent start-ups, thus reducing stress on the motor and extending its lifespan. [44, 58-183; 45, 1.]

7 RO Salt Separation System

This section provides an overview of the actual desalting systems using spiral-wound polyamide thin-film composite RO membrane modules. The RO separation system typically comprises the following main parts:

- Filtered water transfer pumps
- High-pressure pumps
- RO pressure vessels
- Energy recovery devices
- Membrane cleaning systems

The separation of salts occurs in so-called RO trains. A typical RO train is a combination of a RO feed pump, pressure vessels, pipes for feed/concentrate and permeate water, control valves, the energy recovery system and supplying devices such as VSDs. A single RO train normally produces 10 to 20 percent of the total amount of the permeate flow. [29, 386.]

Figure 16 illustrates a typical configuration of a RO separation system. The component setup can vary between desalination plants depending on the plant intake type, quality of the source water, energy recovery system and design structure. For instance, the filtrate storage tank and transfer pump may not be necessary if the source water is suitable to be pumped from the plant intake directly through the cartridge filters to the high pressure pump. Especially brackish water RO plants treating ground water commonly use these kind of configurations, as the source water does not go through an extensive pretreatment process. [29, 359-360.]

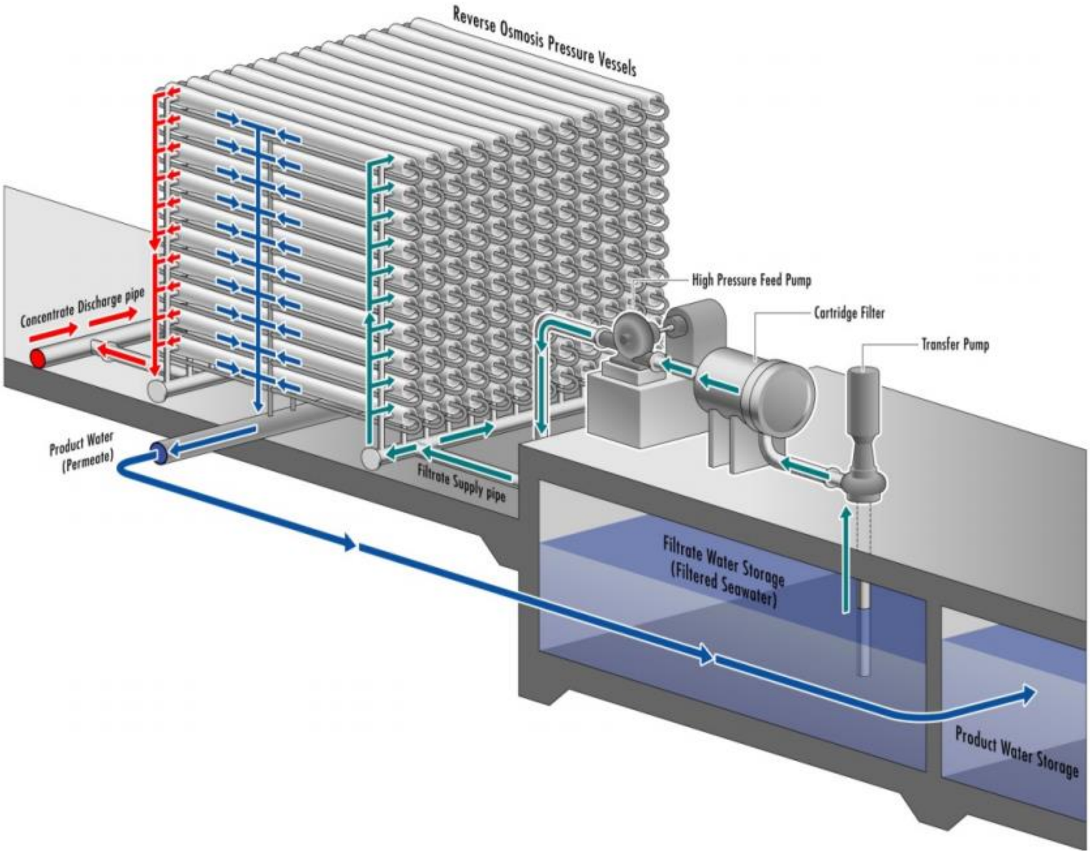

Figure 16 A typical configuration of RO separation system. Copied from [29, 360].

In the configuration shown in figure 16, the pretreated water is stored in a filtrated water storage tank, where it is delivered into the high pressure pump through cartridge filters by a transfer pump. The high-pressure pump increases the pretreated feed water pressure to a level that is suitable for the membrane elements and the feed water salinity, while delivering the water to the pressure vessels. [29, 359.]

Even though the cartridge filters are shown in figure 16, they are usually considered to be a part of the pretreatment phase instead of a part of the RO membrane system. Cartridge filters protect the RO membranes from matter that may occasionally get past the actual pretreatment process. [29, 360.]

The key components of the RO separation system are presented in more detail in the following sections. In addition, the role of VSDs is discussed. The control of the high-pressure feed pumping and the energy recovery systems by VSDs is discussed separately in the last section, because these are especially important applications for a VSD in RO.

7.1 Filtered Water Transfer Pumps

Filtered water from the pretreatment system could either pass through a direct flow-through desalination system or through a desalination system with interim pumping. The direct flow-through system is illustrated in figure 17.

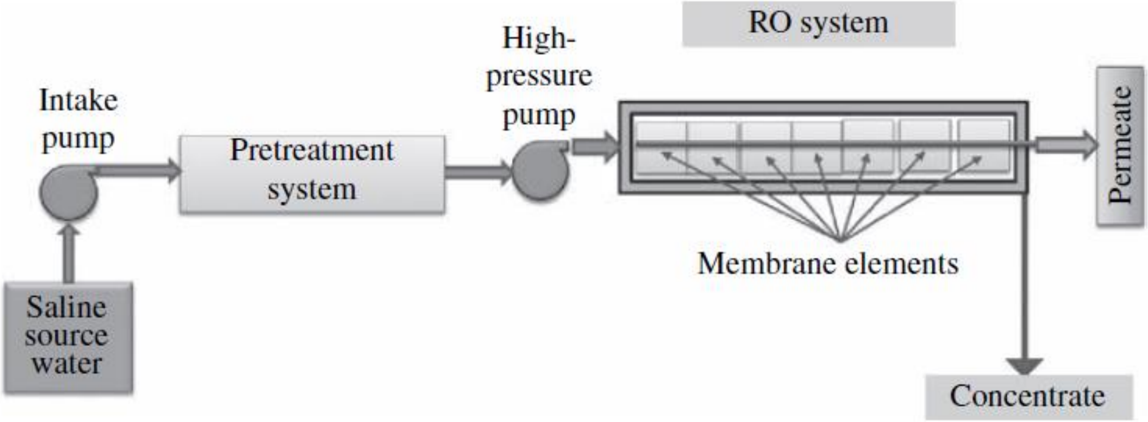

Figure 17 RO system with direct flow-through. Copied from [29, 361].

In the direct flow-through desalination system, the intake pump station is designed to give a suction pressure that will optimize the operation of the high-pressure feed pump. The pretreatment system must be equipped with pressure granular media filters or pressure-driven membranes to ensure that it does not break the pressure. For this reason, the pretreatment system should be designed to be able to cope with the extra pressure required by the suction of the high pressure RO pump. For SWRO desalination systems the suction pressure could be between 2 and 6 bars. For BWRO plants the suction pressure is typically below 1 bar. [29, 361.]

In the desalination system with an interim filtered water transfer, an additional pump station (filtered water transfer pump) is used to boost the suction pressure of the filtered source water, in order for the high-pressure pump to operate efficiently. Generally, filtered water transfer pumps are either vertical turbine pumps or horizontal centrifugal pumps. The interim pumping system in figure 18. [29, 361.]

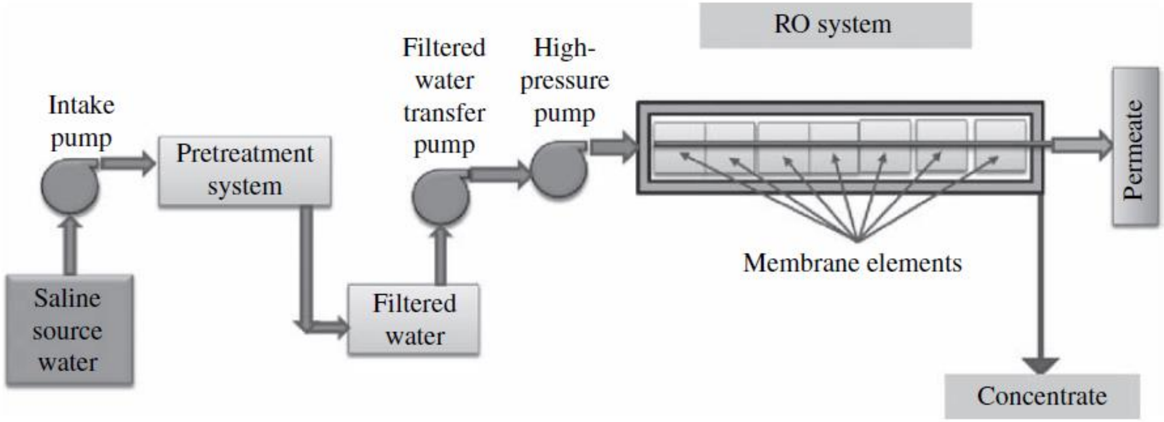

Figure 18 RO system with an interim filtered water transfer. Copied from [29, 361].

In modern SWRO systems, VSDs are installed on the filtered water transfer pumps to control the feed pressure of the filtered water transfer pumps, which in turn control the feed pressure of the RO system. The VSD provides a cost-effective way to control for the feed pressure. This is important because water quality changes due to seasonal changes in the temperature of source water or salinity can have an effect on the osmotic pressure and net driving pressure (NDP) required by the desalination process. These changes in turn mean the RO membrane feed pressure needs to be altered accordingly. For example, a decrease in the temperature of the source water and/or an increase in the salinity of the source water requires an adjustment (i.e. increase in this case) in the NDP and feed water pressure so that the same permeate volume can be produced. This type of adjustment process maximizes the efficiency of the RO feed pumps and allows for constant feed flows. Thus, VSDs help reduce the total energy used by plants. [29, 361-362.]

Alternatively, VSDs could be used to control the pressure by installing them on the high-pressure RO pumps instead of the transfer pumps. However, because the size of the transfer pumps tends to be smaller, and since the cost of VSDs depends on the size of the pump, installing the VSDs on the transfer pumps can provide cost savings. This is particularly true in the case of SWRO desalination systems. In the case of BWRO plants, the operating pressures are much lower and installing VSDs might not bring similar cost advantages. [29, 362.]

7.2 High-Pressure Feed Pumps

The purpose of a high pressure feed pump is to convey feed water to the RO membranes at sufficient pressure throughout the design life of the system. Usually, the pressure required for salt separation in BWRO is 5 to 25 bars and 55 to 70 bars in SWRO. The source water TDS level and temperature along with target product water quality and the design of the RO system determine the amount of pressure needed. In addition, membranes lose their permeability over time (membrane fouling), which raises the pressure needed to maintain the productivity. [29, 362.]

In order to optimize the high pressure pump efficiency with these changing pressure requirements, the feed flow and pressure must be adjusted during the system operation. Unless the filtered water transfer pump or high pressure pump is equipped with a VSD, the adjustment of high pressure pump can be performed with pressure control valves. In addition, as the pumps operate at high pressures, during pump start-up the feed pressure has to be increased carefully up to the target level, in order to prevent a hydraulic surge in the feed line. Hydraulic surges can cause damage to several parts of the membranes. Generally, the pressure should not be raised faster than 0.7 bars per second. By using a VSD, the speed of the pump or motor can be adjusted to achieve the target output flow or pressure. [29, 362-363.]

The pump size depends on the flow and operating pressure. These are determined by standard performance curves supplied by pump manufacturers. The most popular high-pressure pumps in RO systems are centrifugal pumps. [29, 363.]

Centrifugal high-pressure pumps are common for RO plants of all sizes. Pump produces a pressure that changes in relation to flow, meaning that the pump curve is not flat. In order to maintain efficiency in a large scale of operating pressures, either the centrifugal high-pressure pump or the filtered water transfer pump would need to be equipped with a variable speed drive. Often, centrifugal pumps used in these applications are a multi-stage type, because the pump curve becomes flatter when the number of pump stages increases. [29, 365.]

Centrifugal pumps have a feature of providing efficiency proportional to the square of the pump flow capacity, while the pressure and speed are the same. In other words, one large pump delivers the same flow more efficiently than two smaller pumps that deliver an equal flow in total. Primarily due to this, there has been a new trend of designing using fewer but larger pumps that supply several RO trains simultaneously. In comparison, the normal RO train configuration involves each RO train having an individual high pressure feed pump. A 9500 m^3/day SWRO train is typically supplied by a centrifugal pump of 83 percent efficiency. If, however, this pump is designed to supply 2 SWRO trains of the same capacity (total delivery of 19,000 m^3/day), the pump efficiency would rise to 85 percent. As the high pressure pumps in SWRO applications may consume up to 70-85 percent of the energy used for the entire plant, using fewer but larger pumps has the potential to save substantial amounts of energy. [29, 365.]

However, in some situations the conventional single-pump/single-train configuration is still preferred over the new configuration design. For example, this is the case when there are reliability concerns of losing huge portions of production capacity in case of pump failures, and when maximum pump efficiency may not be feasible if the RO plant has to operate in a wide range of production flows. VSDs provide cost effective flow control, supporting the use of fewer larger pumps to some extent. However, even pumps controlled by VSDs cannot maintain maximum pump efficiency if the plant needs to turn down its capacity to as low as 10 to 20 percent of its maximum flow. [29, 365.]

Most popular types of centrifugal high pressure RO feed pumps are split-case multistage pumps, segmental ring multistage pumps, high-speed single-stage pumps and vertical turbine pumps (BWRO only). In RO applications, these pumps typically run at 3000 to 3500 rpm. [29, 365.]

Currently, horizontal split-case multistage centrifugal pumps are the most popular pumps for high-pressure SWRO feed applications in medium- and large-size plants. Pumps typically operate at high efficiency (80 to 88 percent) and the capacities for large-sized pumps vary from 600 to 3000 m^3/h. The Ashkelon SWRO desalination plant in Israel, with product capacity of 330,000 m^3/day, operates with two sets of three duty and one standby horizontal split-case centrifugal pumps. Each pump has a capacity of 2500 m^3/h and is run by a 7000-hp (about 5.2 MW) motor. The plant uses a specialized “pressure center principle”, where the high-pressure pumps are combined in one pumping unit. The feed pumping center operates via a common pipeline and allows the use of fewer but significantly larger horizontal split-case pumps. This configuration is discussed in more detail in section 7.5.3. [29, 366-367.]

Over the last years, radially split-case multistage centrifugal pumps have also become a popular choice for new medium and large-size SWRO plants. These pumps require less space and allow easier maintenance, compared to horizontal split-case pumps. The 250,000 m^3/day Sydney Water SWRO plant in Australia, for instance, operates with 12 duty and one standby radially split-case pumps. Each pump is run by a 2800-hp (2.1 MW) motor with efficiency of 85 to 87 percent. [29, 367.]

7.3 Energy Recovery Systems

In SWRO, the feed pressure decreases about 1.5 to 2 bars as the water passes the membrane pressure vessels. This means that the released concentrate is at high pressure. The concentrate holds 40 to 50 percent of the energy used for salt separation. This energy can be transferred to part of the entering feed water by an energy recovery device (ERD). As energy consumption in SWRO covers the majority of the total plant O&M costs, using energy recovery systems is cost effective. In fact, technological developments in energy recovery equipment over the past 20 years have cut down the energy consumption for water production by 80 percent. [29, 386-387.]

Due to significantly lower applied feed pressures and higher recoveries, energy recovery systems are typically not as cost-effective to install on brackish water systems. However, recently there has been more interest in advanced low-energy BWRO, where ERDs designed specifically for BWRO are used. In some configurations, ERDs allow reducing the size of the high-pressure pump, thus lowering capital costs. [29, 387; 46.]

Energy recovery systems are categorized into two: centrifugal and isobaric ERDs. The operation principles and key features of these devices are introduced in the following chapters. Simplified process diagrams of these systems are presented in appendix 1.

7.3.1 Centrifugal Energy Recovery Systems

Centrifugal ERDs are equipped with an impeller that receives the pressure energy contained in the concentrate. The energy is transformed into rotational energy, which is then used to reduce the energy required to operate the high-pressure pump. The most used types of centrifugal ERDs are Pelton wheel and hydraulic turbocharger (HTC). [29, 387.]

Pelton wheel is an enclosed turbine in which the pressure of the concentrate is transformed into rotational energy, driving the shaft of the wheel. This shaft is directly connected to the shaft of the high-pressure pump. After the concentrate has transferred its energy to the wheel, it is discharged by gravity and directed for disposal. The energy conversion efficiency of this ERD is 80 to 90 percent. Because the Pelton wheel is directly paired with the pump motor the maximum RO train size is determined by the maximum size of commercially available Pelton wheels (currently 21,000 m^3/day). Large RO plants using Pelton wheel turbines include, for example, the Beckton desalination plant (London) with a production capacity of 150,000 m^3/day and the Tampa Bay SWRO plant in Florida. [29, 388.]

The hydraulic turbocharger is a configuration consisting of a centrifugal pump and a turbine, which are connected on the same shaft. The pump of the HTC is in series with a single-stage motor driven medium pressure centrifugal pump. The HTC is driven by the concentrate pressure. The medium pressure centrifugal pump provides between 50 and 75 percent of the total RO feed pressure required for salt separation (normally 35 to 46 bars). The remaining pressure is delivered by the HTC. The HTC has an energy efficiency of 90 to 92 percent. The total energy efficiency of this setup is between 70 and 80 percent. [29, 388.]

7.3.2 Isobaric Energy Recovery Systems

In isobaric energy recovery systems, the low pressure feed water is divided in two separate streams. One stream flows towards the high pressure centrifugal pump, while the other one is conveyed to the isobaric ERD. In the ERD, the hydraulic energy of the concentrate is transferred via positive displacement to the entering low pressure feed water. In other words, inside an isobaric chamber, a portion of high-pressure brine displaces a portion of low-pressure feed water, turning it to high pressure feed water. After this pressure-exchange, the concentrate is discharged from the system as low-pressure brine.

The pressurized feed water from the ERD is combined with the feed water pumped by the high-pressure pump. Isobaric ERDs deliver about half of the total amount of feed water into the RO membranes. 4 to 6 percent of the energy is lost via the ERD, which is why an additional small booster pump (circulation pump) is installed to cover the loss. The rest of the required feed flow is gained from the high pressure pump. Isobaric ERDs transfer and reuse the energy for RO typically at efficiencies of 93 to 96 percent, reducing overall plant energy costs significantly. [29, 391.]

Compared to centrifugal ERDs, isobaric systems are not coupled with the high pressure pumps, thus the RO train size is not limited by the individual size of the ERD. The high system efficiency combined with the fact that designing SWRO systems with fewer but larger RO trains is trending (i.e. with larger size RO elements, such as 18”), has led to a wider use of the isobaric ERDs during the last 10 years. [29, 391-392.]

Isobaric energy recovery systems typically use either a pressure exchanger (PX), developed by Energy Recovery International (ERI), or a dual work exchanger energy recovery system (DWEER), designed by Calder (Flowserve Corp.). Generally, the PX pressure exchanger structure is simpler and more compact than the DWEER system. However, DWEER systems may have slightly better overall energy efficiency and performance in some configurations. Today, the ERI system is the most popular type of ERDs in medium and large SWRO facilities globally. [29, 392-394.]

7.4 RO Membranes

The reverse osmosis membranes can be made of different materials with varying structures and configurations. The most popular membranes contain a semi-permeable thin film (0.2 um) made of aromatic polyamide (PA) or cellulose acetate (CA). As a reinforcement, a microporous layer (about 40 um) and reinforcing fabric (typically 120 um) are supporting the film structure to maintain membrane integrity and durability. The 0.2-µm ultrathin polymeric film enables the RO membrane to reject salt. The structure of a typical membrane is shown in figure 19. [29, 45-47.]

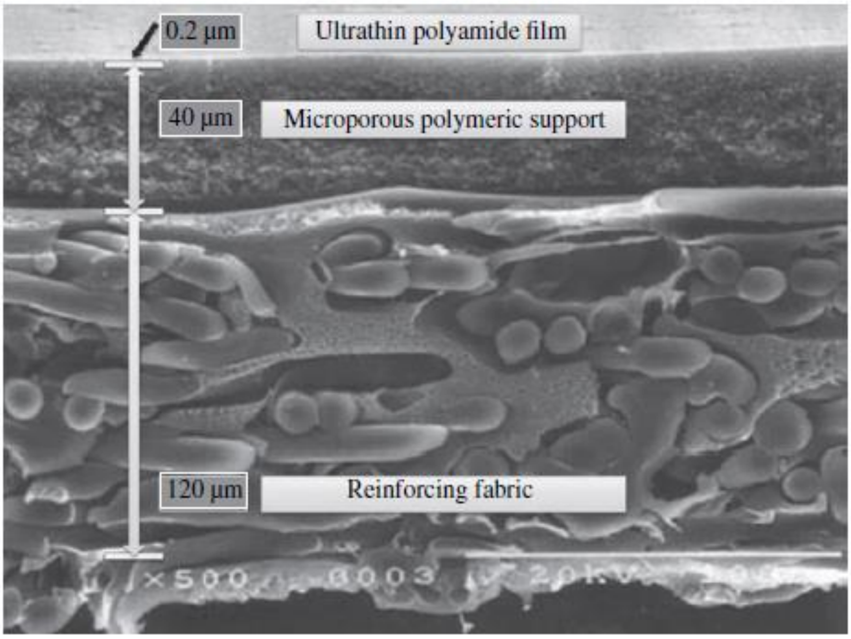

Figure 19 Typical membrane structure. Copied from [29, 45].

This type of membrane construct is currently dominating the RO industry. Nevertheless, newer thin-film membranes with better permeability are currently being developed worldwide. Moreover, nanocomposite membrane technology has the potential to increase the fresh water production efficiency in RO significantly, if the material science keeps evolving. [29, 45-47.]

Aromatic polyamide and cellulose acetate membranes set their own limits to plant operation while having different benefits. In general, PA membranes provide higher salt rejection and operate in lower pressures, compared to CA membranes. Primarily due to this, PA membranes are used in most RO plants today. However, CA membranes are less prone to biofouling, require lower pretreatment and cleaning frequency. Therefore CA membranes are a viable choice for applications e.g. in the Middle East, where the source water contains more organics, while the power costs are low. Nevertheless, CA membranes are expected to exit the membrane market in the future, as PA membranes with lower fouling abilities are going to be introduced. [29, 49.]

7.4.1 Spiral-Wound Membrane Elements

PA and CA membranes are packed into configurations that hold a large surface area, forming membrane elements (or modules). The most popular membrane elements configuration in municipal treatment applications are called spiral-wound membranes, which are classified by diameter. A normal 8” spiral-wound RO membrane element contains 40 to 42 flat membrane sheets, which are assembled into 20 to 21 membrane envelopes (or leaves). Each envelope thus consists of two membrane sheets. Between the sheets, a thin plastic net (known as permeate spacer) is added in, forming a channel for the desalinated water to leave the membrane envelope. Membrane envelope is illustrated in figure 20. [29, 49-50; 31, 3.]

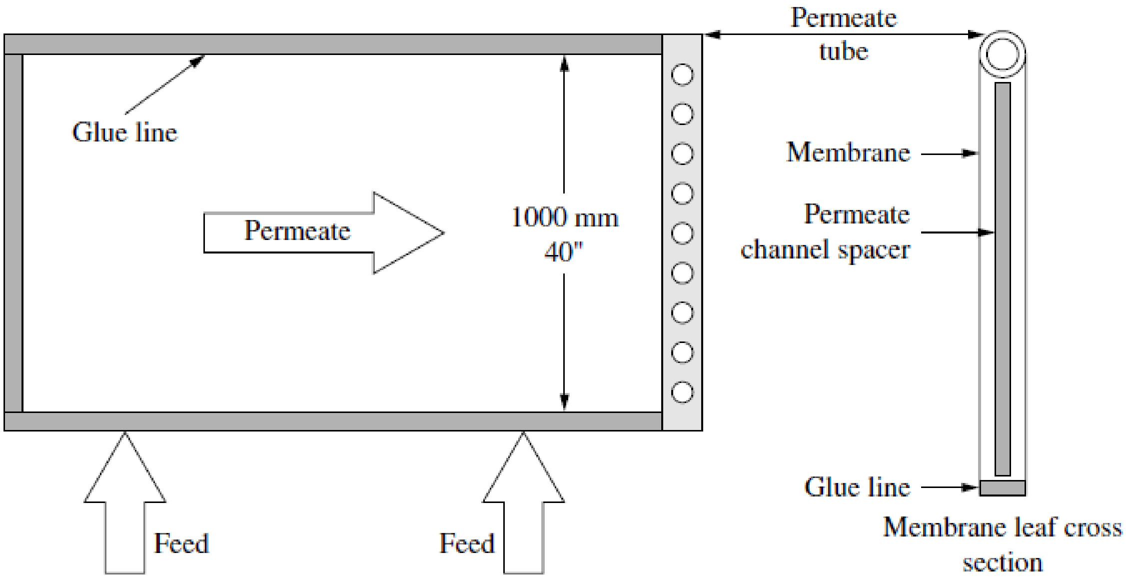

Figure 20 A membrane leaf attached to a permeate collector tube. Copied from [29, 50].

As illustrated in figure 20, one of the four sides of the membrane leaf is left open, while the other sides are sealed with glue. The pressurized feed water (and the concentrate) stream travels along feed spacers, which separate the membrane envelopes from each other. The permeate is collected inside the membrane leaf between the two sheets from where it flows to a permeate collector tube, which is located in the center of the membrane element. This tube, also known as permeate carrier, collects desalinated water from every membrane leaf of the module and discharges it out of it. [29, 51.]

The structure and function of a spiral-wound membrane module is illustrated in figure 21. The flat-sheet membrane envelopes (and the separating feed spacers) are wrapped around the punctured permeate carrier, forming a spiral-wound assembly with a tape wrapped around. [29, 51.]

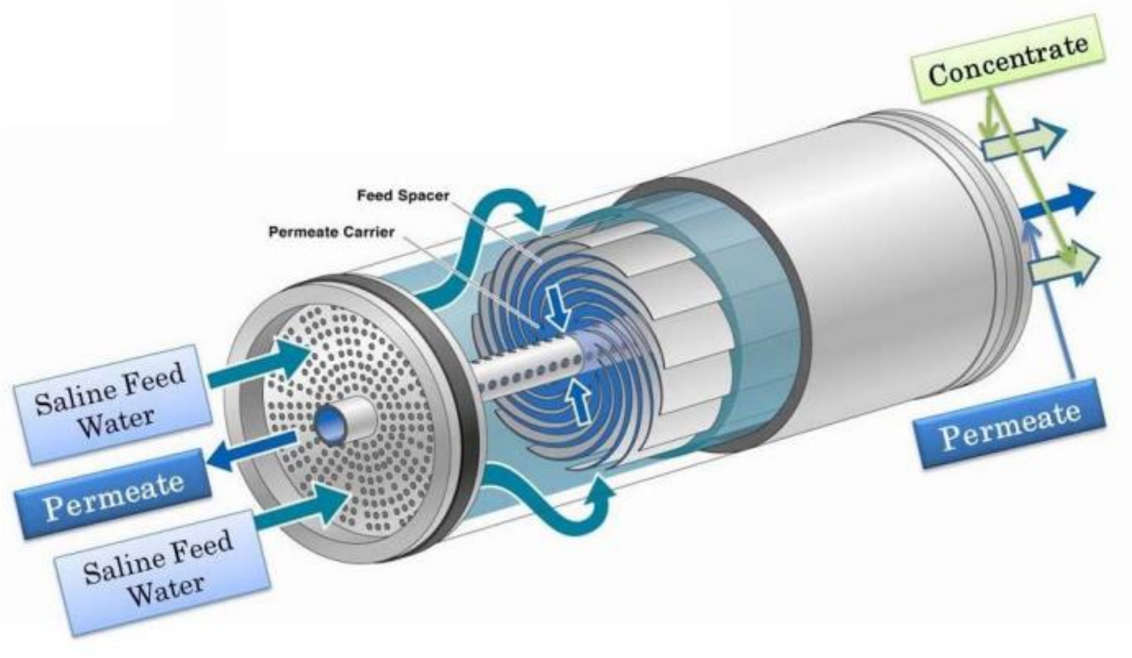

Figure 21 The structure and function of spiral-wound membrane element. Copied from [29, 51].

The pressurized saline water flows in from one end of the module and travels on a straight path along the surface of the leaves on the membrane element. A part of the feed flow passes through the membrane and is gathered as fresh water. The rejected salts are mixed with the remaining feed water, thus raising the salinity of the feed water. This solution exits the element as concentrate. [29, 51.]

7.4.2 Pressure Vessels

Membrane elements/modules are installed inside a pressure vessel in a row by connecting the permeate carrier tubes to each other, as shown in figure 22. Short plastic pipes with O-rings are typically used to seal the connection points and to avoid the concentrate from entering the product water collector tubes. The latest trend in SWRO system design is to install eight elements per vessel, which allows using less pressure vessels in the process, providing equipment cost savings. [29, 379.]

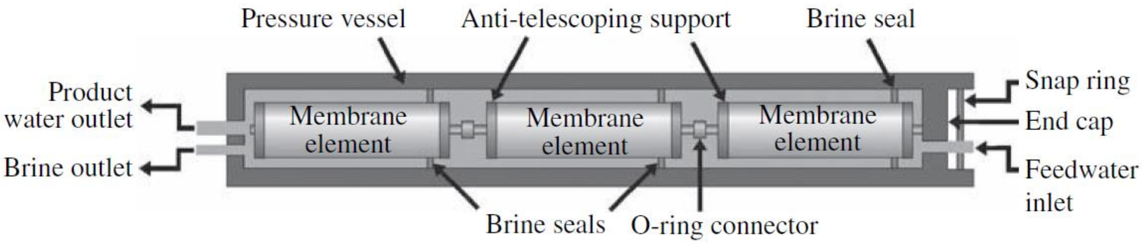

Figure 22 Membrane modules installed in a pressure vessel. Copied from [29, 52].

Feed water is conducted into the front end of the vessel and applied onto the first membrane module. In a typical pressure vessel with membrane modules of 8 inches in diameter, the recommended minimum and maximum feed flows are 10 and 17 m^3/h. In turn, the concentrate flow should be at least 2.7 m^3/h. BWRO pressure vessels are designed for operation in pressure range of 10.5 to 42 bars, while SWRO pressure vessels are designed to handle operating pressures of 42 to 105 bars. In conventional pressure vessels, fresh water and brine are collected from the last element, as shown in figure 22. This is the most common configuration for pressure vessels. SWRO pressure vessels collecting permeate water from both ends of the vessel have also been designed in recent years. [29, 379-380.]

7.5 RO System Configurations

Inside the desalination plant, individual RO systems are often arranged in sequential arrays. RO Plant configurations can be categorized in two main groups: (1) single and multipass RO systems, and (2) single and multistage RO systems. These configurations can be also combined, in order to optimize the plant design for specific source waters. This section briefly describes these RO pass and stage configurations. In addition, the three-center SWRO configuration is explained. [29, 404.]

7.5.1 Single and Multipass RO Systems

Single-pass RO system refers to a system where the feed water is treated by RO membranes only once, before the permeate is conveyed to the post-treatment facility. When the permeate is re-treated multiple times, the system is called multipass RO system. Setups for single-, two-, and three-pass RO systems are shown in figure 23. [29, 404.]

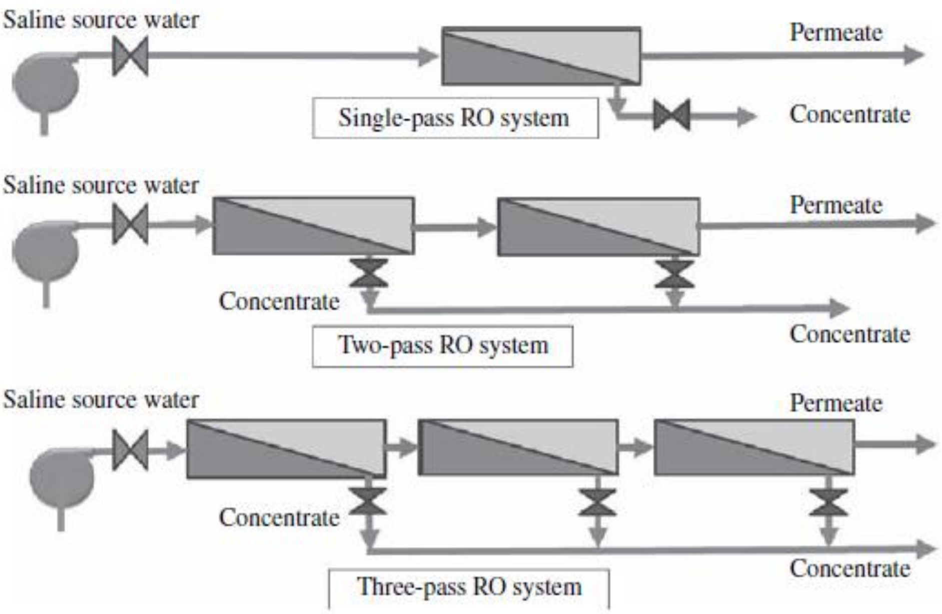

Figure 23 Single and multipass RO systems. Copied from [29, 404].

Each pass enhances the quality of water as each pass provides more treatment to the permeate. As a result, multipass RO systems are generally used when the source water is high in salinity and a single-pass RO system would not be enough. On the downside, multipass systems are costlier and are able to produce less water than single-pass RO systems. [29, 404.]

RO membranes foul at a rate that is exponentially proportional to the membrane flux. The membrane flux is proportional to the difference between the RO system feed and permeate pressure. Using a two-pass RO system decreases the membrane flux and fouling rate because the feed pressure to the first pass can be lowered to 65-75 percent of the total feed pressure. This in turn, for example, reduces the number of times the RO membranes need to be cleaned. However, the remaining 25-35 percent of pressure needs to be provided by an additional interpass pump (booster pump) that increases the permeate pressure from the first pass to the second one. [29, 405.]

7.5.2 Single and Multistage RO Systems

When using multipass RO systems, the total recovery decreases as the number of passes increases. Less fresh water is produced, because a part of the saline source water is converted into concentrate at each pass. To be able to produce more fresh water from the same amount of source water, the concentrate from each pass should be treated with another RO system called a stage. Figure 24 demonstrates the single and multistage RO system configurations. [29, 405.]

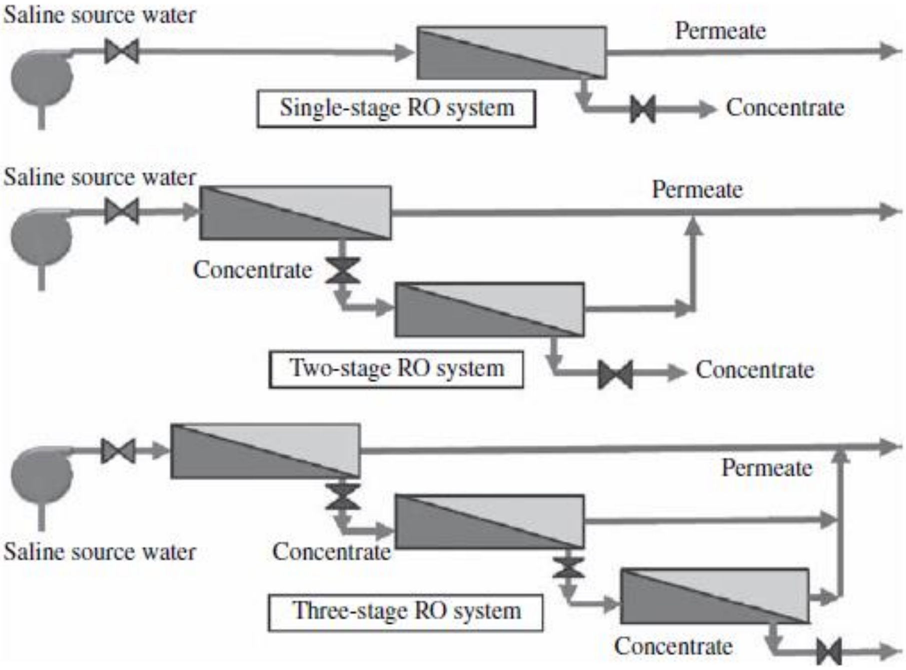

Figure 24 Single and multistage RO systems. Copied from [29, 406].

The ratio between the number of pressure vessels in the first and second stages is 2:1. In three stage systems, the ratio is 3:2:1. This means that the number of pressure vessels in the first stage is three times higher than in the third stage and the second stage has twice the number of vessels as the third stage. Using multiple stages increases the overall recovery of the RO system. On the downside, this is also costlier. [29, 405.]

As brackish water contains much lower TDS levels, using the concentrate from the first stage as a feed to the second stage is typical for BWRO plants. This results in the higher recovery rates of BWRO plants. Low-salinity brackish water often requires only one RO stage. High salinity BWRO plants typically operate with two RO stages. Between the stages the pressure of the concentrate is boosted with interstage pumps. The second stage processing the concentrate from the first stage usually produces 15 to 25 percent of the total RO permeate flow. [1, 2335; 29, 407-408.]

On the contrary, it is more common that SWRO plants have to treat the permeate multiple times, because after the first pass it may still contain too much salts. SWRO plants often have multipass configurations where the feed water is first processed through a SWRO unit, and then the permeate is treated by BWRO membranes to achieve higher quality product water. The ideal number of stages and passes depends on the source water quality, the target permeate water quality, the fresh water production flow, and the cost of equipment and energy. [29, 405.]

Although the most used configurations for SWRO are single and two-pass systems, many large-sized SWRO plants today have to deal with higher boron concentrations in feed water. These SWRO plants may use a multistage configuration. In the first RO stage, by collecting a portion of the permeate from the first membranes of pressure vessels, two separate permeate streams can be formed. The remaining permeate collected from the end side of pressure vessels flows through additional RO stages, because it contains higher amounts of boron. Multistage configurations are currently used in the Ashkelon, Hadera and Sorek SWRO plants in Israel. The first RO stage in these modern mega-sized SWRO plants makes use of so called “three-center” configuration, which is presented in the next section. [29, 416.]

7.5.3 Modern Three-Center SWRO Configuration

As mentioned previously, SWRO systems typically consist of individual equally sized RO trains, and each train has a dedicated transfer pump, high-pressure pump and an ERD. This kind of design is suitable for operating at constant permeate output. The majority of large SWRO plants worldwide are desired to support existing conventional water supply sources, rather than operating as the primary or the only fresh water source in an area. This means that the product water demand from the SWRO plant in a given area does not fluctuate and the plant can operate at constant permeate output. However, e.g. due to urbanization and population growth, it is expected that SWRO will become the primary source of drinking water in many areas in the future. The SWRO plants in such areas have to react to the fluctuations of fresh water demands. Therefore, these plants have to be designed to operate at variable permeate flow. [29, 420.]

Changing from constant to variable permeate flow requires changing the RO system design from the traditional RO-train based configuration to a three-center configuration. In the three-center configuration (also known as pressure-center concept), all of the plant’s RO membrane vessels, high-pressure pumps and ERDs are combined in three functional centers: a high-pressure pumping center, a membrane center, and an energy recovery center. All components are connected to one common piping system, as shown in figure 25. [29, 420.]

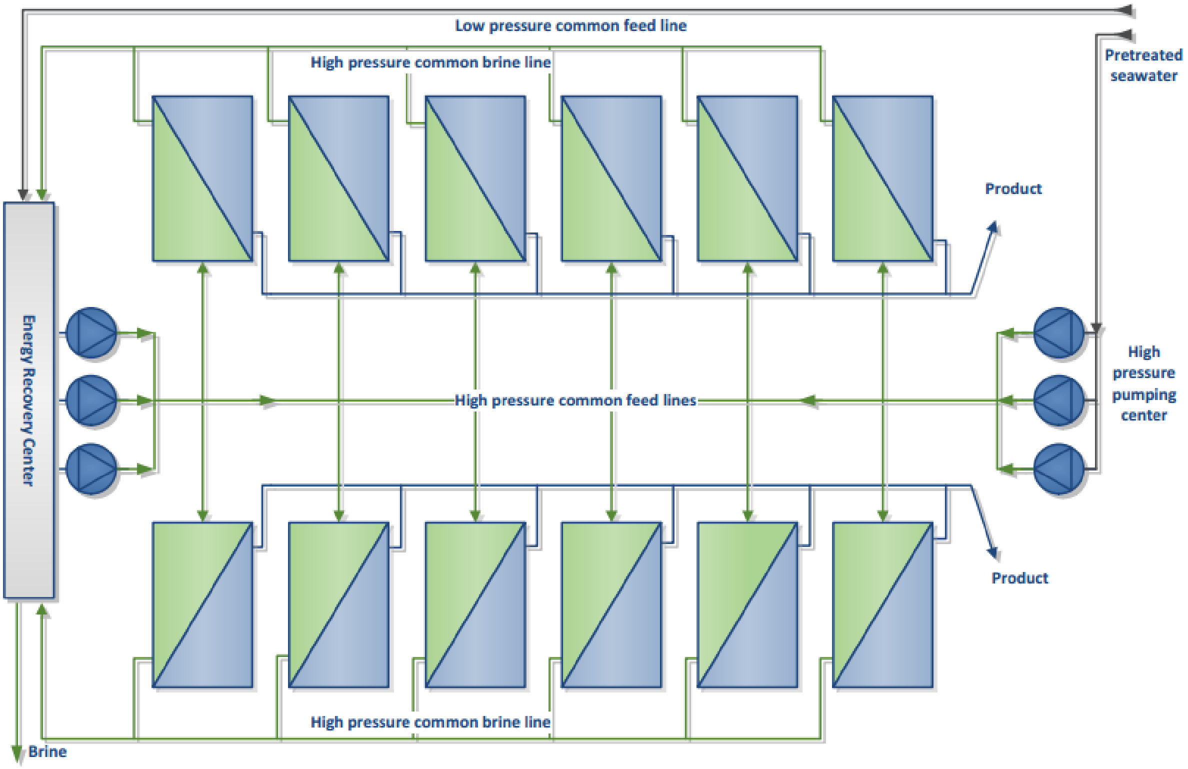

Figure 25 Three-center SWRO configuration. Copied from [47, 6].

The high-pressure pumping center in figure 25 requires fewer but larger feed pumps working in parallel, as compared to the conventional RO-train configuration. The pump sizes can be ten times larger in the three-center configuration. Pumping efficiency is increased when the ratio between the output pressure and flow rate decreases. This can be achieved either by decreasing the output pressure or increasing the pump flow rate. Since the RO process requires specific levels for operating pressures, the pump efficiency is improved by increasing the pump flow rate. This function is valuable for the three-center configuration, as it is designed to deliver variable permeate flow. [29, 420.]

Typically when using traditional ERDs, such as Pelton wheel, the energy recovery decreases significantly when lowering the SWRO plant recovery. The recovery efficiency of isobaric ERDs, on the other hand, increases when the plant recovery rate is lowered.

Therefore, the energy recovery center in three-center configuration is equipped with isobaric-type ERDs, allowing cost-effective operations under variable permeate flows. [29, 421.]

The three-center design has already been used for some years in some of the largest SWRO plants in the world: Ashkelon, Hadera and Sorek. In Israel, where these plants operate, the cost of electricity varies according to the period of year, day of the week and the hour of the day. The RO plant production capacities have to be adjusted drastically according to changing electricity tariffs to optimize energy costs. Especially in large RO plants, drastic changes in production capacities immediately affect the stability of process parameters, the performance of the plant and the quality of the produced water. The three-center design allows for managing the fluctuations of production quantities with minimal problems. [47, 1-7.]

Changing capacities requires changes in the process parameters (e.g. feed flow and recovery). VSDs are essential for controlling these parameters. The permeate recovery, for example, is controlled by adjusting the speed of the booster pumps in the isobaric energy recovery system. VSD operations with isobaric ERDs are discussed in more detail in section 7.7.2. [47, 6.]

7.6 Membrane Cleaning System

As mentioned previously, RO membranes gather foulants over time, resulting in a pressure increase. For maintaining performance, membranes have to be cleaned at times. Membrane cleaning is a process that dissolves and expels the inorganic scales, particulate and colloidal foulants and biological film that collect in the feed/brine spacers. [29, 395.]

Typically, the cleaning of membranes is applied in following situations:

- 10 to 15 percent elevation in pressure difference between feed and concentrate pressures
- 10 to 15 percent reduction in permeate flow
- 10 to 15 percent increase in product water TDS concentration

The system can track whether changes in the membrane performance is due to fouling or temperature changes. Depending on how fast the membrane fouls, RO trains might need to be cleaned as often as once per month, or once per year for plants that treat high quality source waters. Most desalination plants with well intakes have membranes cleaned once every four to six months. In addition, membranes are cleaned prior to and after long RO train downtime. [29, 395.]

The CIP system includes one or more CIP tanks with possible mixers and heaters, at least one cleaning pump (CIP pump), cartridge filter and control equipment. In RO systems equipped with 8 inch (200 mm) membranes, the optimal flow rate of the cleaning solution is normally between 8 to 10 m^3/h. The discharge pressure of the CIP pump is normally 4.5 to 4.8 bars. The pressures and flow rates are controlled with valves and/or VSDs. [29, 396.]

7.7 VSDs in RO Salt Separation Systems

In order to achieve an optimal energy efficiency for the RO separation, the system has to operate inside its duty range. In other words, the feed pumps combined with ERDs have a specific range of values for flow rate and pressure. Operating outside of this area will result in lower efficiency. The duty range is also referred as “hydraulic envelope”. [2, 2-3.]

Generally, the hydraulic envelope is defined by the following parameters: feed pressure, brine pressure and plant recovery rate. The hydraulic envelope is illustrated in figure 26.

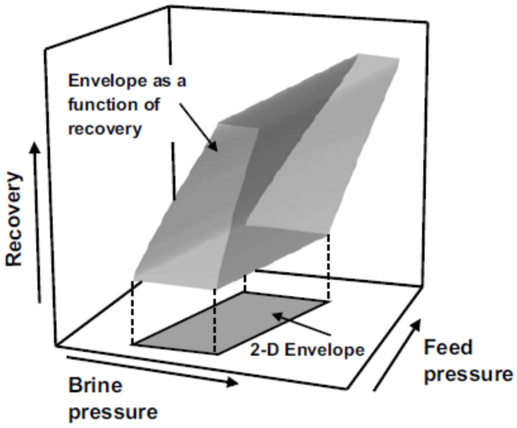

Figure 26 Three-dimensional hydraulic envelope. Copied from [2, 3].

The variables feed pressure and brine pressure are determined by feed salinity and temperature, as well as pressure losses e.g. from membranes and valves. Plant recovery is determined by feed flow rate, brine flow rate and permeate flow rate. The hydraulic envelope in figure 26 shows the optimal area of operation for pressures and flow rates. [2, 3.]

A critical aspect for the pumping system is to stay inside the hydraulic envelope, while operating conditions change. When the pressures and flow rates are adjusted by throttling valves some inefficiencies in energy use occur. For example, among the actual energy requirements (e.g. by membranes), the hydraulic energy generated by the pump has to cover the energy dissipated by the valve. Energy use will also be higher than needed in cases where feed water has better quality (i.e. lower salinity). In addition, the dissipated energy is lost and cannot be recovered in the ERD. A feed pump with a VSD will introduce only the necessary amount of energy into the system. In addition, dissipation is minimized. The feed pump’s output conditions can be controlled by altering the speed and torque of the motor shaft. Regarding RO energy efficiency, the larger the hydraulic envelope of a system is, the more favorable it is to use VSDs instead of throttling valves. [2, 4.]

7.7.1 VSDs on Centrifugal ERDs

In systems where centrifugal ERDs are employed, the process is usually controlled by adjusting either the high pressure feed flow or high pressure concentrate flow. The control is performed by using flow control valves or VSDs. [48, 3.]

Several control strategies for using VSDs with feed pumps and centrifugal ERDs exist. One method is a configuration where a high-pressure feed pump is directly driven by a VSD. The required RO feed conditions are set by the VSD as mentioned in the previous section. The use of a VSD on the high-pressure pump eliminates the need for a valve on the feed side of the membranes. Figure 27 illustrates the configuration of this system.

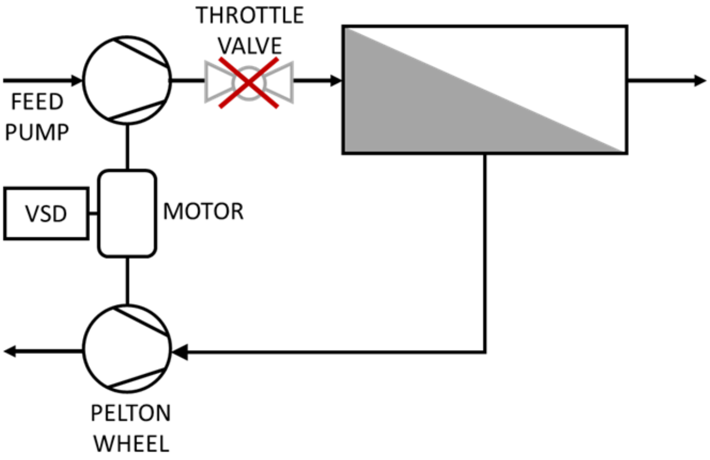

Figure 27 System with a Pelton wheel controlled by a VSD instead of throttling. Modified from [2, 5].

In this configuration, the remaining concentrate energy is recovered by a Pelton turbine wheel. The brine pressure and flow received by the Pelton turbine (i.e. the input energy for ERD) will vary according to pressure drops and selected recovery ratio. [2, 5.]

In systems where a HTC is used, a bypass valve can be used on the concentrate stream. This way, the overall RO feed pressure is controlled, as the amount of pressure energy recovered back to the feed stream is adjusted by the valve. The feed pressure from the centrifugal pump is constant. More efficient control is achieved with a VSD. A system using HTC and VSD is illustrated in figure 28. [2, 5.]

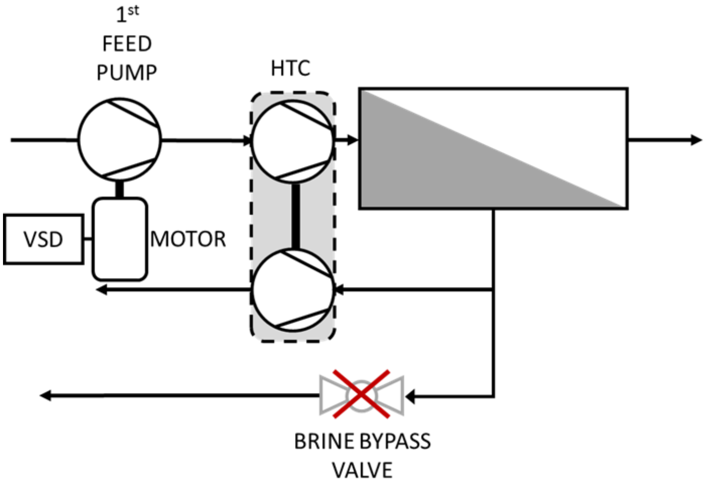

Figure 28 System with a HTC controlled by a VSD instead of throttling. Modified from [2, 5].

If a VSD is installed to this configuration, the concentrate bypass valve is not needed anymore. The VSD controls the feed pump pressure, thus adjusting the feed conditions for the HTC. [2, 5-6.]

A newer development in centrifugal ERDs is the Pelton-driven RO Pump (PROP) configuration. The idea behind the PROP is to make use of the most reliable energy recovery tools, Pelton turbines, VSDs and booster pumps to rearrange the setup to decrease total energy losses. In this configuration, the high pressure feed pump has been divided in two, and the Pelton wheel turbine is connected to the shaft of the second feed pump. This booster pump is driven by a motor with a VSD. PROP configuration is illustrated in figure 29.

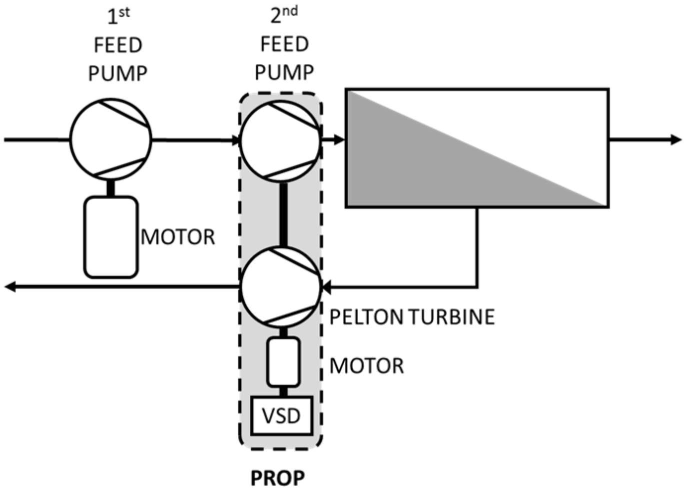

Figure 29 PROP configuration. Modified from [2, 6].

The first feed pump operates at constant speed. The second feed pump boosts the feed pressure to the required level. The energy gained from the Pelton wheel is nearly sufficient to drive the booster pump in situations where minimum feed pressure and flow rate are used. In this case, the additional energy input from the motor and VSD is marginal. The energy input from the motor and VSD is maximized when the feed pressure and flow rate requirements are at the highest level. A RO system using PROP can operate at the same dynamic range as with the simpler Pelton-VSD configuration (figure 27). However, as the motor in PROP is relatively small, the power requirement for the VSD is therefore only a small part of what would be needed in the simpler Pelton-VSD configuration. [2, 7.]

The PROP configuration can be used in two-stage RO systems, where the concentrate of the first membrane stage is directed into a second membrane stage. Between the stages, the concentrate pressure is boosted with the booster pump of the PROP. Without a VSD, this type of a system would use e.g. a standard HTC setup. The PROP operating in a two-stage system is illustrated in figure 30.

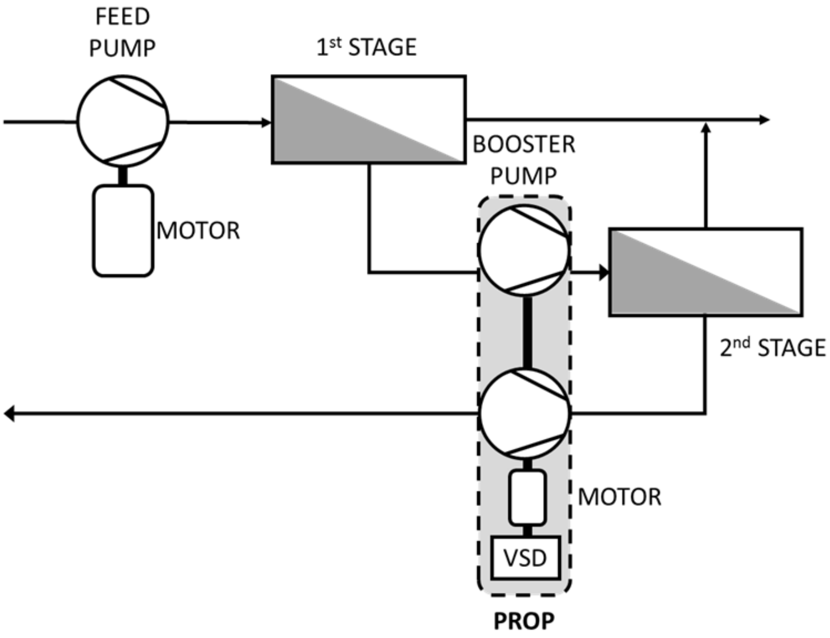

Figure 30 PROP in a two-stage RO system. Modified from [2, 7].

The benefit of using the PROP in these types of membrane stage configurations is the possibility to control the feed pressure for the second membrane stage. This results in more efficient operations, as compared to e.g. having a HTC in a similar place. [2, 8.]

7.7.2 VSDs on Isobaric ERDs

As illustrated in appendix 1, the isobaric energy recovery systems include pipelines for the low pressure water (incoming low pressure seawater and outgoing depressurized brine) and high pressure water (high-pressure brine from the membranes and pressurized seawater generated by the ERD). In order to maintain efficient and reliable performance of the ERD, these independent high and low pressure flows must be monitored and controlled [49, 8].

As seen in appendix 1, the high pressure stream flows in a circuit through the membranes back to the ERD and booster pump. The flow rate of this stream is determined by the circulation pump speed. It is recommended that the booster pump is controlled by a VSD. The flow rate in the low pressure line is controlled by controlling the downstream supply pump speed (also controlled by a VSD) and by throttling the depressurized concentrate stream with a valve. Typically, flow meters are installed on both lines, placed on either before or after the ERD (one for high-pressure and one for low-pressure line). [49, 8; 48, 2-3.]

The high pressure pump controls the permeate flow rate, whereas the booster pump controls the concentrate flow rate. The high pressure pump is often over-sized, because it needs to have enough pumping capacity in conditions where feed water quality is very low and the fresh water requirements for the end users have increased. RO membranes will also age and foul over time. Therefore, the pump output flow has to be controlled. The following methods are common for adjusting the flow in changing conditions:

- A flow control valve on the pump discharge
- Backpressure valve on the permeate side
- The high-pressure pump is straight controlled by a VSD
- A filtered water transfer pump (upstream of the high-pressure pump) is controlled by a VSD. [48, 6.]

Because the isobaric ERDs are not directly coupled with the high pressure pump (like for example the Pelton turbine is), it is possible to control the permeate recovery rate of the SWRO system simply by adjusting the booster pump speed with the VSD. If the booster pump output flow rate is set to as high as the flow rate of the high pressure pump, the system will operate at 50 percent recovery. By raising the booster pump’s flow rate to double the high pressure pump’s flow rate, the recovery of the system decreases to 33 percent. As seen in Table 1, decreasing the recovery rate results in lower membrane pressures. This lowers the load on the high pressure pump. Correspondingly, if the recovery rate is increased, membrane pressures are increased. However, now the SWRO plant requires less feed water. These adjustments have meaningless impact on isobaric ERD performances, yet they can significantly affect membrane performance. Therefore, with a VSD on the booster pump, a SWRO plant operator can manipulate and optimize the system’s performance, decreasing the energy use. The operation of adjusting recovery rates gives huge advantages to SWRO systems with isobaric ERDs. [50, 5.]

As an example, the Gold Coast SWRO plant in Australia, with a product capacity of 133,000 m^3/day, operates with isobaric ERDs (DWEERs). The RO system is equipped with three duty and one standby high pressure pumps, each driven by a 4.8 MW rated electric motor. Medium voltage VSDs in the power range of 1,120 kW and 4,800 kW are installed on the ERD booster pumps and high pressure pumps in order to maintain efficiency of the energy recovery as well as constant pressure in the RO membranes. Overall, the plant contains VSDs with a total power of 40.3 MW. A number of low voltage VSDs in the power range between 1.1 kW to 710 kW control smaller applications, such as intake and backwash pumps. The plant's energy consumption is approximately 3 kWh/m^3. [51, 717; 52, 53; 53; 54.]

8 Post-Treatment

The permeate from SWRO has to be treated before it is distributed. It is processed in the post treatment facility, which is the last component in a RO plant. Hydrated lime (calcium hydroxide) or limestone contactors (calcite) can be used to increase the hardness, alkalinity and pH. Hardness is required for the taste of drinking water and to prevent corrosion. Alkalinity is required to act as a buffer for natural waters and to stabilize the pH during distribution and use. If neither are needed, caustic soda (NaOH) can be used to alter pH levels. The permeate is also disinfected with chlorine, sodium hypochlorite or chloramines. [1, 2336-2337.]

Like SWRO permeate, BWRO permeate is often very low in mineral content (i.e. low in hardness), pH and alkalinity. To alter hardness and alkalinity a part of the pretreated brackish feed water is commonly mixed with the RO permeate. In case feed water mixing is not an option, which might occur because of lower source water quality, lime or limestone contractors can be used. BWRO permeate is also disinfected before it is distributed. [1, 2337.]

In addition, the quality of product water is often determined by other valuable uses as well, such as agricultural irrigation and industrial use [29, 445]. Moreover, drinking water standards for boron, for example, have become more and more strict [1, 2326]. Therefore, post-treatment usually involves also further polishing of product water quality by enhanced removal of some minerals such as boron and/or supplemental addition of other minerals, e.g. magnesium [29, 445].

8.1 Remineralization Systems

Today, over 90 percent of SWRO plants worldwide use chemical feeding systems where hydrated lime (calcium hydroxide) and carbon dioxide are added sequentially to the product water, in order to protect the distribution system and household piping from corrosion. Lime is typically stored at the plant site as bulk powdered hydrated lime, inside silos of minimum capacity of 50m^3. The powdered lime is delivered into a slurry mixing tank, where it is blended with desalinated water, forming lime slurry (milk of lime). [29, 453-461.]

After the mixing, lime slurry is transferred to the lime saturation system by progressive cavity pumps. The slurry is pumped at a very high velocity to avoid accumulation in the pipelines. Lime saturators are metal tanks that produce homogenized and fully dissolved lime solutions. The system also contains re-circulation pumps or mixers, saturated limewater tanks, and limewater dosing pumps. The general structure of lime saturation system is presented in figure 31. [29, 461.]

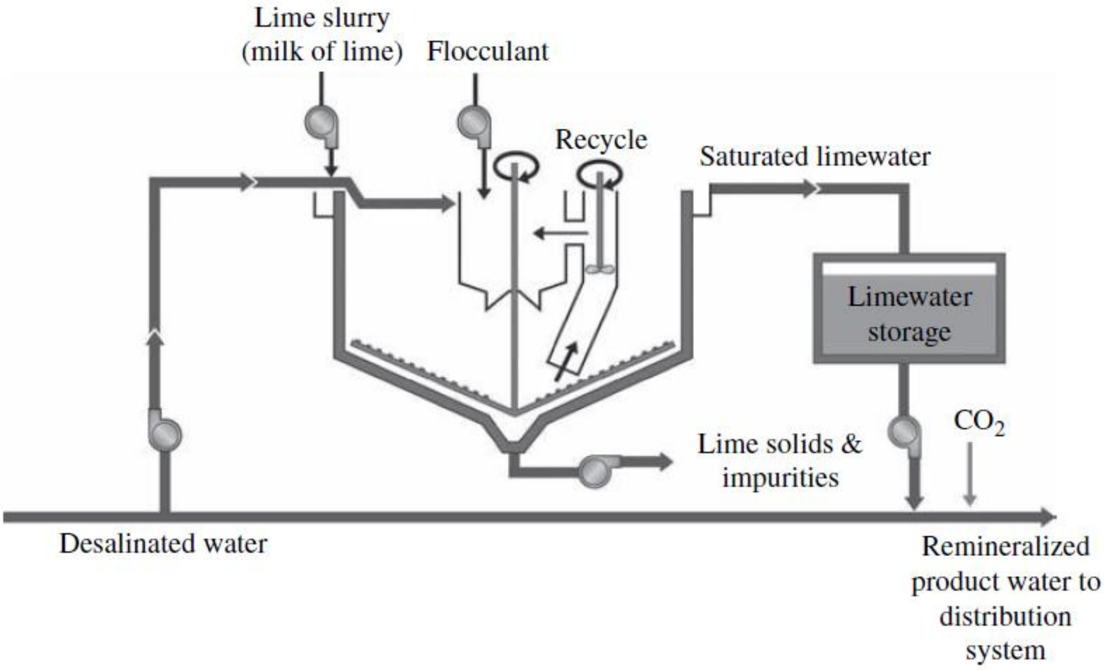

Figure 31 Lime saturation. Copied from [29, 454].

As the lime product is often only 85 to 94 percent pure, solid lime impurities will get in the system. These solids are separated and removed by a bottom scraper and hopper.

Lime slurry is dissolved and diluted by desalinated water from 10 percent to 0.1 percent. In addition, a small amount of polymer is fed regularly into the solution to accelerate particle flocculation and decrease the limewater turbidity. [29, 461.]

Lime slurry from the tank bottom is fed constantly into the reaction zone and blended to quicken the process. The circulation is performed using pumps or mechanical propeller-operated mixers. The saturated limewater overflows from the saturator tank into launders. From there, the limewater flows by gravity to the limewater tank. This storage tank should have capacity to hold the entire amount of limewater required to treat the plant's daily volume of permeate (mainly due to periodic system cleaning maintenance). From the tank, limewater is delivered with centrifugal pumps to the permeate pipeline via dozing points. [29, 462.]

8.2 Disinfection Systems

Generally, desalination plant disinfection systems are similar to those used in the conventional water treatment facilities. Currently, the majority of disinfection systems for desalination plants use a chlorination method with sodium hypochlorite as the disinfectant. Chlorination with chlorine gas is also a widely used disinfection method worldwide. However, using a 10 to 15 percent solution of sodium hypochlorite is more popular than chlorine gas because it is safer to use and store. [29, 481-486.]

The typical target chlorine dosage that provides sufficient disinfection is 0.5 to 2.5 mg/L. RO plant sites are normally equipped with 15 to 30 day bulk storage tanks. A plant of 40,000 m^3/day product capacity typically needs approximately 160 kg of chlorine for disinfection per day. The daily consumption of sodium hypochlorite, for a plant of this capacity, is around 1.3 to 3.0 m^3, depending on the solution. [29, 487.]

8.3 Considerations for VSDs in Post-Treatment

Post-treatment processes typically include the addition of a number of chemicals. Therefore, the system includes several pumps and mixers for dosing and blending the chemicals into the product water. Some of the motors driving the pumps and mixers may be equipped with VSDs, depending on if the application needs a precise control.

Progressive cavity pumps are commonly used for pumping chemicals, especially those of higher viscosities, like lime slurry. Fluid is transferred through the pump when a rotor inside the body of the pump turns. This type of a pump provides a flow rate that is proportional to the rotor speed, meaning that the chemical dosing can be adjusted directly by controlling the rotation speed of the rotor. During start-ups, these applications usually require higher torques. It is convenient to control the progressive cavity pumps with VSDs. [55, 510-511.]

In the lime saturation systems, the lime slurry is circulated in order to accelerate the dissolving of lime in water. The circulation and mixing of lime is performed by mixers or pumps, which are often equipped with VSDs in order to have a better control over the process [29, 461]. The centrifugal pumps, which transfer the produced limewater to the permeate water pipeline, are also equipped with VSDs [29, 462].

9 Summary and Discussion

The purpose of this thesis was to study the structure of a RO plant and outline how VSDs can be used in different plant applications. This thesis is a good starting point for those wanting to understand the RO process, the different parts of a RO plant and the role of VSDs in the different plant applications.

Section 2 discussed the basics of VSDs, as some insight into how they function was needed. Section 3 discussed water, as feed water characteristics have a large impact on the structure and operation of a RO plant. Section 4 looked at desalination, and outlined the RO process, its process parameters and the energy use of the system. Sections 5 to 8 discussed the specific components of a RO plant and the VSD applications in them.

This thesis showed that VSDs have a role in ensuring energy efficiency, precise operations and equipment protection. These factors improve the RO plant’s performance and decrease operation and capital costs. The energy efficiency of a RO plant was an important factor to take into consideration throughout the thesis, because energy costs account for a large part of the plant’s total operation costs. Increasing the energy efficiency of plants is one of the biggest challenges facing RO plants so that fresh water can be produced at lower costs in the future.

High pressure pumps account for majority of the energy use in the plant. One of the most important factors in an energy efficient SWRO plant is ensuring the optimal use of energy recovery systems together with the high pressure pumps. As discussed in section 7.7, VSDs play an important role in controlling these systems.

RO plants also have regular pump applications where energy can be saved relatively easily with the use of VSDs. One example can be found in the saline water intake pump station. In these applications, however, the energy consumption is much smaller in comparison to high-pressure applications, and thus have less potential to reduce energy consumption.

The control of a RO plant is very much based on responding to fluctuations in feed water characteristics, such as temperature or salinity increases and decreases. These parameters often determine the feed pressure that the RO feed pumps have to provide to the membranes, in order to maintain specific target permeate flow rates. In general, VSDs are the most accurate and energy-efficient way to control the pressurizing.

RO plants contain equipment, such as transfer pumps, pipelines and membranes, which can be damaged by pressure surges. VSDs play an important role in preventing pressure surges, as they can slow down the startup and shutdown of pumps. Submersible pumps, however, are specialized pumps that are prone to wearing at low speeds. For this reason, the startup and shutdown of a submersible pump should occur fast. VSDs can be used to optimize the pump ramp speeds to decrease the time during which pumps operate at low speeds in a way that pressure surges are still avoided.

An important part of the RO process is the addition of chemicals in the pretreatment and post-treatment phases. These applications use chemical dosing pumps which are normally positive-displacement types. It is important that the pumps can feed specific amounts of chemicals into the water. VSDs can be used to control the flow rates of the chemical dosing pumps according to the pump’s real time needs. It is also important to control the mixing of the chemicals. A VSD should also be used in the mixing of chemicals by installing a VSD on the motor of the mixer. This way plant operators can respond to changes in factors that affect the mixing process, e.g. changes in water temperature.

This thesis mainly discussed the opportunities and benefits of VSDs in the RO process. However, when designing these systems, there are several other aspects of VSDs that need to be considered. VSDs can be costly, so whether the initial investment is necessary needs to be evaluated on an individual basis. For example, VSDs might not be necessary in situations where motor speeds do not need to be adjusted. In addition, VSDs contain many components that might break easily. For this reason, critical points in the plant might require backup systems, for example valves. Future research could expand on this thesis by evaluating what risks are involved in using VSDs.

At the end of section 7, the power range of the VSDs used in the Gold Coast SWRO plant was briefly discussed. This thesis also did not explicitly focus on the power ranges and types of VSDs in RO. Future research could also evaluate what types and sizes of VSDs should in general be used in different applications in RO plants.

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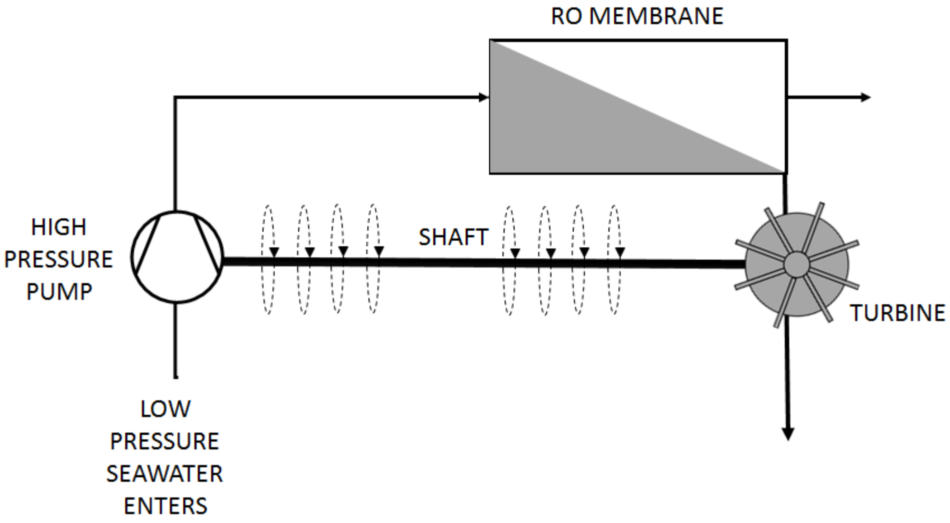
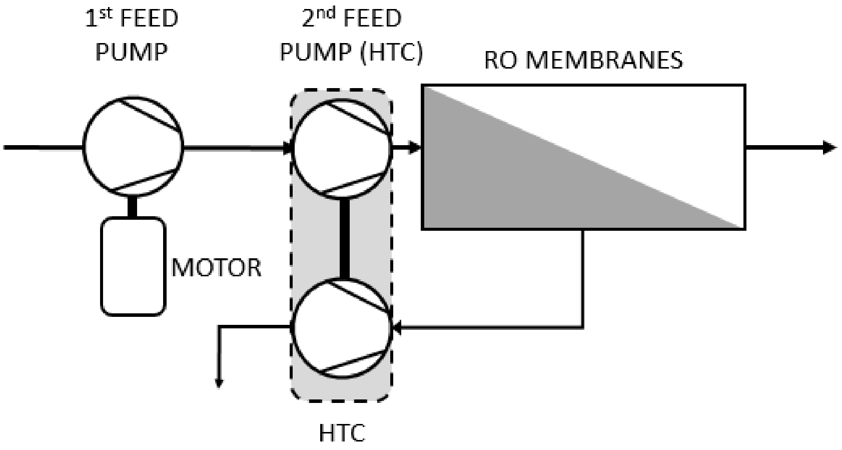
Centrifugal and Isobaric ERDs

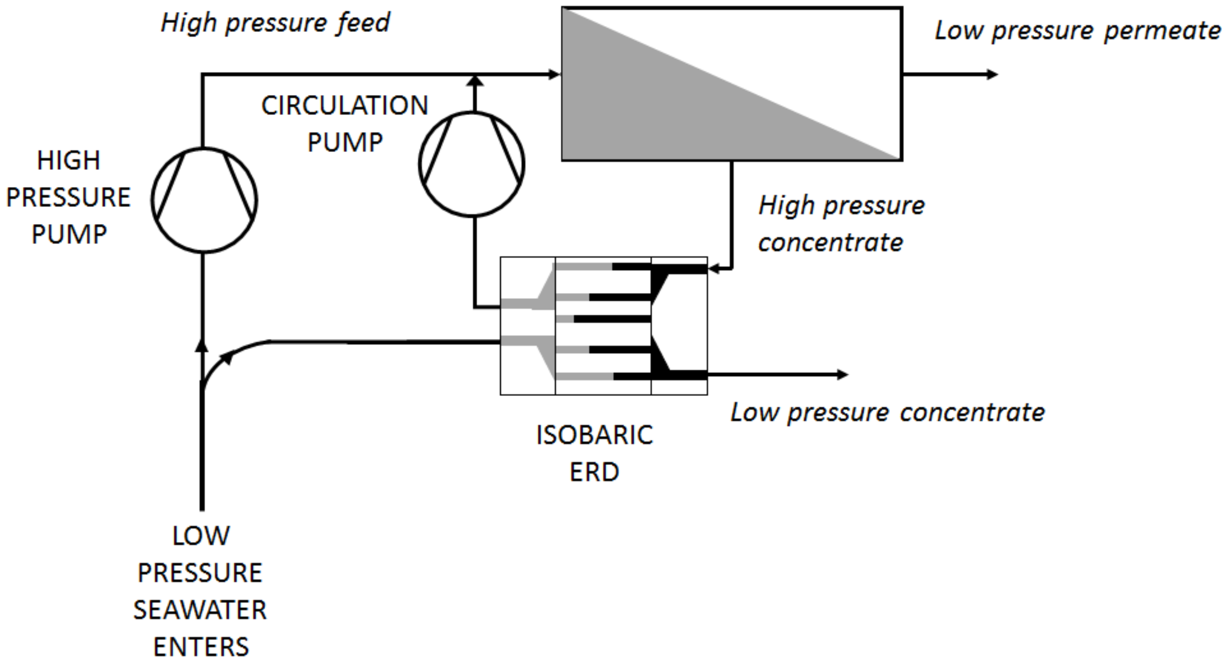
Modified from [5, 5]



Pelton wheel operation



Hydraulic turbocharger operation



Isobaric ERD operation