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Techno-Economic Assessment of a Photovoltaic-Powered Reverse Osmosis Desalination System with Partial Grid Integration

DEPARTMENT OF ELECTRICAL, COMPUTER AND BIOMEDICAL ENGINEERING

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ABSTRACT: This thesis presents the design and preliminary techno-economic assessment of a seawater reverse osmosis (SWRO) desalination system integrated with renewable energy technologies. The proposed system is developed for a production capacity of 1000 m^3/day and is intended to operate under typical Mediterranean conditions.

The study focuses on the selection and evaluation of reverse osmosis membranes, with particular attention to their impact on operating pressure, specific energy consumption (SEC), and overall system performance. A comparative analysis of different commercial membranes highlights the trade-off between energy efficiency and salt rejection, leading to the selection of a low-energy membrane configuration suitable for the proposed application.

A detailed process design is carried out, including the development of a process flow diagram and a Process and Instrumentation Diagram (P&ID), which defines the main system components, control elements, and energy integration architecture. The electrical power demand of the plant is estimated based on both SEC-based calculations and equipment-level load analysis, resulting in an average operating power of approximately 75–83 kW and an annual energy demand of about 657,000 kWh.

To reduce dependence on grid electricity, a hybrid energy system combining photovoltaic (PV) generation and battery energy storage (BESS) is integrated into the plant. The PV system is sized to supply approximately 85% of the annual energy demand, while the battery system provides operational flexibility through peak shaving and load balancing.

A simplified system-level simulation model is developed to evaluate the interaction between the desalination process and the energy supply system. Although based on simplified assumptions, the

model provides a consistent framework for estimating energy flows, PV utilization, and grid dependency.

Finally, a preliminary economic analysis is performed, including capital and operational costs, as well as the estimation of the levelized cost of water (LCOA). The results indicate that the proposed system is both technically feasible and economically competitive, with a calculated LCOA of approximately 1.25 €/m^3.

Overall, the study demonstrates that the integration of SWRO desalination with renewable energy systems represents a promising solution for sustainable water production, combining energy efficiency, economic viability, and reduced environmental impact.

Riassunto:

Questa tesi presenta la progettazione e la valutazione tecnico-economica preliminare di un sistema di dissalazione ad osmosi inversa (SWRO) alimentato da fonti energetiche rinnovabili. Il sistema proposto è dimensionato per una capacità produttiva di 1000 m^3/giorno ed è concepito per operare in condizioni tipiche dell'area mediterranea.

Lo studio si concentra sulla selezione e sull'analisi delle membrane ad osmosi inversa, con particolare attenzione al loro impatto sulla pressione operativa, sul consumo energetico specifico (SEC) e sulle prestazioni complessive del sistema. Un confronto tra diverse membrane commerciali evidenzia il compromesso tra efficienza energetica e capacità di rimozione dei sali, portando alla scelta di una configurazione a basso consumo energetico.

Viene sviluppato un progetto dettagliato del processo, comprensivo di diagramma di flusso e di un Process and Instrumentation Diagram (P&ID), che descrive le principali unità di processo, gli elementi di controllo e l'integrazione dei sistemi energetici. Il fabbisogno elettrico dell'impianto è stimato attraverso un approccio combinato basato sul consumo energetico specifico e sull'analisi dei carichi elettrici, risultando in una potenza media di esercizio pari a circa 75–83 kW e un consumo annuo di circa 657.000 kWh.

Al fine di ridurre la dipendenza dalla rete elettrica, il sistema è integrato con un impianto fotovoltaico (PV) e un sistema di accumulo energetico (BESS). Il sistema fotovoltaico è dimensionato per coprire circa l'85% del fabbisogno energetico annuo, mentre il sistema di accumulo consente una maggiore flessibilità operativa attraverso il bilanciamento dei carichi e la riduzione dei picchi di domanda.

È stato inoltre sviluppato un modello di simulazione a livello di sistema per analizzare l'interazione tra il processo di dissalazione e il sistema energetico. Nonostante le semplificazioni adottate, il modello fornisce una rappresentazione coerente dei flussi energetici e della dipendenza dalla rete.

Infine, è stata condotta un'analisi economica preliminare, considerando i costi di investimento e operativi, nonché il costo livellato dell'acqua (LCOA). I risultati indicano che il sistema proposto è tecnicamente fattibile ed economicamente competitivo, con un LCOA pari a circa 1,25 €/m^3.

Nel complesso, questo studio dimostra che l'integrazione tra dissalazione SWRO e sistemi energetici rinnovabili rappresenta una soluzione promettente per la produzione sostenibile di acqua, combinando efficienza energetica, sostenibilità economica e ridotto impatto ambientale.

1. Introduction

The availability of freshwater resources is increasingly recognized as a critical global challenge. Rapid population growth, expanding industrial activities, and the intensification of climate change effects are exerting unprecedented pressure on conventional water supplies [1], [27]. This issue is particularly pronounced in coastal and arid regions, where natural freshwater availability is inherently limited and often insufficient to meet growing demand. Under such conditions, desalination has emerged as a strategic and reliable solution for the production of potable water [2].

Desalination technologies are generally classified into two main categories: thermal processes and membrane-based processes [4], [9]. Thermal methods, including multi-stage flash (MSF) and multi-effect distillation (MED), have historically been deployed at large scale, especially in regions with access to inexpensive thermal energy sources. Despite their robustness, these technologies are typically associated with high energy consumption and substantial infrastructure requirements [4]. In contrast, membrane-based technologies—most notably reverse osmosis (RO)—have gained widespread adoption over the past decades due to their comparatively lower specific energy consumption and improved operational efficiency [3], [5].

Reverse osmosis operates by applying hydraulic pressure to saline feed water, driving it through a semi-permeable membrane that selectively allows water molecules to pass while rejecting dissolved salts and contaminants [7], [20]. Although RO systems are significantly more energy-efficient than thermal desalination processes, energy demand remains a dominant factor influencing both operational costs and system feasibility. In particular, the required operating pressure, membrane properties, and overall system configuration play a central role in determining energy consumption [9], [10]. Recent studies have also highlighted the importance of integrating renewable energy sources into membrane desalination systems to further improve sustainability and reduce dependence on conventional energy supplies [28].

Recent advances in desalination technology have focused on improving RO system performance through the development of high-efficiency membranes and the implementation of energy recovery devices (ERDs) [6], [25] . Among these factors, membrane selection is a key design variable, as it directly affects permeability, salt rejection, fouling resistance, and long-term system stability [7], [13], [29]. These parameters, in turn, influence both energy requirements and maintenance costs. Furthermore, the integration of renewable energy sources—particularly solar energy—has gained increasing attention as a viable pathway to reduce environmental impact and enhance the sustainability of desalination systems [22], [23], [31].

In this study, a seawater desalination system with a nominal production capacity of approximately 1000 m^3/day is investigated. The analysis focuses on the selection and performance evaluation of reverse osmosis membranes, with particular emphasis on energy consumption and economic implications. Different membrane options are assessed based on their operating conditions, specific energy consumption, and compatibility with system design requirements. In addition, a simplified economic analysis is performed, considering capital expenditure (CAPEX) and its relationship with key design parameters [17], [18].

The remainder of this thesis is structured as follows. First, a general overview of desalination technologies is provided, followed by a detailed description of reverse osmosis processes and their main components. Subsequently, the energy performance of RO systems is examined, with emphasis on the factors influencing efficiency. Different membrane technologies are then introduced and comparatively evaluated. A case study is presented to identify the most suitable membrane configuration based on technical and energy criteria. Finally, an economic assessment is conducted, and the main findings of the study are summarized.

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2. Desalination Technologies Overview

Desalination refers to the removal of dissolved salts and impurities from seawater or brackish water to produce freshwater suitable for human consumption and industrial use. In recent decades, desalination has gained increasing importance as a response to water scarcity, particularly in regions where conventional freshwater resources are limited or unreliable [1], [2]. The continuous growth in water demand has driven the development and optimization of various desalination technologies.

In general, desalination technologies are classified into two main categories: thermal processes and membrane-based processes [4], [9]. Thermal desalination relies on phase change, where saline water is heated to generate vapor, which is subsequently condensed to produce freshwater. The most widely implemented thermal technologies are multi-stage flash (MSF) and multi-effect distillation (MED) [4]. In MSF systems, preheated seawater undergoes rapid evaporation when introduced into successive chambers operating at decreasing pressures. In MED systems, evaporation occurs in multiple stages, with latent heat recovery between stages improving overall thermal efficiency. Despite their operational reliability and long-term stability, these processes are typically associated with high energy consumption and significant infrastructure requirements, which limit their economic feasibility in many applications [4], [9].

Membrane-based desalination processes, on the other hand, rely on selective separation through semi-permeable membranes. Among these, reverse osmosis (RO) has become the dominant technology for large-scale desalination [3], [5]. In RO systems, hydraulic pressure is applied to overcome the natural osmotic pressure of saline water, forcing water molecules through the membrane while rejecting the majority of dissolved salts and contaminants. Compared to thermal methods, RO systems generally exhibit lower specific energy consumption and greater operational flexibility, making them more suitable for modern desalination plants [3].

Other membrane processes, such as nanofiltration (NF) and ultrafiltration (UF), are commonly employed in water treatment systems, primarily as pretreatment steps [12]. These processes are effective in removing suspended solids, organic matter, and certain multivalent ions; however, they are not capable of achieving complete salt rejection and therefore cannot be used as standalone desalination technologies.

One of the main advantages of reverse osmosis is its relatively lower energy requirement compared to thermal processes. Nevertheless, RO desalination still depends on high-pressure pumping systems, and energy consumption remains a key factor affecting both operational cost and overall system performance [9], [10]. To address this limitation, modern RO plants are typically equipped with energy recovery devices (ERDs), which significantly reduce energy losses by recovering pressure energy from the brine stream [6].

In recent years, increasing attention has been given to the integration of desalination systems with renewable energy sources. In particular, solar energy can be utilized either as a thermal input for distillation processes or as an electricity source for membrane-based systems [22], [23]. This integration represents a promising pathway toward reducing greenhouse gas emissions and enhancing the sustainability of desalination technologies.

Overall, while both thermal and membrane-based technologies play important roles in water treatment, reverse osmosis has emerged as the most widely adopted solution due to its superior energy efficiency, scalability, and adaptability. For this reason, the present work focuses on RO systems, with particular emphasis on membrane selection and performance optimization.

3. Reverse Osmosis Process

Reverse osmosis (RO) is one of the most widely used membrane-based technologies for desalination, particularly in seawater and brackish water treatment applications. The process is based on the principle of osmosis, a natural phenomenon in which water flows through a semi-permeable membrane from a region of lower solute concentration to a region of higher solute concentration. In reverse osmosis, this natural process is counteracted by applying external pressure to the feed water, thereby forcing water molecules to move in the opposite direction while retaining dissolved salts and impurities [7], [20].

In practical applications, the feed water is first pressurized using a high-pressure pump and then directed toward membrane modules. Under these conditions, water molecules permeate through the membrane, while the majority of dissolved salts and contaminants are rejected. As a result, the process produces two output streams: permeate, which represents the purified water, and brine, which contains the concentrated rejected salts.

The performance of an RO system depends on several key operating parameters. Among these, the applied pressure is critical, as it must exceed the osmotic pressure of the feed solution to enable water transport across the membrane. Another important parameter is the recovery ratio, defined as the fraction of feed water converted into permeate. In this study, a recovery ratio of approximately 45% is considered, which is representative of typical seawater reverse osmosis (SWRO) systems operating under practical conditions [8], [10]. Under these assumptions, the system is designed for a production capacity of 1000 m^3/day.

Energy consumption is a fundamental aspect in the evaluation of RO systems. Due to the high pressures required—typically in the range of 50–70 bar for seawater desalination—RO processes can be energy-intensive [9]. To improve overall efficiency, modern desalination plants are commonly equipped with energy recovery devices (ERDs), which recover hydraulic energy from the high-pressure brine stream and reuse it within the system. This approach significantly reduces the specific energy consumption of the process and improves overall plant performance [6], [25].

A typical RO desalination system consists of several main components, including feed pumps, high-pressure pumps, membrane modules, energy recovery devices, and control systems. Among these components, the membrane plays a central role in determining system performance, as it directly influences permeability, salt rejection, fouling behavior, and operating pressure requirements [7], [13]. Consequently, membrane selection represents a critical step in the design and optimization of RO systems.

In general, reverse osmosis is considered a highly efficient and flexible desalination technology. However, its performance is strongly dependent on both operating conditions and system design parameters. In particular, membrane characteristics and operating pressure must be carefully balanced to achieve optimal performance. For this reason, membrane selection is a key focus of the present study and will be analyzed in detail in the following sections.

To provide a simplified description of the transport mechanism in RO systems, a basic mathematical formulation can be introduced. The water flux through the membrane is commonly expressed as:

$$J_w = A(P - \pi)$$

where $J_w$is the water flux ($m^3/m^2 \cdot s$), often expressed in $L/m^2 \cdot h$ in practical applications, $A$is the membrane permeability coefficient, $P$is the applied pressure, and $\pi$is the osmotic pressure difference across the membrane [7].

The osmotic pressure can be estimated using the Van't Hoff equation:

$$\pi = iCRT$$

where $i$is the van 't Hoff factor, $C$is the molar concentration of the solution, $R$is the universal gas constant, and $T$is the absolute temperature [7]. This relationship highlights that the effective driving force for water transport is the difference between the applied hydraulic pressure and the osmotic pressure. As a result, higher salinity levels lead to higher osmotic pressure, which in turn requires increased operating pressure and consequently higher energy consumption.

3.1 Process Description

The overall configuration of the photovoltaic-powered reverse osmosis desalination system is illustrated in Figure 3.1. The system consists of four main stages: intake, pretreatment, desalination, and post-treatment. The intake system is responsible for supplying seawater to the plant, while the pretreatment stage removes suspended solids, organic matter, and other contaminants that could negatively affect membrane performance.

Following pretreatment, the water is pressurized by high-pressure pumps and directed to the membrane modules, where the separation process takes place. The permeate stream is then subjected to post-treatment to meet drinking water standards, while the concentrated brine is discharged. An energy recovery device is integrated into the system to recover pressure energy from the brine stream and improve overall energy efficiency. The entire system is powered by a photovoltaic energy source, contributing to reduced environmental impact and enhanced sustainability.

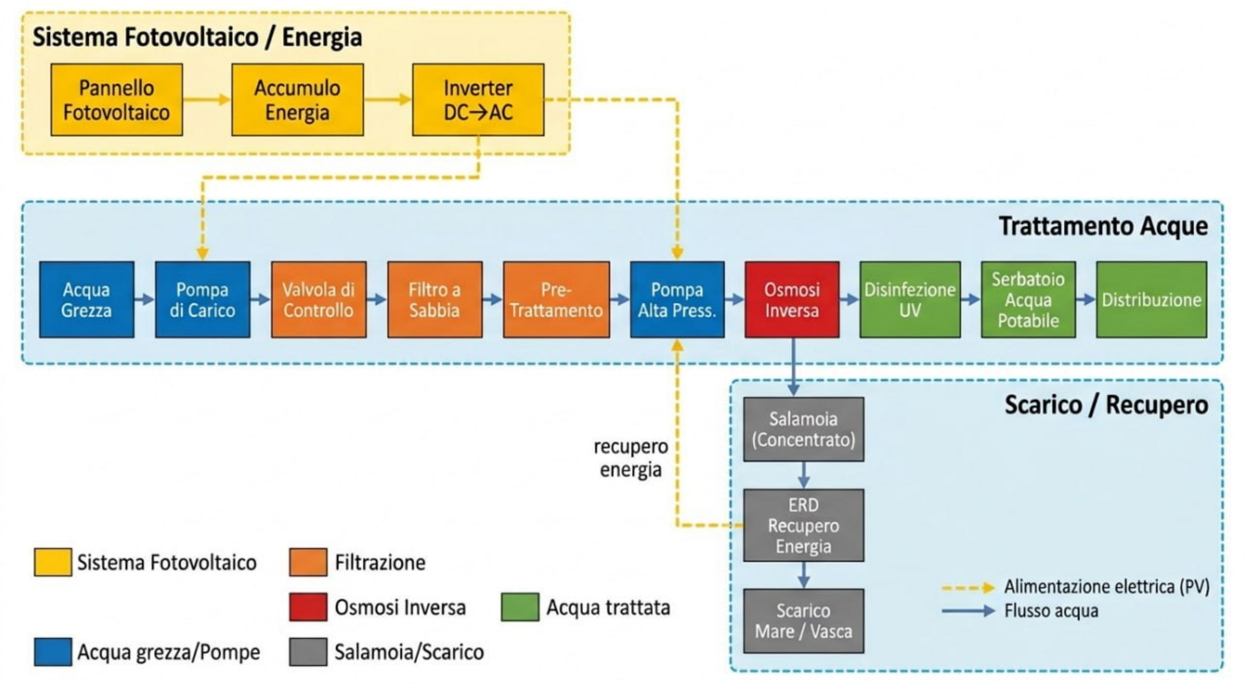


Figure 3.1 – Integrated reverse osmosis (RO) desalination system powered by a photovoltaic energy source and equipped with an energy recovery device (ERD). The schematic illustrates the complete process flow, including feed water intake, pretreatment, high-pressure pumping, membrane separation, permeate production, brine discharge, and energy recovery loop. The integration of renewable energy and ERD significantly reduces the overall specific energy consumption of the system.

4. Energy Considerations in Reverse Osmosis Systems

Energy consumption represents one of the most critical factors affecting both the performance and economic feasibility of reverse osmosis (RO) desalination systems. In most practical applications, energy demand accounts for a substantial portion of the total operating cost. Consequently, improving energy efficiency has become a primary objective in the design and optimization of modern RO plants [9].

The main contributor to energy consumption in RO systems is the high-pressure pump, which is required to increase the feed water pressure above its osmotic pressure in order to drive water transport through the membrane. In seawater desalination, this operating pressure is typically in the range of 50–70 bar, which explains the relatively high energy demand associated with the process [9], [10].

A key parameter used to evaluate the energy performance of RO systems is the specific energy consumption (SEC), defined as the amount of energy required to produce one cubic meter of permeate water. It is commonly expressed in kWh/m³. In a simplified form, the SEC can be estimated as:

$$SEC = \frac{P \cdot Q_f}{\eta \cdot Q_p}$$

where $P$is the operating pressure (Pa), $Q_f$is the feed flow rate (m³/s), $Q_p$is the permeate flow rate (m³/s), and $\eta$is the overall efficiency of the pumping system.

By introducing the recovery ratio (RR), defined as:

$$RR = \frac{Q_p}{Q_f}$$

the SEC expression can be simplified to:

$$SEC = \frac{P}{\eta \cdot RR}$$

This relationship clearly indicates that the specific energy consumption is directly proportional to the operating pressure and inversely proportional to both the system efficiency and the recovery ratio. As a result, higher operating pressures or lower efficiencies lead to increased energy consumption, whereas higher recovery ratios can improve energy performance.

However, increasing the recovery ratio is subject to operational limitations, particularly membrane fouling and scaling phenomena, which can negatively affect system performance and long-term stability [13]. Therefore, an optimal balance between recovery and operational reliability must be achieved during system design.

In practical seawater reverse osmosis (SWRO) systems equipped with high-efficiency energy recovery devices (ERDs), typical SEC values range between approximately 2 and 4 kWh/m^3. Under optimized conditions, advanced systems can achieve values as low as 1.8–2.0 kWh/m^3 [2], [9]. As illustrated in Figure 4.1, the specific energy consumption increases with operating pressure.

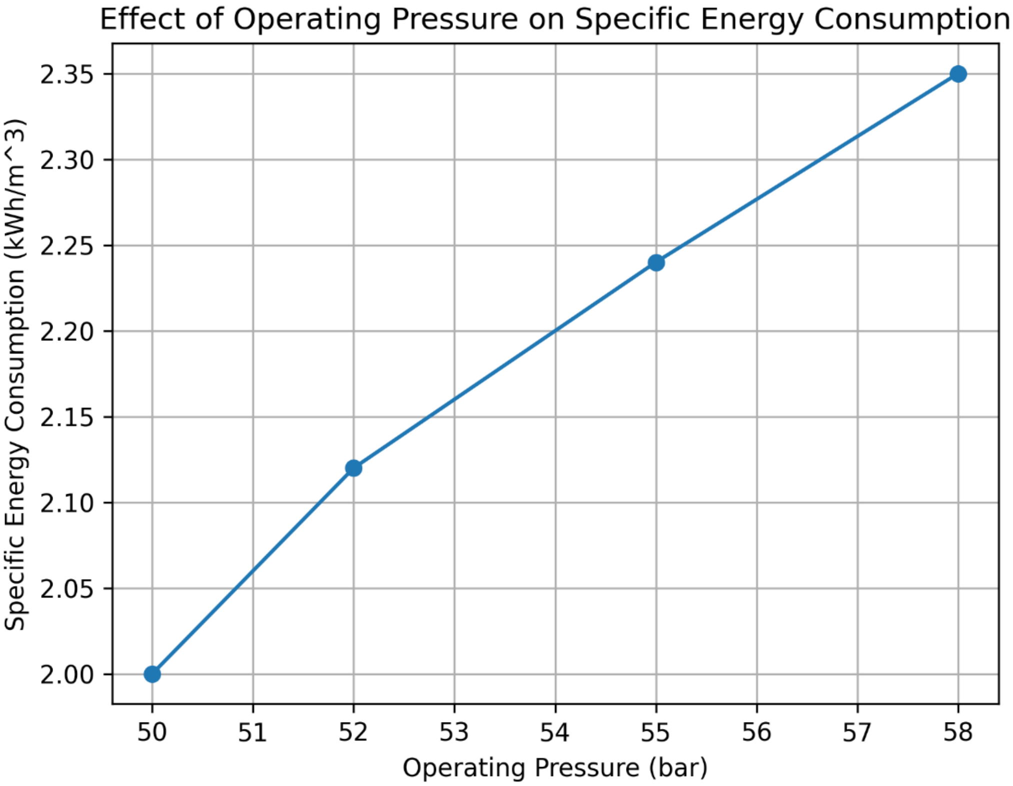


Figure 4.1 – Effect of operating pressure on specific energy consumption (SEC) in reverse osmosis systems.

The dependence of SEC on operating conditions highlights the importance of system design parameters, including feed water salinity, operating pressure, recovery ratio, and membrane characteristics. For modern SWRO systems equipped with ERDs, maintaining SEC within the range of 2–4 kWh/m³ is generally considered a benchmark for efficient operation [10].

Osmotic pressure is another fundamental parameter influencing energy requirements. It represents the minimum pressure required to counteract the natural osmotic flow. For typical seawater salinity, osmotic pressure ranges between approximately 25 and 30 bar, requiring significantly higher applied pressures to achieve effective separation [9].

The recovery ratio also plays a crucial role in determining system efficiency. Increasing recovery allows more freshwater to be produced from the same feed flow, improving overall performance.

However, excessive recovery can lead to increased risks of scaling and fouling, necessitating careful optimization. In this study, a recovery ratio of 45% is adopted as a compromise between efficiency and operational stability.

To further reduce energy consumption, modern RO systems are equipped with energy recovery devices (ERDs), which recover hydraulic energy from the high-pressure brine stream and transfer it back to the feed stream. This significantly reduces the load on the high-pressure pump and improves overall system efficiency. The use of ERDs is now considered standard practice in large-scale desalination plants [6].

In addition to system configuration, membrane properties have a direct impact on energy consumption. Membranes with higher water permeability allow operation at lower pressures, resulting in reduced energy demand. Therefore, membrane selection plays a dual role, influencing both water quality and operating costs.

In the present work, the desalination system is designed for a production capacity of 1000 m^3/day. At this scale, even small variations in SEC can result in significant differences in long-term operational costs. For this reason, energy performance is a key criterion in the comparison and selection of membrane technologies.

The reduction of energy consumption is particularly important in systems integrated with renewable energy sources, such as photovoltaic (PV) generation. Lower energy demand enables more efficient utilization of available solar energy and reduces the required size of the PV system, thereby improving the overall feasibility of the plant [23].

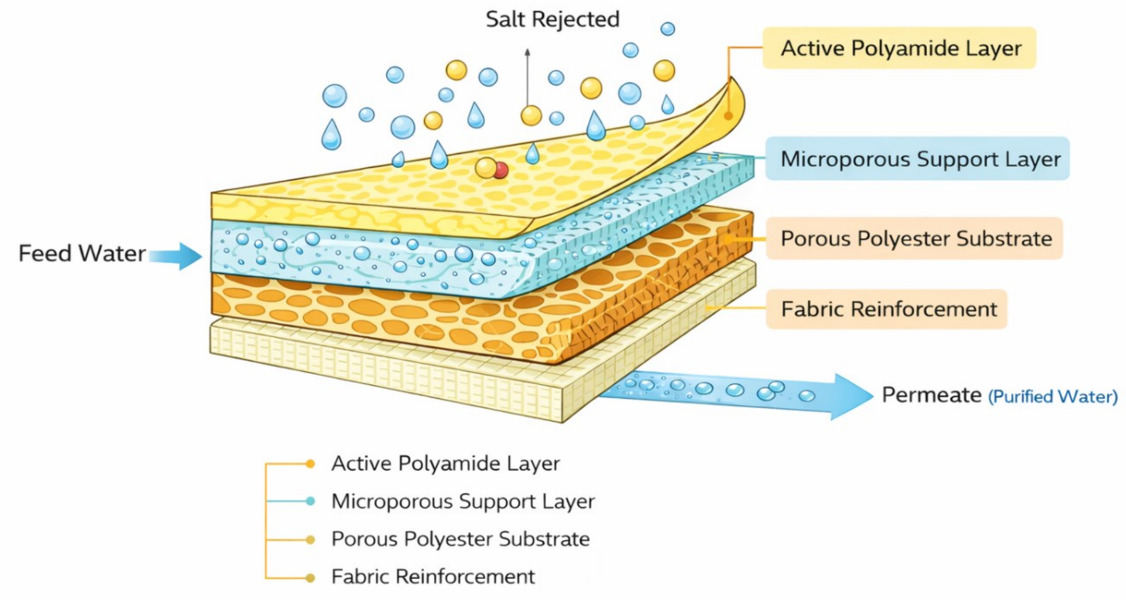
Overall, energy consumption remains one of the most critical aspects in reverse osmosis desalination. Achieving an optimal balance between operating pressure, recovery ratio, membrane performance, and system efficiency is essential for developing an economically viable and sustainable desalination system.

5. Membrane Technologies for Reverse Osmosis (Final Version)

Membranes represent the core component of reverse osmosis (RO) systems, as the separation between water and dissolved salts occurs across the membrane interface. Consequently, membrane selection has a direct impact on overall system performance, influencing water production, energy consumption, and long-term operational stability [7].

In modern desalination plants, thin-film composite (TFC) polyamide membranes are the most widely used configuration [11]. These membranes consist of a multi-layer structure, in which a very thin selective active layer is formed on top of a porous support. This design enables high salt rejection while maintaining relatively high water permeability, making TFC membranes particularly suitable for seawater desalination applications.

The multilayer structure of thin-film composite (TFC) membranes is illustrated in the figure 5.1.



Structure of a thin-film composite (TFC) reverse osmosis membrane, showing the active polyamide layer, microporous support layer, and substrate layers, as well as the separation of permeate and rejection of salts.

As shown in figure 5.1, the selective polyamide layer is responsible for salt rejection, while the underlying porous layers provide mechanical support and facilitate water transport.

RO membranes are typically assembled in spiral-wound modules, where flat membrane sheets are wrapped around a central permeate collection tube. This configuration provides a high membrane surface area within a compact volume, offering an effective balance between efficiency, cost, and space requirements. For this reason, spiral-wound modules are the preferred solution in large-scale RO desalination systems [12].

The performance of RO membranes is commonly characterized by several key parameters. One of the most important is water permeability, which indicates the ease with which water can pass through the membrane. Higher permeability generally allows operation at lower pressure, thereby reducing energy consumption. Another critical parameter is salt rejection, which reflects the membrane's ability to remove dissolved salts and ensure adequate permeate quality.

Salt rejection (R) can be defined as:

$$R = \left(1 - \frac{C_p}{C_f}\right)$$

where $C_p$is the solute concentration in the permeate and $C_f$is the solute concentration in the feed solution. Higher rejection values correspond to improved water quality and more effective separation performance.

In addition to permeability and rejection, membrane fouling is a major factor affecting system performance. Fouling occurs due to the accumulation of suspended particles, organic matter, and microorganisms on the membrane surface, leading to a decline in flux and an increase in operating pressure over time [5],[28]. As a result, fouling directly impacts both energy consumption and maintenance requirements. Modern membrane designs aim to mitigate fouling effects and improve long-term stability.

In practical applications, different membrane types are available depending on design priorities. Low-energy membranes are optimized to operate at reduced pressure, thereby lowering energy consumption, while high-rejection membranes are designed to maximize water quality. In desalination system design, a balance between these objectives must be achieved.

For the system considered in this study, with a production capacity of 1000 m^3/day, membrane selection plays a decisive role. Since energy consumption is a primary driver of operating costs, membranes capable of operating at lower pressures are generally preferred. However, this must be achieved without compromising permeate quality or system reliability. In modern seawater reverse osmosis (SWRO) plants, this approach is typically combined with the use of energy recovery devices (ERDs) to further enhance overall efficiency [6].

Based on the comparative evaluation of available membrane technologies and the design objectives of the proposed system, a spiral-wound thin-film composite (TFC) polyamide membrane is selected as the reference configuration. In particular, a low-energy seawater reverse osmosis membrane with characteristics comparable to the SW30XLE class is adopted [14]. A comparison of the selected membrane characteristics is presented in Table 5.1.

Table 5.1 – Comparison of selected SWRO membranes

Parameter	**SW30XLE (DuPont)**	**SW30HRLE (DuPont)**	**SWC5-LD (Toray)**
Membrane Type	TFC Polyamide	TFC Polyamide	TFC Polyamide
Configuration	Spiral-wound	Spiral-wound	Spiral-wound
Active Area (m^2)	~37	~37	~40

Parameter	**SW30XLE (DuPont)**	**SW30HRLE (DuPont)**	**SWC5-LD (Toray)**
Operating Pressure (bar)	55–60	60–65	55–60
Water Permeability	High	Medium	High
Salt Rejection (%)	99.6	99.75	99.75
Specific Energy Demand	Low	Medium–High	Low
Fouling Resistance	Moderate	Moderate	Improved
Typical Application	Low-energy SWRO	High rejection SWRO	Energy-efficient SWRO

A comparative analysis of the selected SWRO membranes highlights the trade-off between energy efficiency and salt rejection performance. The SW30XLE membrane is specifically designed for low-energy operation, allowing reduced operating pressure and consequently lower specific energy consumption. However, this advantage is associated with slightly lower salt rejection compared to high-rejection membranes.

In contrast, the SW30HRLE membrane provides higher salt rejection, making it more suitable for applications requiring stricter water quality standards. This improved separation performance is achieved at the expense of higher operating pressure and increased energy demand.

The Toray SWC5-LD membrane represents an intermediate solution, offering a balance between energy efficiency and salt rejection, while also incorporating design features aimed at improving fouling resistance.

Considering the design objectives of the present study, which prioritize energy efficiency and operational cost reduction, membranes with lower operating pressure requirements are preferred.

Therefore, low-energy membrane configurations, such as the SW30XLE class, are considered more suitable for the proposed system.

This selection reflects a design strategy focused on minimizing energy consumption while maintaining adequate salt rejection and operational stability. The selected membrane therefore provides a suitable basis for the process design and energy analysis developed in the following chapters.

Overall, membrane technology represents a critical element in RO desalination systems. A careful evaluation of membrane characteristics is essential to achieve an efficient, reliable, and economically viable process.

6. Process Design and System Configuration

6.1 System Overview

This chapter presents the design of a seawater reverse osmosis (SWRO) desalination system integrated with photovoltaic (PV) generation, battery energy storage (BESS), and an energy recovery device (ERD). The proposed plant is designed for a production capacity of 1000 m^3/day and is intended to operate under the environmental conditions of southern Italy.

The system combines a conventional SWRO process with a hybrid energy supply configuration consisting of a photovoltaic array, a battery energy storage system, and a grid connection. This configuration is intended to reduce energy costs while maintaining operational reliability and flexibility.

The desalination process includes the following main stages: seawater intake, pretreatment, high-pressure pumping, reverse osmosis separation, energy recovery, post-treatment, and water storage. Each stage is designed to ensure efficient operation, adequate product water quality, and long-term system stability.

Particular attention is given to the integration of the energy recovery device, since this component plays a key role in reducing the specific energy consumption of the plant [6], [25]. The selection of the main process units and operating conditions is therefore based on achieving a balanced compromise between energy efficiency, operational reliability, and economic feasibility.

The design presented in this chapter forms the basis for the subsequent assessment of process performance, including membrane selection, electrical load estimation, PV and BESS sizing, and preliminary energy-economic evaluation.

6.2 Membrane Selection

In this section, a comparison among different reverse osmosis membranes is carried out in order to identify the most suitable option for the proposed desalination system. The analysis is based on a plant with a production capacity of 1000 m^3/day and a recovery ratio of approximately 45%, which represents a typical operating condition for seawater desalination [8].

Membrane selection is primarily influenced by its effect on operating pressure, specific energy consumption (SEC), and overall process performance. Since energy represents a major fraction of the operating cost, even relatively small differences in membrane characteristics can lead to meaningful differences in long-term plant performance.

For this analysis, three commercial spiral-wound membranes are considered: SW30XLE, SW30HRLE, and SWC5-LD. These membranes are commonly applied in seawater reverse osmosis systems and are designed to provide high salt rejection together with reliable operating performance [14]–[16]. However, they differ in terms of pressure requirement, fouling behavior, and energy demand.

A comparison of the main characteristics of the selected membranes is summarized in **Table 6.1**.

Table 6.1 – Comparison of Selected RO Membranes

Parameter	**SW30XLE**	**SW30HRLE**	**SWC5-LD**
Membrane Type	TFC Polyamide	TFC Polyamide	TFC Polyamide
Configuration	Spiral-wound	Spiral-wound	Spiral-wound
Operating Pressure	Lower	Higher	Medium
Specific Energy Consumption (SEC)	Lower	Higher	Medium

Parameter	**SW30XLE**	**SW30HRLE**	**SWC5-LD**
Salt Rejection	High	Very High	High
Fouling Resistance	Standard	Standard	Improved
Main Advantage	Low energy consumption	High salt rejection	Low fouling
Main Limitation	Slightly lower rejection	Higher energy demand	Performance depends on conditions

As shown in **Table 6.1**, the SW30XLE membrane operates at lower pressure and is therefore associated with lower energy consumption, whereas the SW30HRLE offers higher salt rejection. The SWC5-LD membrane provides improved fouling resistance, which may be advantageous under specific operating conditions.

A graphical comparison of the specific energy consumption of the selected membranes is presented in **Figure 6.1**.

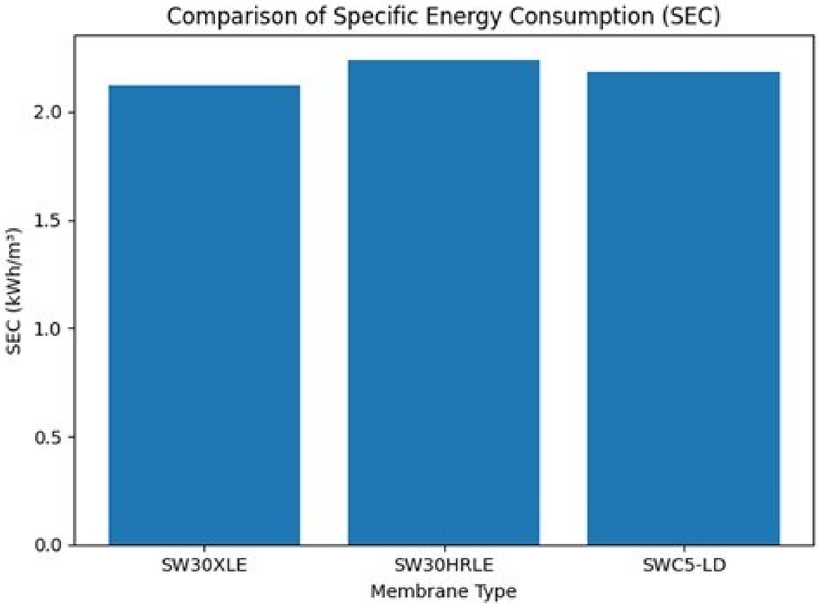


Figure 6.1 – Comparison of specific energy consumption for selected RO membranes.

The observed differences in SEC are directly related to the operating pressure required by each membrane. Even a modest increase in pressure produces a proportional increase in energy demand, consistent with the SEC relationship discussed in Chapter 4. This confirms that membrane selection directly affects system energy performance through its influence on operating pressure.

For a plant operating at 1000 m³/day, small SEC differences become significant when evaluated over long operating periods. Assuming 350 operating days per year, the annual water production is:

$$1000 \times 350 = 350{,}000 \text{ m}^3/\text{year}$$

Based on this production level, even a difference of 0.1–0.2 kWh/m³ can produce a noticeable variation in annual energy consumption and operating cost.

A more quantitative comparison of the selected membranes, including specific energy consumption, number of elements, and estimated motor power, is reported in **Table 6.2**.

Table 6.2 – Quantitative Comparison of the Selected RO Membranes

Membrane	**SEC (kWh/m³)**	**Operating Pressure (bar)**	**Number Elements**	**of Pressure Vessels**	**Estimated Motor Power (kW)**
SW30XLE	2.12	52	27	5	200
SW30HRLE	2.24	55	27	5	210
SWC5-LD	2.35	58	30	5	220

Table 6.2 confirms that SW30XLE is associated with the lowest energy demand and the lowest estimated motor power. The SW30HRLE requires slightly higher pressure, while the SWC5-LD

shows the highest SEC and requires a larger number of membrane elements for the same production capacity.

From a design perspective, membranes operating at lower pressure offer an advantage not only in terms of SEC, but also in terms of pump sizing and overall energy demand. While higher-rejection or low-fouling membranes may offer benefits under specific conditions, these advantages must be balanced against higher pressure requirements and associated energy penalties.

Based on the overall comparison, the SW30XLE membrane appears to be the most suitable option for the proposed system. This choice is mainly justified by its lower energy requirement, which is a key design criterion for efficient desalination plants, while still maintaining adequate water quality and reliable operating performance under the selected conditions.

In summary, membrane selection is a critical step in the design of reverse osmosis systems. The results of this analysis show that low-energy membranes can significantly improve long-term plant performance and reduce operational costs, particularly in medium-scale SWRO applications such as the one considered in this study.

6.3 Process Flow Description

The proposed SWRO desalination system is designed to produce potable water from seawater through a sequence of interconnected treatment stages. The plant includes seawater intake, pretreatment, high-pressure pumping, reverse osmosis separation, energy recovery, post-treatment, and storage.

In addition, the plant is integrated with a photovoltaic system and a battery energy storage system, which provide a significant share of the required electrical energy and contribute to reducing the overall operating cost.

Following the conceptual representation of the system, a more detailed process description is provided to better illustrate the main operational stages of the desalination plant. As shown in Figure 6.2, the process begins with seawater intake from the Mediterranean Sea through a submerged screened intake structure, which prevents the ingress of large particles and debris.

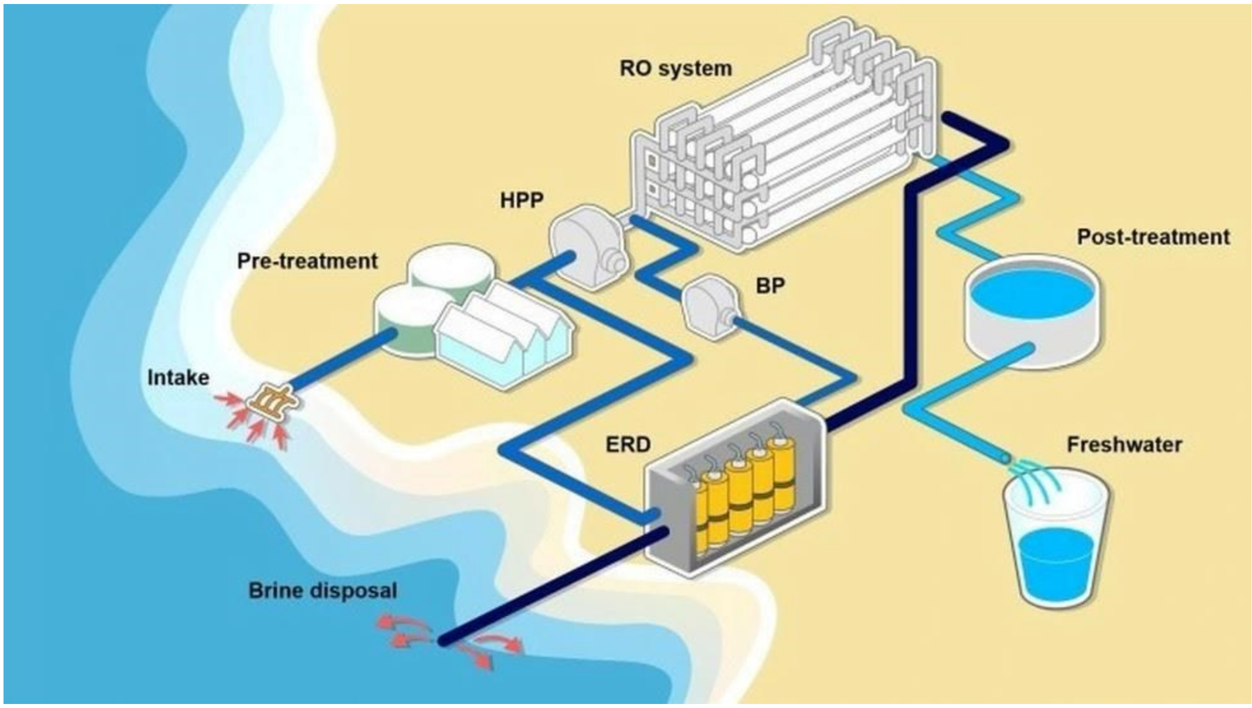


Figure 6.2 – Simplified process flow diagram of a seawater reverse osmosis (SWRO) system with energy recovery and brine discharge.

After intake, the feed water passes through a pretreatment stage consisting of a dual-media filter and a cartridge filter, which are required to remove suspended solids and protect the downstream membrane system from fouling. Chemical dosing systems, including sodium hypochlorite and antiscalant, are incorporated to improve water quality and reduce scaling risk.

Following pretreatment, the water is pressurized by the high-pressure pump and directed to the SWRO membrane train, where the separation between permeate and concentrated brine takes place. A pressure exchanger is integrated into the system to recover hydraulic energy from the high-pressure brine stream and transfer it to the incoming feed, thereby reducing the specific energy consumption of the process [6], [25].

The permeate stream is directed to the post-treatment unit, where remineralization and UV disinfection are applied to ensure that the produced water meets potable standards. The treated water is then stored in the product water tank and subsequently distributed to users.

The brine stream is discharged through a controlled reject line, with the possibility of future integration with mineral recovery or additional energy recovery technologies, depending on environmental and economic considerations.

From an energy perspective, the system is partially powered by a photovoltaic array, supported by a battery energy storage system and connected to the grid for reliability. This hybrid configuration allows peak shaving, reduces grid dependence, and improves the overall energy sustainability of the plant.

The P&ID therefore provides the basis for the subsequent design calculations, including equipment sizing, electrical load estimation, and control strategy development.

6.4 Design Basis

The design basis of the proposed SWRO desalination system is defined to support the development of the P&ID, the estimation of electrical power demand, and the subsequent sizing of the photovoltaic and battery storage systems.

The plant is designed for a nominal water production capacity of 1000 m^3/day, corresponding to an annual production of approximately 350,000 m^3/year, assuming 350 operating days per year. Under continuous operation, the equivalent permeate flow rate is:

$$Q_p = 41.67 \text{ m}^3/\text{h}$$

The feedwater is assumed to be seawater under representative Mediterranean conditions, with a total dissolved solids concentration of approximately 40,000 mg/L and a design temperature of 25 °C, consistent with typical seawater desalination conditions reported in the literature [10], [24].

A recovery ratio of 45% is adopted, representing a practical compromise between energy efficiency and operational stability [8]. Based on this assumption, the corresponding feed and brine flow rates are:

$$Q_f = 92.59 \text{ m}^3/\text{h}$$

$$Q_b = 50.92 \text{ m}^3/\text{h}$$

The desalination system is configured as a single-pass SWRO process including seawater intake, pretreatment, cartridge filtration, chemical dosing, high-pressure pumping, reverse osmosis membranes, and an energy recovery device. The selected ERD is a pressure exchanger, which allows the recovery of hydraulic energy from the high-pressure brine stream and significantly reduces the overall energy consumption of the system [6], [25].

The operating pressure of the RO system is assumed to be 60 bar, which is typical for seawater desalination at the considered salinity level [5]. The membrane train considered in the present design is based on low-energy spiral-wound seawater reverse osmosis elements with performance characteristics comparable to the selected reference membrane. This design choice supports the adopted operating pressure and the target SEC considered in the following calculations.

From an energy perspective, the system is designed with a target SEC in the range of 1.8–2.0 kWh/m^3, achievable through the integration of a high-efficiency ERD [6]. This value is consistent with modern SWRO plants and represents a substantial improvement compared with systems operating without energy recovery.

The plant is assumed to operate continuously at 24 h/day, and the dominant electrical load is associated with the high-pressure pump [19]. Additional loads include the feed pump, booster pump, chemical dosing units, control systems, and auxiliary equipment.

The main design assumptions adopted for the preliminary sizing of the proposed SWRO plant are summarized in **Table 6.3**.

Table 6.3 – Main Design Basis of the Proposed SWRO Desalination Plant

Parameter	**Value**
Water production	1000 m^3/day
Operating days	350 days/year
Annual production	350,000 m^3/year
Permeate flow rate	41.67 m^3/h
Feed flow rate	92.59 m^3/h
Brine flow rate	50.92 m^3/h
Recovery ratio	45%
Feed salinity (TDS)	40,000 mg/L
Feed temperature	25 °C
RO operating pressure	60 bar
ERD type	Pressure Exchanger
SEC (with ERD)	1.8–2.0 kWh/m^3

Parameter	**Value**
Operating mode	Continuous (24 h/day)
Reference membrane	SW30XLE-class low-energy SWRO membrane

As shown in **Table 6.3**, the selected design assumptions provide a balanced compromise between freshwater production, process efficiency, and operational reliability. These assumptions form the technical basis for process development, equipment selection, electrical load assessment, and renewable energy integration in the following sections.

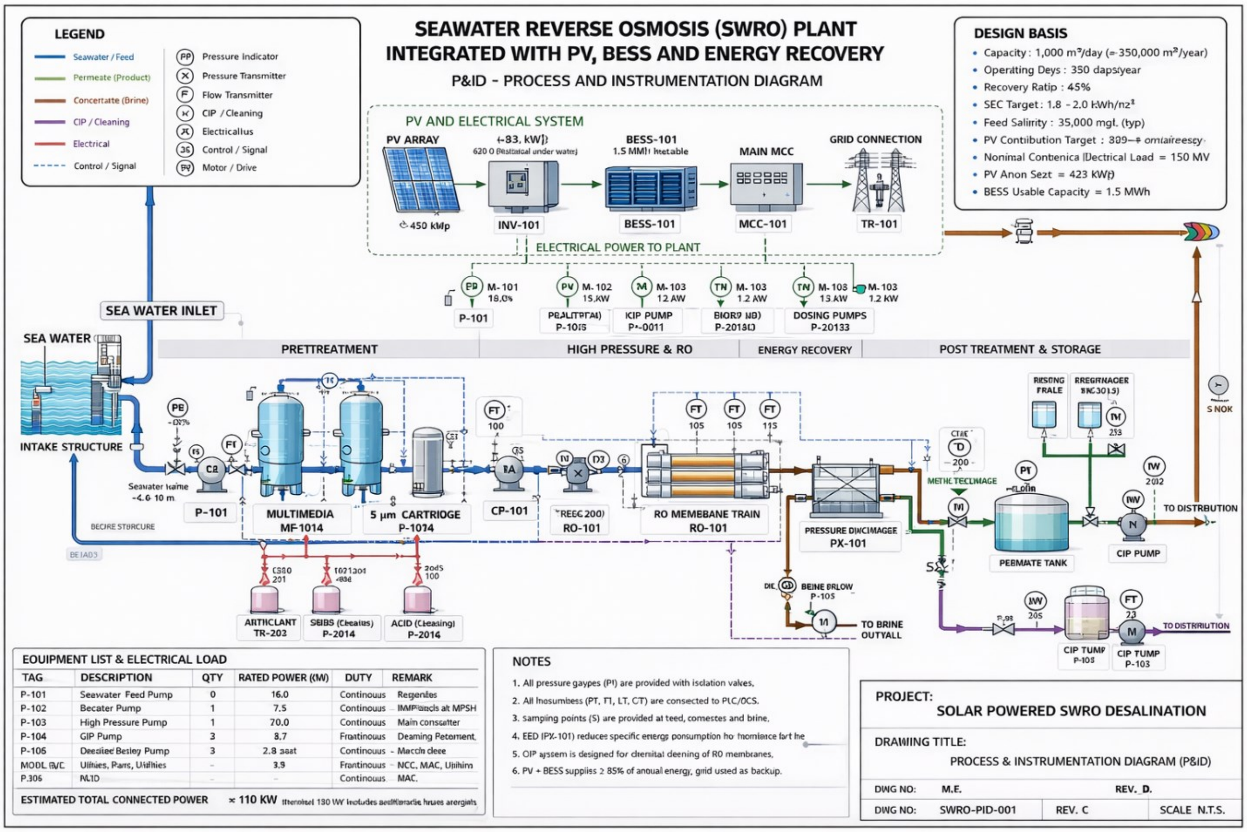
6.5 Process Configuration and P&ID Development

Based on the design basis defined in the previous section, the overall process configuration of the proposed SWRO desalination plant was developed and represented through a detailed Process and Instrumentation Diagram. The diagram includes the main hydraulic units, from seawater intake and pretreatment to high-pressure pumping, reverse osmosis separation, energy recovery, post-treatment, and product water storage.

In addition, the P&ID integrates the electrical energy system, including the photovoltaic field, battery energy storage system, inverter, and grid connection, in order to provide a complete representation of the plant architecture.

Particular attention was given to the inclusion of the controllers and sensors required for preliminary engineering design, so that the main process variables can be monitored and controlled during operation. The P&ID also forms the basis for identifying the electrically driven equipment installed in the plant, which is essential for the subsequent assessment of power demand and for the appropriate sizing of the PV and storage systems.

A detailed Process and Instrumentation Diagram (P&ID) of the proposed SWRO system is presented in Figure 6.3, providing a comprehensive representation of the main process units, control elements, and integrated energy subsystems. The diagram highlights the interaction between the desalination process and the photovoltaic (PV), battery energy storage system (BESS), and energy recovery devices (ERD), offering an engineering-level overview of the entire system configuration.



DESIGN BASIS

- Capacity : 1,000 m^3/day (≈ 350,000 m^3/year)
- Operating Deys : 350 daps/year
- Recovery Ratip : 45%
- SEC Target : 1.8 - 2.0 kWh/nz³
- Feed Salirity : 35,000 mgl. (typ)
- PV Contiibution Target : 309–# omlaireescy
- Nonimal Contienica Dectrical Laad = 150 MV
- PV Anon Sezt = 423 KWp)
- BESS Usable Capacity = 1.5 MWh

EOUIPMENT LIST & ELECTRICAL LOAD

TAG	DESCRIPTION	QTY	RATED POWER (KW)	DUTY	REMARK
P-101	Seawater Feed Pump	0	16.0	Continous	Regenles
P-102	Becater Pump	1	7.5	Continous	IMMPaincls alt MPSH
P-103	High Pressure Pump	1	70.0	Continous	Main conscatter
P-104	GIP Pump	3	8.7	Frontinous	Deaming Peterment,
P-106	Deeditec Besley Pump	3	2.8 aaat	Continous	Maccin deee
MODL BVC	Ulities, Pars, Uidities	-	3.9	Frontinous	NCC, MAC, Uhihim
P.306	NLID	-	-	Continous	MAC.

ESTIMATED TOTAL CONNECTED POWER ≈ 110 KW (thenoisel 130 W includes aedificatie hraes arergints)

NOTES

1. All pressure gaypes (PI) are provided with isclation vakes,
2. All lnosumbess (PT, FI, LT, CT) are consected to PLC/DCS.
3. samping points (S) are provided at teed, comestes and brine,
4. EED (PX-101) reduces specific energy ponsumption ho fnomiarce fart lne
5. OIP aysem is designed for chemical deening of RO membranes,
6. PV + BESS suppliss ≥ 85% of anoual energy, grid used as backup.

PROJECT: SOLAR POWERED SWRO DESALINATION

DRAWING TITLE: PROCESS & INSTRUMENTATION DIAGRAM (P&ID)

DWG NO: M.E. REV. D.

DWG NO: SWRO-PID-001 REV. C SCALE N.T.S.

Figure 6.3 – Process and Instrumentation Diagram (P&ID) of the proposed SWRO desalination system integrated with photovoltaic (PV) generation, battery energy storage system (BESS), and energy recovery devices (ERD), showing the main process units, piping network, control elements, and energy integration architecture.

6.6 Instrumentation and Control

The proposed SWRO desalination system requires a basic but reliable instrumentation and control scheme in order to ensure stable operation, water quality monitoring, and safe process management. The main variables to be monitored are flow rate, pressure, conductivity, and tank level. These variables are essential for controlling the desalination process and for detecting abnormal operating conditions.

Flow measurement is required at the intake and feed sections to verify that the system operates within the expected hydraulic range. Pressure monitoring is particularly important before and after the reverse osmosis unit, since operating pressure directly affects membrane performance and energy consumption. In addition, conductivity monitoring is necessary to assess the quality of the produced water and verify that the permeate meets the desired standards. Finally, level measurement in the storage tank is required to manage the water inventory and maintain a stable distribution flow.

A simplified instrumentation layout is adopted in this study, consistent with the preliminary design level. The main instruments included in the P&ID are listed in

Table 6.4.

Table 6.4 – Main Instrumentation of the SWRO Desalination System

Instrument Tag	**Measured Variable**	**Location**	**Main Function**
FIT-101	Flow rate	Intake line	Monitoring seawater inflow
PIT-101	Pressure	Pretreatment/feed section	Monitoring pressure losses and operating conditions

Instrument Tag	**Measured Variable**	**Location**	**Main Function**
FIT-201	Flow rate	RO feed line	Monitoring feed flow to membranes
PIT-201	Pressure	High-pressure pump discharge / RO inlet	Monitoring operating pressure
AIT-301	Conductivity	Permeate outlet	Monitoring product water quality
LIT-301	Level	Product water tank	Monitoring storage level and distribution availability

As shown in **Table 6.4**, the selected instrumentation focuses on the most critical process variables. The instrumentation strategy is intentionally limited in order to maintain a realistic preliminary design framework. At this stage, the objective is not to develop a complete industrial control philosophy, but rather to identify the minimum set of instruments required for process monitoring and performance evaluation.

From a control perspective, the low-lift pump and the high-pressure pump are the main active components of the system. Their operation must be coordinated with measured process conditions. In particular, the high-pressure pump must maintain the feed pressure required by the SWRO membranes, while the ERD reduces the net pressure demand by recovering hydraulic energy from the brine stream.

The conductivity analyzer at the permeate outlet is particularly important because it provides an immediate indication of membrane performance and product water quality. Similarly, the tank level indicator ensures that the storage capacity is adequately monitored and that stable distribution can be maintained.

Overall, the proposed instrumentation scheme provides the essential monitoring functions required for safe and efficient operation of the SWRO-PV system. Although simplified, the selected layout is consistent with standard preliminary engineering practice. In a more detailed engineering phase, additional instruments such as differential pressure transmitters, temperature sensors, and control valves could be incorporated to improve process automation and diagnostics.

6.7 Electrical Power Requirement of the SWRO Plant

The electrical power requirement of the proposed SWRO plant was estimated on the basis of the finalized process configuration and the preliminary P&ID layout. The assessment was developed by identifying all the main electrically driven components involved in normal plant operation, including the seawater feed pump, high-pressure pump, ERD-associated booster pump, product water pump, chemical dosing pumps, RO skid auxiliaries, and control and instrumentation systems. The purpose of this evaluation is to define a realistic electrical load basis for the subsequent sizing of the photovoltaic system, battery energy storage system, and the overall plant electrical infrastructure.

For the adopted design basis, the desalination plant is intended to produce 1,000 m^3/day of freshwater, corresponding to 350,000 m^3/year over 350 operating days. Based on the selected recovery ratio of 45%, the feed flow rate is approximately 92.59 m^3/h and the brine flow rate is approximately 50.92 m^3/h. The plant is designed with a target specific energy consumption (SEC) in the range of 1.8–2.0 kWh/m^3, which corresponds to an annual electricity demand of about 630,000–700,000 kWh/year.

It is important to distinguish between the average absorbed operating power and the nominal installed electrical design capacity. Based on the SEC target and annual water production, the average absorbed power during normal operation is expected to fall in the range of approximately 75–83 kW. In parallel, a more conservative nominal electrical design capacity of 150 kW is retained for plant integration and electrical system design. This latter value is intended to cover installed equipment capacity, startup effects, auxiliary systems, operational margins, and future design flexibility, and therefore should not be interpreted as the constant absorbed process power during normal operation.

Based on this approach, the preliminary electrical load distribution shown in Table 6.5 was defined. The selected values are consistent with the process scheme, the expected hydraulic duty of the SWRO unit, and the inclusion of an energy recovery device based on a pressure exchanger. Under normal plant operation, the estimated absorbed power is approximately 78 kW, which is fully consistent with the SEC-based estimate. This results in an approximate daily electrical consumption of 1,878 kWh/day and an annual electricity demand of about 657,300 kWh/year, which lies within the expected design range.

The load estimate reported here should be considered a preliminary engineering assessment intended for design development. Final motor ratings, electrical efficiencies, and auxiliary loads should be confirmed at the detailed design stage using the manufacturers’ datasheets and rating plate data of the selected equipment. This approach is consistent with the professor’s indication that the exact electrical power demand must be determined in order to properly dimension the photovoltaic system.

Tag	Equipment	Qty	Absorbed Power (kW)	Duty	Operating Mode	Daily Operating Hours	Daily Energy (kWh/day)	Remarks
P-101	Seawater feed pump	1	8.0	Continuous	Normal operation	24	192.0	Intake/feed pumping
P-201	High-pressure pump	1	52.0	Continuous	Normal operation	24	1248.0	Main electrical consumer
P-104	Booster pump / ERD support pump	1	4.0	Continuous	Normal operation	24	96.0	Pressure support after ERD integration
P-301	Product water pump	1	3.0	Continuous	Normal operation	24	72.0	Product water transfer
P-201A	Antiscalant dosing pump	1	0.75	Continuous	Normal operation	24	18.0	Chemical dosing
P-202A	SMBS dosing pump	1	0.75	Continuous	Normal operation	24	18.0	Dechlorination / chemical dosing
P-203A	Acid/cleaning chemical dosing pump	1	0.75	Continuous	Normal operation	24	18.0	pH control / chemical support
AUX-RO	RO skid auxiliaries and	1	2.0	Continuous	Normal operation	24	48.0	Flushing/auxiliary loads

Tag	Equipment	Qty	Absorbed Power (kW)	Duty	Operating Mode	Daily Operating Hours	Daily Energy (kWh/day)	Remarks
	actuated valves							
AUX-EL	Instrumentation, PLC, MCC auxiliaries, analyzers and control system	1	7.0	Continuous	Normal operation	24	168.0	Control and monitoring
P-401	CIP pump	1	5.5	Intermittent	Cleaning only	0	0.0*	Not included in normal daily production load

Total absorbed power during normal operation = 78.25 kW

Estimated daily electrical consumption = 1,878 kWh/day

Estimated annual electrical consumption = 657,300 kWh/year

Table 6.5 Preliminary electrical load assessment of the proposed SWRO plant under normal operating conditions.

*The CIP pump is considered an intermittent load and is therefore excluded from the daily energy demand under normal production operation.

The results reported in Table 6.5 indicate that the total absorbed electrical load during normal plant operation is approximately 78.25 kW. This value is consistent with the expected SEC-based operating range for the selected plant capacity and recovery ratio. When multiplied by 24 operating hours per day and 350 operating days per year, the resulting annual electricity demand is approximately 657,300 kWh/year, which falls within the previously established design interval of 630,000–700,000 kWh/year. Therefore, the estimated electrical load can be considered coherent with both the process design assumptions and the targeted energy performance of the proposed SWRO system.

In addition to the absorbed operating load, a nominal installed electrical design capacity of 150 kW is retained as the reference value for the plant electrical architecture. This value should be interpreted as a conservative design basis for electrical integration, rather than as the actual continuous absorbed power of the desalination process. It includes installed motor capacity, auxiliaries, startup margins, and reserve capacity for safe and flexible operation. This distinction is important in order to avoid confusion between the real process energy demand and the electrical design capacity used for system integration and photovoltaic-battery sizing.

Parameter	**Value**
Freshwater production capacity	1,000 m^3/day
Annual freshwater production	350,000 m^3/year
Feed flow rate	92.59 m^3/h

Parameter	**Value**
Brine flow rate	50.92 m^3/h
Recovery ratio	45%
SEC target	1.8–2.0 kWh/m^3
Expected average absorbed operating power	75–83 kW
Calculated absorbed operating power from load list	78.25 kW
Estimated daily electrical consumption	1,878 kWh/day
Estimated annual electrical consumption	657,300 kWh/year
Nominal installed electrical design capacity	150 kW

Table 6.6 Summary of the main electrical design parameters adopted for the proposed SWRO desalination plant.

6.7.1 SEC-Based Energy Demand Estimation

The annual electrical energy demand of the desalination process is first estimated based on the SEC definition:

$$E_{ann} = Q_{ann} \times SEC$$

where $Q_{ann} = 350{,}000\ \mathrm{m}^3/\mathrm{year}$.

Therefore:

$$E_{ann,1.8} = 350{,}000 \times 1.8 = 630{,}000\ \mathrm{kWh/year}$$

$$E_{ann,2.0} = 350{,}000 \times 2.0 = 700{,}000\ \mathrm{kWh/year}$$

Assuming continuous operation over 350 days per year, the corresponding average absorbed electrical power is:

$$P_{avg} = \frac{E_{ann}}{350 \times 24}$$

which gives:

$$P_{avg,1.8} = 75.0\ \text{kW}, P_{avg,2.0} = 83.3\ \text{kW}$$

Accordingly, the expected average absorbed electrical power of the plant during normal operation lies in the range of approximately **75–83 kW**. This value represents the effective process energy demand under steady operating conditions.

6.7.2 Distinction Between Operating Load and Installed Capacity

It is important to distinguish between the **average absorbed operating power** and the **nominal installed electrical design capacity**.

The SEC-based calculation provides an estimate of the actual energy required by the desalination process during normal operation. However, for electrical system design, a more conservative value must be adopted. In this study, a nominal installed electrical capacity of **150 kW** is retained as the design basis for sizing the electrical infrastructure, inverter interface, and battery system.

This value includes installed motor capacity, auxiliary systems, startup margins, and operational flexibility, and therefore should not be interpreted as the continuous absorbed process power.

6.7.3 Hydraulic Estimation of High-Pressure Pump Demand

The electrical demand of the high-pressure pump, which represents the dominant energy consumer of the system, can also be evaluated using a hydraulic approach:

$$P_{HP} = \frac{Q_f \times \Delta P}{\eta_p}$$

where $Q_f$is the feed flow rate, $\Delta P$is the pressure increase, and $\eta_p$is the pump efficiency.

For the proposed system:

- $Q_f \approx 0.0257\ \mathrm{m}^3/\mathrm{s}$
- $\Delta P = 60\ \mathrm{bar} = 6 \times 10^6\ \mathrm{Pa}$
- $\eta_p = 0.8$

Thus:$P_{HP} \approx 193\ \mathrm{kW}$

This value represents the **gross hydraulic power requirement**. However, due to the presence of a pressure exchanger (ERD), a significant portion of the hydraulic energy is recovered from the brine stream. As a result, the net electrical demand of the high-pressure section is typically reduced to approximately **40–60 kW**, in agreement with modern SWRO systems.

6.7.4 Electrical Load Distribution

A preliminary distribution of the electrical loads among the main plant components is presented in Table 6.7.

Tag	Equipment	Qty	Absorbed Power (kW)	Duty	Operating Mode	Daily Operating Hours	Daily Energy (kWh/day)	Remarks
P-101	Seawater feed pump	1	8.0	Continuous	Normal operation	24	192.0	Intake/feed pumping
P-201	High-pressure pump	1	52.0	Continuous	Normal operation	24	1248.0	Main electrical consumer
P-104	Booster pump / ERD support pump	1	4.0	Continuous	Normal operation	24	96.0	Pressure support after ERD integration
P-301	Product water pump	1	3.0	Continuous	Normal operation	24	72.0	Product water transfer
P-201A	Antiscalant dosing pump	1	0.75	Continuous	Normal operation	24	18.0	Chemical dosing
P-202A	SMBS dosing pump	1	0.75	Continuous	Normal operation	24	18.0	Dechlorination / chemical dosing
P-203A	Acid/cleaning chemical dosing pump	1	0.75	Continuous	Normal operation	24	18.0	pH control / chemical support
AUX-RO	RO skid auxiliaries and	1	2.0	Continuous	Normal operation	24	48.0	Flushing/auxiliary loads

Tag	Equipment	Qty	Absorbed Power (kW)	Duty	Operating Mode	Daily Operating Hours	Daily Energy (kWh/day)	Remarks
	actuated valves							
AUX-EL	Instrumentation, PLC, MCC auxiliaries, analyzers and control system	1	7.0	Continuous	Normal operation	24	168.0	Control and monitoring
P-401	CIP pump	1	5.5	Intermittent	Cleaning only	0	0.0*	Not included in normal daily production load

Table 6.7 – Preliminary Electrical Load Distribution of the SWRO Desalination Plant

The results reported in Table 6.7 indicate that the total absorbed electrical load during normal operation is approximately **78 kW**, which is fully consistent with the SEC-based estimation.

This corresponds to a daily electricity consumption of approximately **1,878 kWh/day** and an annual demand of about **657,300 kWh/year**, which falls within the expected design range of 630,000–700,000 kWh/year.

6.7.5 Summary of Electrical Design Parameters

A summary of the key electrical design parameters adopted for the plant is provided in Table 6.8.

Parameter	**Value**
Freshwater production capacity	1,000 m³/day
Annual freshwater production	350,000 m³/year
Feed flow rate	92.59 m³/h
Brine flow rate	50.92 m³/h
Recovery ratio	45%
SEC target	1.8–2.0 kWh/m³
Expected average absorbed operating power	75–83 kW
Calculated absorbed operating power from load list	78.25 kW
Estimated daily electrical consumption	1,878 kWh/day
Estimated annual electrical consumption	657,300 kWh/year
Nominal installed electrical design capacity	150 kW

Table 6.8 – Summary of Electrical Design Parameters for the Proposed SWRO Plant

6.7.6 Final Remarks

The results obtained from the SEC-based estimation, hydraulic calculation, and load distribution analysis are mutually consistent and confirm the reliability of the preliminary design.

The electrical demand is dominated by the high-pressure pump, while auxiliary loads remain relatively limited. The estimated absorbed operating power of approximately 75–83 kW provides a realistic basis for energy analysis, whereas the nominal installed capacity of 150 kW ensures a conservative and robust framework for electrical system design.

The values reported in this section should be considered as preliminary engineering estimates. Final electrical ratings and power consumption values should be verified during the detailed design phase using manufacturers' datasheets and rating plate data.

Overall, this assessment establishes a consistent and physically meaningful basis for the photovoltaic and battery storage sizing presented in the following section.

6.8 Photovoltaic, Battery Storage and Energy Recovery Integration

The sizing of the photovoltaic (PV) system and the battery energy storage system (BESS) was carried out based on the electrical demand estimated in Section 6.7. The objective of this stage is to define a realistic hybrid energy configuration capable of supplying the majority of the plant's annual electricity demand while maintaining operational reliability through grid support.

The proposed SWRO plant is expected to consume approximately **657,000 kWh/year**, as derived from the load analysis and SEC-based estimation. In order to maximize the use of renewable energy and reduce dependency on external electricity supply, a target PV contribution of **85%** of the annual demand was adopted.

6.8.1 Photovoltaic System Sizing

The installed PV capacity was estimated using the standard relationship:

$$P_{PV} = \frac{E_{PV}}{H \times PR}$$

where P_{PV} is the installed PV capacity (kWp), E_{PV} is the annual energy to be supplied by the PV system (kWh/year), H is the annual solar irradiation (kWh/kWp·year), and PR is the performance ratio.

Based on the selected design target:

$$E_{PV} = 0.85 \times 657{,}000 \approx 558{,}000 \text{ kWh/year}$$

For southern Italy, an average annual irradiation of **1760 kWh/kWp·year** was considered, including a slight enhancement due to bifacial modules. A performance ratio of **0.78** was adopted to account for inverter losses, temperature effects, and other system inefficiencies.

Substituting these values:

$$P_{PV} \approx \frac{558{,}000}{1760 \times 0.78} \approx 406 \text{ kWp}$$

In practice, PV systems are typically oversized to account for seasonal variability, degradation, and operational uncertainties. Therefore, the installed capacity was conservatively increased to the range of:

430–450 kWp

For the present design, a nominal value of:

433 kWp

was selected as a balanced and realistic solution.

Parameter	**Value**
Installed PV capacity	433 kWp
Annual irradiation	1760 kWh/kWp·year
Performance ratio (PR)	0.78
Annual PV production	~560,000 kWh
PV contribution	~85% of total demand

This configuration allows the plant to achieve a high level of energy autonomy while maintaining a practical and implementable system size.

Table 6.9 – Main Photovoltaic System Design Parameters

6.8.2 Battery Energy Storage System Sizing

A battery energy storage system is integrated into the proposed configuration in order to improve the utilization of the generated photovoltaic energy and enhance operational flexibility.

It is important to note that the BESS is **not intended to provide long-term backup operation**, but rather to support:

- short-term load balancing,
- peak shaving,
- smoothing of solar power fluctuations,
- and increased self-consumption of PV energy.

A first estimate of the minimum storage requirement can be obtained from the average plant load and a short autonomy period:

$$E_{BESS,min} = P_{avg} \times t$$

Assuming:

- $P_{avg} \approx 80$ kW
- autonomy $t = 4–6$ hours

$$E_{BESS,min} \approx 320–480 \text{ kWh}$$

However, in real industrial applications, battery systems are intentionally oversized relative to the minimum requirement in order to improve system stability and operational flexibility. Taking this into account, a storage system in the range of:

1.25–2.25 MWh (nominal capacity)

was selected, corresponding to a usable capacity of:

1.0–1.8 MWh (assuming a depth of discharge of 80%).

Table 6.10 – Main Battery Energy Storage System Design Parameters

Parameter	**Value**
Nominal capacity	1.25–2.25 MWh
Usable capacity (DoD = 80%)	1.0–1.8 MWh
Depth of discharge (DoD)	80%
Main function	Peak shaving and load balancing

This configuration provides sufficient flexibility to manage short-term variations in both load and solar generation, without introducing excessive capital cost.

6.8.3 Energy Recovery Device (ERD) Integration

The energy consumption of the SWRO desalination process is strongly influenced by the high-pressure pumping requirements, which are necessary to overcome the osmotic pressure of seawater and enable membrane separation. In conventional systems, this results in a significant electrical energy demand.

To improve the overall energy efficiency of the plant, a pressure exchanger (PX) type energy recovery device was integrated into the system. The ERD recovers hydraulic energy from the high-pressure brine stream leaving the RO unit and transfers it to the incoming feed water.

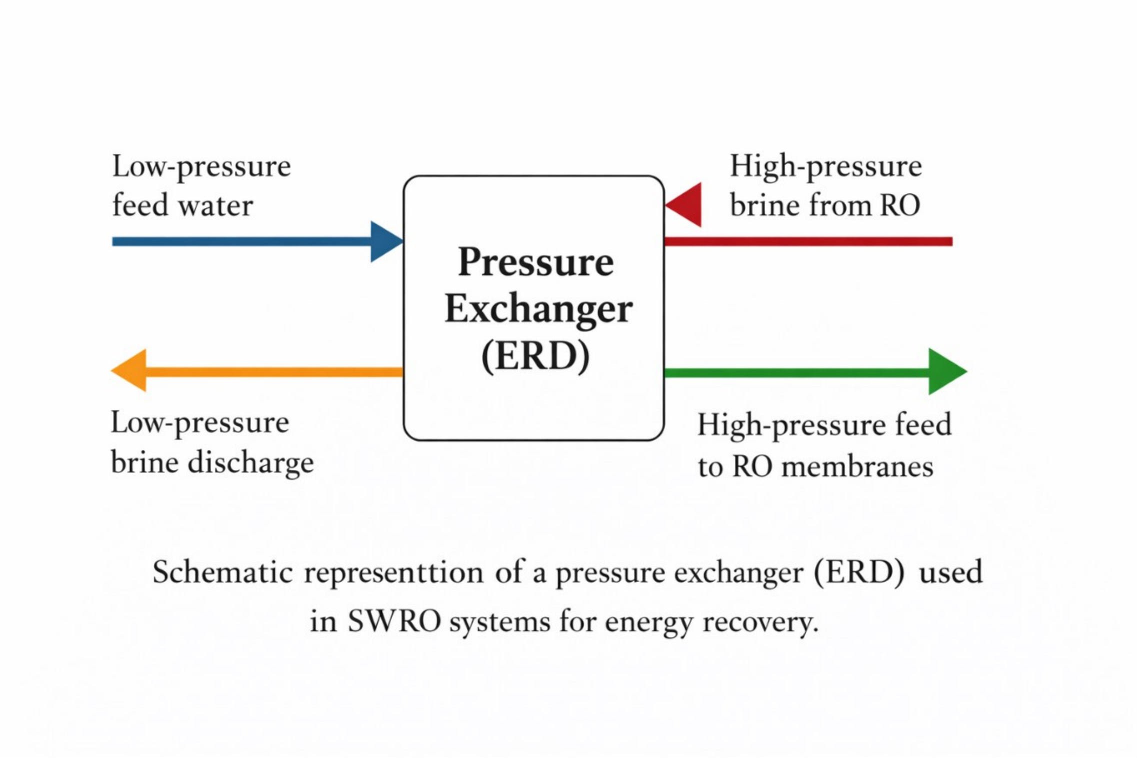


Figure 6.4 – Schematic representation of a pressure exchanger (ERD) showing the transfer of hydraulic energy from the high-pressure brine stream to the incoming feed water.

This mechanism significantly reduces the net power required by the high-pressure pump. As discussed in Section 6.7, while the gross hydraulic power demand of the high-pressure system can exceed 190 kW, the effective electrical demand is reduced to approximately 40–60 kW when high-efficiency ERDs are employed.

The integration of the ERD plays a key role in achieving the target specific energy consumption of 1.8–2.0 kWh/m³ and directly contributes to lowering both operational costs and overall system energy demand.

In addition, the reduced electrical load resulting from ERD integration has a direct impact on the sizing of the photovoltaic and battery systems, enabling a more compact and economically feasible renewable energy configuration.

As a result, the reduced plant demand improves the feasibility of renewable integration and simplifies the overall energy management strategy.

Despite the high PV contribution, a grid connection is maintained to ensure continuous and reliable plant operation. Approximately **15%** of the annual electricity demand is expected to be supplied by the grid, particularly during periods of low solar generation or increased demand.

Priority is given to on-site consumption of the PV-generated electricity in order to directly offset the plant's operational energy demand. Nevertheless, a fraction of the generated energy may not be immediately consumed.

Assuming that approximately **10–15%** of the PV production is exported, the surplus energy can be estimated as:

$$E_{surplus} \approx 0.12 \times 560{,}000 \approx 67{,}000 \text{ kWh/year}$$

Parameter	**Value**
Annual demand	657,000 kWh
PV production	~560,000 kWh
PV contribution	~85%
Grid contribution	~15%
Surplus energy	~67,000 kWh

Table 6.11 – Summary of Energy Balance of the SWRO-PV-BESS System

6.8.4 Final Remarks

The proposed hybrid PV–BESS–grid configuration provides a balanced solution between energy autonomy, operational flexibility, and system reliability. The selected PV capacity allows the plant to cover the majority of its annual electricity demand through renewable energy, while the BESS enhances short-term stability and improves the utilization of on-site generation.

Overall, the system significantly reduces dependence on grid electricity and contributes to lowering the operational cost and environmental impact of the desalination process. The results obtained in this section establish a consistent basis for the subsequent economic and performance analyses.

6.9 Simulation Model of the SWRO Desalination Plant

The development of a simulation model represents a key step in the detailed design phase of the proposed SWRO desalination system. While the previous sections focused on the definition of process configuration, energy demand, and renewable energy integration, the simulation model provides a dynamic and quantitative framework to evaluate the overall system performance under realistic operating conditions.

The model was developed based on the process layout defined in the P&ID and the design assumptions introduced in the previous sections. Particular attention was given to maintaining consistency between the hydraulic, energetic, and operational aspects of the system. In addition, the modeling approach was aligned with the methodology described in the reference article provided by the supervisor, ensuring coherence with established research practices.

6.9.1 Modeling Approach and Objectives

The primary objective of the simulation model is to reproduce the behavior of the SWRO-PV-BESS system under different operating conditions and to evaluate the interaction between the desalination process and the energy supply system.

More specifically, the model aims to:

- estimate the electrical power demand of the SWRO unit as a function of operating conditions,
- evaluate the contribution of the photovoltaic system throughout the year,
- assess the role of the battery system in smoothing short-term fluctuations,
- and quantify the residual dependence on the electrical grid.

Rather than focusing on highly detailed component-level modeling, the approach adopted here is a **system-level simulation**, which captures the main physical and energy flows while maintaining a manageable level of complexity. This choice is particularly suitable for preliminary design and techno-economic assessment.

6.9.2 Process Representation

The desalination process was modeled using a simplified but physically consistent representation of the main system components:

- seawater intake and feed pumping,
- pretreatment and filtration,
- high-pressure pump and reverse osmosis membranes,
- energy recovery device (pressure exchanger),
- permeate production and brine discharge.

The RO unit was represented through its key operating parameters, including feed flow rate, recovery ratio, and specific energy consumption. Instead of explicitly modeling membrane transport phenomena, the process performance was defined using the target SEC range (1.8–2.0 kWh/m^3) derived from design assumptions and literature data.

The energy recovery device was incorporated as an efficiency factor that reduces the net electrical demand of the high-pressure section. This approach allows the model to account for the energy savings associated with modern pressure exchanger systems without introducing unnecessary complexity.

6.9.3 Energy System Integration

The energy subsystem includes three main components:

- the photovoltaic generator,
- the battery energy storage system,

- and the grid connection.

The photovoltaic production was modeled using annual average irradiation data for southern Italy, combined with the selected performance ratio. For simplicity, the PV output can be represented either as an average daily profile or as a normalized production curve scaled to the installed capacity.

The battery system was modeled using a simplified energy balance approach, in which charging and discharging are governed by the mismatch between PV production and plant demand. The battery operates within predefined limits of capacity and depth of discharge, and its role is to reduce short-term variability and increase self-consumption of PV energy.

The grid was treated as a backup energy source, supplying the residual demand not covered by PV and BESS.

6.9.4 Energy Balance Formulation

At each time step, the system is governed by a simple energy balance:

$$P_{load} = P_{PV} + P_{BESS} + P_{grid}$$

where:

- P_{load} is the plant electrical demand,
- P_{PV} is the instantaneous PV production,
- P_{BESS} is the battery charge/discharge power,
- P_{grid} is the power exchanged with the grid.

The model prioritizes the direct use of PV energy to supply the desalination process. When PV production exceeds the load, the excess energy is stored in the battery (subject to capacity limits) or exported to the grid. Conversely, when PV production is insufficient, the battery is discharged, and any remaining deficit is supplied by the grid.

6.9.5 Model Implementation

For the purpose of this study, the simulation model was developed as a simplified system-level framework based on a time-step energy balance approach. The model structure was formulated to represent the interaction between the SWRO plant electrical demand, photovoltaic power generation, battery charge/discharge behavior, and grid support.

Rather than focusing on a full numerical implementation, the objective at this stage was to establish a coherent and physically consistent modeling methodology suitable for preliminary engineering assessment and system design evaluation. This approach allows the main energy flows of the integrated desalination plant to be represented while maintaining an appropriate level of simplicity for a techno-economic feasibility study.

The proposed modeling framework can be readily implemented in common computational environments such as Excel, MATLAB, or Python in a subsequent development phase, depending on the desired level of temporal resolution and operational detail.

The simplified modeling approach assumes:

- the plant electrical load is approximately constant over the day,
- PV production follows a representative daily or monthly generation profile,
- battery operation is governed by energy balance constraints and storage limits,
- and the grid supplies any residual unmet demand while receiving possible surplus electricity.

This level of modeling is adequate to estimate:

- annual energy flows,
- photovoltaic self-consumption,
- battery utilization trends,
- residual grid dependency,
- and the overall contribution of renewable energy to plant operation.

Accordingly, the model provides a practical basis for evaluating the integrated SWRO–PV–BESS configuration and for supporting future detailed numerical implementation, optimization, and operational analysis studies.

6.9.6 Model Limitations and Assumptions

The proposed model is intended for preliminary design and feasibility assessment. Consequently, several simplifying assumptions were adopted in order to maintain a manageable and transparent system-level representation.

The main assumptions include:

- constant operating conditions of the SWRO unit,
- neglect of short-term hydraulic transients and startup effects,
- simplified representation of photovoltaic generation profiles,
- aggregated treatment of auxiliary electrical loads,
- and simplified battery charge/discharge control logic.

These assumptions are considered acceptable for the present stage of analysis, where the objective is to evaluate annual energy flows, renewable energy contribution, and overall grid dependency rather than detailed dynamic plant behavior.

Although a full dynamic simulation is beyond the scope of this work, the proposed framework provides a reliable and physically consistent basis for future numerical implementation and more advanced operational studies.

6.9.7 Final Remarks

The modeling framework developed in this work establishes a coherent link between process design, plant energy demand, and renewable energy integration. It allows the proposed SWRO–PV–BESS system to be evaluated as an integrated configuration rather than as a set of independent components.

This system-level perspective is essential for understanding the expected performance of the plant and for supporting subsequent techno-economic and optimization analyses.

Although simplified, the proposed model provides a practical engineering tool for estimating annual energy distribution, photovoltaic contribution, battery utilization, and residual dependence on the electrical grid.

Overall, the framework developed in this section forms a consistent basis for future detailed simulation, optimization, and operational refinement of the proposed desalination system.

6.10 Future Perspectives: Blue Energy Integration

In addition to conventional energy recovery systems, the high-salinity brine stream produced by reverse osmosis desalination plants may represent a promising and largely untapped source of potential energy. This concept, commonly referred to as salinity gradient energy or blue energy, is based on the exploitation of the chemical potential difference between two solutions with different salt concentrations.

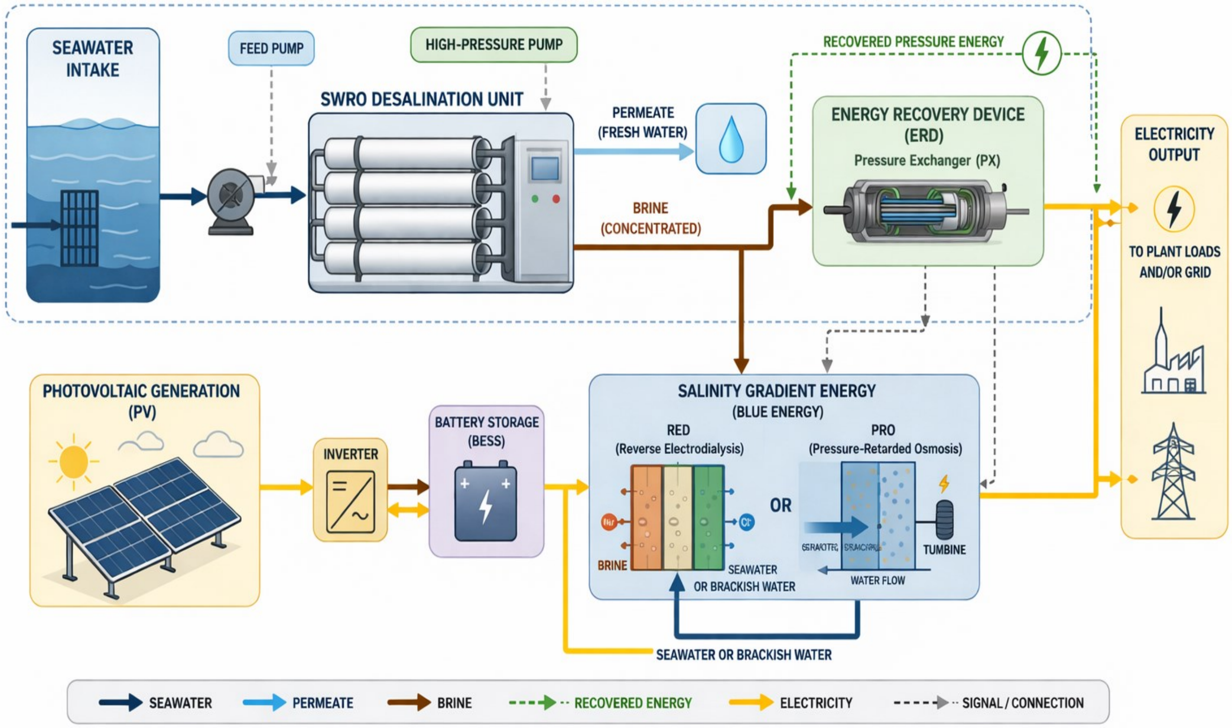
In the proposed SWRO system, the brine stream is characterized by a high salinity and a flow rate of approximately 50.92 m^3/h. This combination suggests that the plant is not only an energy consumer but may also have the potential to act, in a future development stage, as a secondary energy producer.

It should be emphasized that the integration of blue energy technologies is not included in the base-case design of the proposed system, but is considered as a potential future development.

Among the available technologies, reverse electrodialysis is considered one of the most promising approaches. In RED systems, alternating cation- and anion-exchange membranes are used to separate two streams with different salinity levels, generating an electrochemical potential that can be converted into electrical energy. RED systems are particularly attractive because they can operate continuously and independently of weather conditions.

Another relevant technology is pressure-retarded osmosis. In PRO, a semi-permeable membrane separates a low-salinity solution from a high-salinity solution. Water naturally flows toward the more concentrated stream due to osmotic pressure, generating a hydraulic pressure increase that can be used to drive a turbine and produce electricity. Although PRO systems are technically more complex and are still under development, they offer significant potential for large-scale energy recovery.

The overall integration of desalination and energy systems is schematically illustrated in **Figure 6.5**.



Conceptual integration integration of SWRO desalination with photovoltaic generation, battery storage, energy recovery devices (ERD), and salinity gradient energy systems (RED/PRO), illustrating the transition from energy consumption to integrated energy production.

Figure 6.5 – Conceptual integration of the SWRO desalination system with photovoltaic (PV) generation, battery energy storage (BESS), energy recovery device (ERD), and salinity gradient energy technologies (RED/PRO), illustrating the transition from energy consumption to integrated energy production and electricity supply to plant loads and/or the grid.

Conventional ERDs such as pressure exchangers reduce the net energy consumption of the SWRO process, whereas salinity-gradient technologies offer the possibility of converting residual chemical energy into usable electricity. Overall, the integration of salinity-gradient energy technologies represents a forward-looking strategy for enhancing the sustainability of desalination systems. Although not essential for the current design, it highlights the potential evolution of

SWRO plants from pure energy consumers toward hybrid energy systems with partial energy recovery and production capabilities.

A relevant example of this approach is provided by recent circular desalination initiatives in Europe, in which brine is no longer treated solely as a waste stream but rather as a resource for additional energy generation and mineral recovery. In particular, the SEArcularMINE project illustrates how desalination brine can be further utilized for salinity-gradient energy production as well as for the recovery of valuable minerals such as magnesium and lithium [26].

From a system design perspective, the integration of blue energy technologies in the proposed plant can therefore be considered as a future development stage. Although not included in the base-case energy balance, the available brine flow and salinity indicate that additional energy recovery beyond the current ERD configuration may be feasible.

A preliminary estimate suggests that salinity-gradient technologies such as RED or PRO could potentially generate additional electrical power on the order of 5–15 kW, depending on system efficiency and operating conditions. Although this contribution is relatively small compared with the total plant demand, it may still partially offset the net electrical load and improve the overall energy efficiency of the system.

Overall, the combined use of photovoltaic generation, pressure exchanger energy recovery, and future salinity-gradient technologies represents a forward-looking strategy for sustainable desalination. This integrated approach reduces energy consumption, creates opportunities for supplementary energy production, and improves both the environmental and economic performance of the proposed system.

7. Economic Analysis of the SWRO–PV System

The economic performance of the proposed SWRO desalination system was evaluated by considering both capital expenditures (CAPEX) and operational expenditures (OPEX), with particular attention to the integration of photovoltaic (PV) generation and battery energy storage. The adopted design assumptions and system configuration are aligned with typical medium-scale industrial SWRO plants, ensuring that the proposed solution remains technically realistic and practically implementable.

The analysis builds upon the process design developed in Chapter 6. The plant is designed to produce approximately 350,000 m³/year of freshwater, with a specific energy consumption (SEC) in the range of 1.8–2.0 kWh/m³. Based on these values, the annual electrical energy demand is estimated to be between 630,000 and 700,000 kWh/year [9].

Under steady operating conditions, the average absorbed power of the plant is approximately 75–83 kW. However, a higher installed electrical capacity of 150 kW is considered for design and integration purposes. This distinction reflects the difference between actual operating demand and the capacity required to ensure system reliability, flexibility, and proper sizing of the electrical infrastructure and renewable energy components.

7.1 Capital Expenditure (CAPEX)

The total capital investment of the system includes the desalination plant, the photovoltaic installation, the battery storage system, and the associated infrastructure required for plant operation and grid connection.

The main cost components are estimated as follows:

SWRO system (pumps, ERD, pretreatment, post-treatment): €900,000 – €1,200,000

RO membranes and skids: €20,000 – €40,000

Photovoltaic system (430–450 kWp): €320,000 – €420,000

Battery Energy Storage System (1.25–2.25 MWh): €500,000 – €900,000

Civil works, engineering, grid connection, and EPC: €300,000 – €600,000

Based on these estimates, the total CAPEX of the proposed system ranges between approximately €2.0 million and €3.2 million.

These values are consistent with cost ranges reported for comparable SWRO desalination plants and hybrid renewable energy systems [2].

7.2 Operational Expenditure (OPEX)

The operational expenditure (OPEX) of the system includes routine maintenance, membrane replacement, chemical consumption, labor, and residual electricity costs.

Unlike conventional desalination plants that rely entirely on grid electricity, the integration of a photovoltaic system significantly reduces external energy dependence. However, energy costs are not eliminated but rather shifted from operational to capital expenditure through the investment in PV and battery storage systems.

As a result, the effective cost of energy is accounted for through the levelized cost of the installed energy infrastructure, rather than through direct electricity purchases.

The main OPEX components are estimated as follows:

Maintenance and membrane replacement: €120,000 – €180,000/year

Chemicals and consumables: €30,000 – €50,000/year

Personnel and operation: €50,000 – €80,000/year

Miscellaneous and administrative costs: €20,000 – €40,000/year

The total non-energy OPEX is therefore estimated in the range of €220,000 – €350,000 per year, which is consistent with values reported for medium-scale SWRO desalination plants [12].

7.3 Revenue from Surplus Electricity

The economic performance of the system is primarily driven by revenue from water production, with a secondary contribution from surplus electricity export.

Assuming an annual production of 350,000 m^3 and a conservative water selling price of 1.5 €/m^3, the annual revenue from water supply is approximately €525,000.

Due to the variability of solar generation, part of the electricity produced by the PV system is expected to exceed the instantaneous demand of the plant. Assuming that 10–15% of the total PV production is exported to the grid, the surplus energy is estimated at approximately 60,000–80,000 kWh/year.

At an electricity selling price of 0.16 €/kWh, this corresponds to an additional annual revenue of approximately €9,600–€12,800.

Although relatively modest compared to water revenue, this contribution provides an additional economic benefit and supports the integration of renewable energy systems [16].

7.4 Water Production Revenue and LCOA

The Levelized Cost of Water (LCOA) is used as a key indicator to assess the economic viability of the proposed system.

The LCOA is defined as:

LCOA = (CAPEX_ann + OPEX) / V_annual

For the present study, a representative scenario is considered with:

Total CAPEX = €2.6 million

Project lifetime = 20 years

Discount rate = 6%

The annualized CAPEX is approximately €189,000/year. Combined with an average OPEX of €250,000/year, the total annual cost becomes approximately €439,000/year.

This results in:

LCOA ≈ 1.25 €/m^3

This value falls within the range reported for SWRO desalination systems in Mediterranean regions and confirms the economic competitiveness of the proposed configuration [18].

8. Overall Conclusions

This thesis presented the integrated design and preliminary techno-economic assessment of a seawater reverse osmosis (SWRO) desalination system coupled with renewable energy technologies. The work was developed following a structured engineering approach, starting from process definition and system configuration, and progressively incorporating energy analysis, renewable integration, simulation modeling, and economic evaluation.

From a process perspective, the proposed plant was designed to produce 1,000 m³/day of freshwater under representative Mediterranean conditions. A recovery ratio of 45% and a target specific energy consumption (SEC) of 1.8–2.0 kWh/m³ were adopted, ensuring consistency with modern industrial SWRO systems. The inclusion of a pressure exchanger (ERD) was identified as a key design choice, significantly reducing the net electrical demand of the high-pressure section and enabling an overall efficient plant operation.

The electrical analysis demonstrated that the actual absorbed operating power of the system is approximately 75–83 kW, corresponding to an annual electricity demand of about 657,000 kWh. At the same time, a nominal installed electrical capacity of 150 kW was retained as a conservative design basis for system integration. This distinction proved essential in bridging the gap between process-level energy requirements and the sizing of electrical and renewable energy infrastructure.

Building on this energy framework, a hybrid power supply configuration was developed. The photovoltaic system was sized at approximately 433 kWp, allowing the plant to cover around 85% of its annual electricity demand through on-site renewable generation. The integration of a battery energy storage system (BESS), with a nominal capacity of 1.25–2.25 MWh, further enhanced system flexibility by enabling peak shaving, improving PV self-consumption, and mitigating short-term fluctuations in solar production.

The simulation model provided a system-level representation of the interaction between the desalination process and the energy supply components. Although simplified, it offered valuable insight into the distribution of energy flows, the role of storage, and the dependence on grid electricity. The results confirmed that the proposed PV–BESS–grid configuration can ensure reliable operation while substantially reducing external energy requirements.

In addition to the core design, the thesis explored the potential integration of salinity-gradient energy technologies as a future development pathway. While not included in the base-case configuration, the analysis highlighted the possibility of recovering additional energy from the high-salinity brine stream through technologies such as reverse electrodialysis (RED) and pressure-retarded osmosis (PRO). This forward-looking perspective emphasizes the evolving role of desalination plants as part of broader sustainable energy systems.

From an economic standpoint, the proposed system demonstrated promising performance. The total capital investment was estimated in the range of €2.0–3.2 million, with annual operational costs between €220,000 and €350,000. Under a representative scenario, the levelized cost of water (LCOA) was calculated to be approximately 1.25 €/m³, confirming the economic feasibility of the proposed configuration within the Mediterranean context. The integration of PV generation significantly contributes to reducing long-term energy costs, while additional revenues from surplus electricity export provide a secondary economic benefit.

Overall, the results of this study show that the integration of SWRO desalination with renewable energy systems represents a technically feasible and economically competitive solution for sustainable water production. The combined use of photovoltaic generation, energy storage, and advanced energy recovery technologies enables a substantial reduction in energy consumption and environmental impact, while maintaining operational reliability.

Beyond the specific case analyzed, this work highlights the importance of adopting an integrated design approach in desalination engineering, where process performance, energy systems, and economic considerations are addressed simultaneously. Such an approach is essential to meet the growing demand for water in a context of increasing energy constraints and environmental challenges.

Future developments may include the refinement of the simulation model through dynamic analysis, the validation of system performance using real operational data, and the detailed techno-economic assessment of advanced energy recovery technologies such as RED and PRO. These steps would further enhance the accuracy of the design and support the transition toward next-generation sustainable desalination systems.

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