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Comparative Performance Analysis of Multi-Stage Flash (MSF) and Multi-Effect Desalination (MED) Seawater Desalination Systems Using Exergy Analysis and Economic Evaluation

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مقارنة أداء نظامي تحلية مياه البحر بالتبخير الوميضي متعدد المراحل (MSF) والتحلية بالتبخير متعددة التأثيرات (MED) بإستخدام التحليل الإكسيرجي والتقييم الإقتصادي

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Abstract:
Freshwater scarcity is one of the most pressing and increasingly critical global challenges driven by population growth, industrial expansion, and climate change This has made seawater desalination a strategic solution for providing sustainable water resources, particularly in arid and semi-arid regions This study aims to conduct a comprehensive comparison between Multi-Stage Flash (MSF) and Multi Effect Desalination (MED) systems through thermal, energy, exergy, and economic analyses, using simulation models developed in Aspen Plus for a nominal production capacity of (1,000 m³/h) Identical operating conditions were applied to ensure a consistent and fair comparison The simulation results showed that the (MED) system provides superior thermal performance and more efficient utilization of thermal energy as a result of the reuse of latent heat between successive effects, leading to reduced steam consumption and improved utilization of thermal energy On the other hand, the exergy analysis indicated that the (MSF) system achieved higher exergy efficiency and a lower exergy destruction rate than the (MED) system within the investigated feed water temperature range, with the performance of both systems improving as the feed water temperature increased The results also showed that the water recovery ratio of the (MSF) system remained higher than that of the (MED) system over the investigated salinity range, while increasing the feed water temperature improved the recovery ratio of the (MED) system and resulted in converging performance between the two systems at higher temperatures From an economic perspective, the (MSF) system clearly outperformed the (MED) system under the economic scenario considered, achieving higher Net Present Value (NPV), Annual Rate of Return (ARR), and Profitability Index (PI), in addition to a shorter capital payback period Accordingly, the findings indicate that the selection of desalination technology depends on the evaluation criterion and operating conditions (MED) represents a suitable option when priority is given to thermal efficiency and reducing thermal energy consumption, whereas (MSF) provides better exergy and economic performance according to the present results, together with high operational stability These findings provide a basis for multi-criteria decision-making in the design and selection of large-scale thermal desalination systems.

Keywords: Seawater desalination; MSF; MED; Aspen Plus; Exergy analysis; Economic evaluation.

الملخص:
تُعد ندرة المياه العذبة من أبرز التحديات العالمية المتزايدة نتيجة النمو السكاني والتوسع الصناعي والتغيرات المناخية، مما جعل تحلية مياه البحر أحد الحلول الاستراتيجية لتوفير مصادر مياه مستدامة، ولا سيما في المناطق الجافة وشبه الجافة تهدف

هذه الدراسة إلى إجراء مقارنة شاملة بين نظامي التقطير الوميضي متعدد المراحل (MSF) والتقطير متعدد التأثيرات (MED) من خلال التحليل الحراري وتحليل الطاقة والإكسيرجي والتقييم الاقتصادي، باستخدام نماذج محاكاة تم تطويرها ببرنامج (Aspen Plus) لمحطة بطاقة إنتاجية اسمية تبلغ (1000 م³/ساعة) مع تطبيق ظروف تشغيل متماثلة لضمان عدالة المقارنة كما أظهرت نتائج المحاكاة أن نظام (MED) يتميز بأداء حراري أفضل وإستفادة أكثر كفاءة من الطاقة الحرارية نتيجة إعادة إستخدام الحرارة الكامنة بين التأثيرات المتتالية، مما يؤدي إلى تقليل إستهلاك البخار وتحسين الإستفادة من الطاقة الحرارية ومن ناحية أخرى أظهر تحليل الإكسيرجي أن نظام (MSF) حقق كفاءة إكسيرجية أعلى ومعدل هدر إكسيرجي أقل من (MED) ضمن نطاق درجات حرارة مياه التغذية المدروس، مع تحسن أداء النظامين عند إرتفاع درجة حرارة التغذية كما أظهرت النتائج أن نسبة إسترجاع المياه في (MSF) بقيت أعلى من (MED) ضمن نطاق الملوحة المدروس بينما أدى إرتفاع درجة حرارة التغذية إلى تحسين نسبة الإسترجاع في (MED) وتقارب الأداء بين النظامين عند درجات الحرارة المرتفعة أما من الناحية الإقتصادية، فقد تفوق نظام (MSF) بوضوح على (MED) ضمن السيناريو الإقتصادي المدروس، حيث حقق قيمًا أعلى لصافي القيمة الحالية (NPV) ومعدل العائد السنوي (ARR) ومؤشر الربحية (PI)، إضافة إلى فترة إسترداد رأس مال أقصر وعليه، تشير نتائج الدراسة إلى أن إختيار تقنية التحلية يعتمد على معيار التقييم وظروف التشغيل؛ إذ يمثل (MED) خيارًا مناسبًا عند إعطاء الأولوية للكفاءة الحرارية وتقليل إستهلاك الطاقة الحرارية، في حين يوفر (MSF) أداءً إكسيرجيًا وإقتصاديًا أفضل وفق النتائج الحالية، إلى جانب إستقرار تشغيلي مرتفع وتوفر هذه النتائج أساسًا لإتخاذ قرار متعدد المعايير عند تصميم وإختيار أنظمة التحلية الحرارية واسعة النطاق.

الكلمات المفتاحية: : تحلية مياه البحر؛ التبخير متعددة التأثيرات ؛ التبخير الوميضي متعدد المراحل ؛ برنامج (Aspen Plus) تحليل الإكسيرجي؛ ؛ التقييم الإقتصادي.

I. Introduction

More than billions of people are facing increasing pressure on water resources as a result of population growth, industrial expansion, and climate change, leading to a continuous decline in the availability of naturally occurring freshwater [1]. In this context, seawater desalination has become an essential strategic option for securing sustainable water resources, particularly in arid and semi-arid regions that rely heavily on non-conventional water resources [2]. Thermal desalination technologies are among the most widely used technologies in large-scale plants due to their high reliability and ability to operate under harsh operating conditions. Among these technologies, Multi-Stage Flash (MSF) and Multi-Effect Desalination (MED) have emerged as two major options for large-scale industrial desalination plants [3]. The (MSF) system is based on heating seawater to a relatively high temperature and subsequently passing it through multiple stages operating at progressively lower pressures, resulting in flash vaporization. Despite its high reliability and long operational lifetime, (MSF) is considered one of the more energy-intensive thermal desalination technologies because of the large temperature differences between stages and the resulting high levels of thermodynamic irreversibility [4]. This process enables effective reuse of latent heat, significantly improving energy recovery and reducing external steam consumption Recent studies indicate that (MED) is more efficient than (MSF) in terms of thermal energy consumption and offers greater potential for integration with low-grade energy sources and waste heat The assessment of desalination system [5,6]. performance is not limited to conventional energy analysis Exergy analysis has become an essential tool for evaluating energy quality and identifying the locations of energy losses and irreversibility's within a system This analysis enables the determination of the amount of energy that can potentially be converted into useful work, thereby providing a more accurate assessment of actual system performance compared with conventional energy analysis [7]. In addition, economic feasibility has become a decisive factor in selecting an appropriate desalination technology as the cost of water production depends on energy consumption, operation and maintenance costs, and capital investment. Therefore, integrated techno-economic analysis is employed to evaluate the overall performance of desalination systems Recent studies have shown that (MSF) and (MED) technologies continue to represent an important share of global desalination capacity; however, current research trends focus on improving efficiency, reducing energy consumption, and integrating desalination systems with renewable energy sources [8]. Nevertheless, most previous studies have not employed unified detailed simulation models or comprehensive analyses combining energy, exergy, and economic assessments under identical operating conditions [9].

2. Objectives of the Study:

- To compare the thermal and energy performance of (MED) and (MSF) systems at a production capacity of (1,000 m³/h).
- To evaluate the effects of feed water salinity and temperature on exergy efficiency and exergy destruction.
- To compare the water recovery ratio and the specific thermal and electrical energy consumption.
- To evaluate the economic performance using (NPV), (ARR), (PI), and (PBP).
- To provide a multi-criteria basis for selecting the appropriate desalination technology.

3. Operating Principles of Desalination Systems:

3.1 Multi-Stage Flash (MSF):

In the (MSF) system, seawater is initially preheated and then directed to the heating section, where its temperature is increased using an external heat source The heated seawater subsequently passes through a series of stages operating at progressively decreasing pressures. In each stage, a portion of the water undergoes flash vaporization The generated vapor then condenses on heat-transfer surfaces to produce desalinated water, while the remaining brine continues to subsequent stages [16].

3.2 Multi-Effect Desalination (MED):

The (MED) system consists of a series of effects operating at progressively decreasing temperatures and pressures Seawater is distributed over heat-transfer surfaces, and external steam is used to supply heat to the first effect The vapor generated in the first effect is subsequently utilized to supply heat to the second effect, and the process is repeated throughout the successive effects. This configuration enables the reuse of latent heat and reduces the external steam demand [17].

3.3 Comparative Characteristics of the Two Systems:

Table (1): Comparison of the characteristics of the two systems [10].

Standard	(MSF)	(MED)
Evaporation mechanism	Flashing evaporation	Evaporation via cascading effects
Heat reuse	Intra-Phase and Solution Cycle	Reuse of Latent Heat
Reported Thermal Performance	Higher heat consumption	Lower specific steam consumption
Exergy result in this study	Higher Exergy Efficiency	Lower Elixirgy Efficiency
Economic Outcome	More convenient	Less convenient

4. Methodology:

This study employs a scientific methodology combining theoretical analysis and computer-based simulation to evaluate the performance of different desalination technologies. The study is conducted through a systematic sequence of steps designed to achieve the research objectives accurately Initially a comprehensive review of the scientific literature and previous studies related to desalination technologies was conducted to identify the principal models and equations used to analyze the performance of different desalination plants Subsequently, simulation models of the desalination plants were developed using Aspen Plus, an advanced software platform widely used for the simulation of chemical and thermal processes and for analyzing the effects of different operating variables.

4.1 Aspen plus Modeling:

In this study, Aspen Plus was used to model and simulate the two thermal desalination systems, namely Multi-Stage Flash (MSF) and Multi-Effect Desalination (MED) The software was selected because of its high capability to represent thermal equilibrium, phase separation, heat transfer, and energy-integration processes in complex industrial systems The (MSF) model was developed as a series of flash stages operating at progressively decreasing pressures, whereas the (MED) model was developed as a series of effects operating at progressively lower temperatures and pressures Appropriate thermos physical property models for seawater were employed to ensure accurate representation of the behavior of the saline solution.

4.2 Operating Conditions:

Table (2): Operating conditions used for the desalination plants [16].

Variable	Value Used in the Study
Production capacity	1000 m³/h
Feedwater temperature	14–30 °C
Seawater salinity	35,000 ppm
Inlet steam temperature	90–110 °C
(MSF) stages	According to standard industrial stage design basis
(MED) effects	Selected according to thermal-efficiency considerations
Stages/Effects	Through progressively decreasing pressure

4.3 Exergy Analysis of (MED) and (MSF):

Table (3): Exergy analysis of the (MED) and (MSF) plants [10].

The energy balance for the (MSF) system is expressed	Q̇_input = (Q̇_evaporation) + (Q̇_loss)
The exergy balance	x_in = (Ėx_product) + (Ėx_brine) + (Ėx_destruction)
The exergy efficiency of the (MSF)	η_ Ėx = (Ėx_product) / (Ėx_thermal)
The exergy destruction rate in the (MSF)	Ėx_D,MSF = T0*(Ṡ gen)
The exergy associated with heat is expressed	Ėx_heat = Q* (1-T0/T)
The exergy balance for the (MED) system	Ėx_steam + Ėx_feed = (Ėx_product) + Ėx_brine) + (Ėx_loss)
The exergy efficiency of the (MED)	η _ Ėx = (Ėx_product) / (Ėx_steam)
Elixirgy rate and energy wasted in the (MED)	Q̇ loss = (Q̇ in) - (Q̇ usefu)

4.4 Economic Analysis of (MED) and (MSF):

Net Present Value (NPV) was calculated using Equation (1) [11]:

$$NPV = \sum_{t=0}^{n} \frac{R_t - C_t}{(1+r)^t} \quad \ldots\ldots\ldots (1)$$

Internal Rate of Return (IRR) was calculated using Equation (2) [12]:

$$0 = \sum_{t=0}^{n} \frac{R_t - C_t}{(1+IRR)^t} \quad \ldots\ldots\ldots (2)$$

Simple Payback Period (PBP) was calculated using Equation (3) [12]:

$$PBP = \frac{I_0}{CF_{\text{annual}}} \quad \ldots\ldots\ldots (3)$$

Discounted Payback Period was calculated using Equation (4) [13]:

$$0 = \sum_{t=0}^{T} \frac{R_t - C_t}{(1+r)^t} \quad \ldots\ldots\ldots (4)$$

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5. Model Validation:

5.1 Validation of the (MSF) Model:

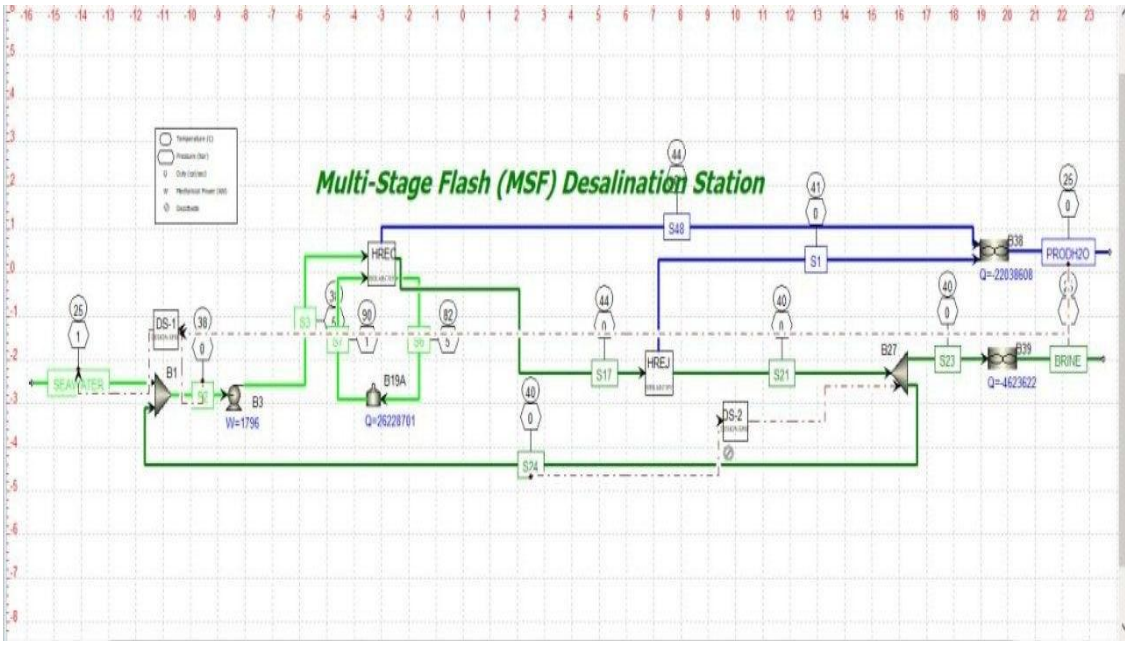

Figure (1): Simulation of the Multi-Stage Flash (MSF) technology using (Aspen Plus)

The accuracy of the simulation model for the (MSF) desalination plant developed using Aspen Plus was validated by comparing the model results, as shown in Figure (1), with the design and operating data of the AZ-Zour South Desalination Plant reported in previous studies The effects of steam temperature and the number of stages on production capacity and energy-use efficiency were investigated. The results showed that increasing the steam temperature by 2°C resulted in an approximately 5% increase in production, which is consistent with the thermal principles governing flash desalination processes. It was also found that increasing the number of stages improves heat-recovery efficiency and reduces thermal losses, thereby positively affecting the overall system efficiency The results showed that implementing effective heat-recovery strategies can improve energy efficiency by up to 12%, representing an important factor in reducing the overall energy consumption of the plant [14].

Table (4): Model inputs for the AZ-Zour South Desalination Plant [14].

Design and operational data of AZ-Zour South Desalination Plant		
Process Variable	**Specifications**	**Units**
Distillate Produced	18.795	T/min
Recycle Brine Flowrate	2.3477	T/min
Seawater rejected flowrate	238.1	T/min
Blowdown flowrate	160.48	T/min
Make-up flowrate	29.96	T/min
Top brine temperature	48.757	°C
Seawater inlet temperature to the heat-rejection section	90	°C
LP Steam temperature to the brine heater	100	°C

Table (5): Comparison of plant performance with the design model [14].

Variable Performance	Aspen Plus Model Results	AZ-Zour Plant Design Specifications	Error (%)
Top Brine Temperature (°C)	90	90.56	0.6
Distillate Produced (T/min)	18.808	18.795	0.5

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5.2 Validation of the (MED) Model:

With the increasing demand for freshwater resulting from population growth and economic expansion, many regions around the world are experiencing increasing shortages of water resources Despite the abundance of water on Earth's surface, only approximately 0.3 % is directly suitable for drinking, while the remaining water is predominantly present as saline water in oceans and seas and in ice caps Estimates indicate that by 2050, approximately 6 billion people may experience water scarcity, making seawater desalination a strategic and essential solution for meeting future water demands [15]. Multi-Effect Desalination (MED) is one of the most efficient thermal desalination technologies. It is based on heating seawater using an external heat source and processing it through multiple successive effects In the first effect, seawater is heated using a heat source such as steam or exhaust gases, causing water to vaporize while the salts remain in the brine The process continues through the successive effects with progressively decreasing pressure and temperature to improve thermal efficiency The thermodynamic performance of the system can be enhanced using a vacuum pump or compressor to maintain the pressure gradient between the effects, which also facilitates the removal of non-condensable gases and residual vapor. The pressure difference between successive effects is a key factor in achieving high efficiency, with typical values ranging from 5 to 50 kPa. System performance is commonly evaluated using the Gain Output Ratio (GOR), which represents the ratio of freshwater production to steam consumption in the system [15].

Table (6): Inputs and flow-simulation results for the Multi-Effect Desalination (MED) plant [15].

(MED)	Seawater	Steam in	Product Water	Brine
Temperature (°C)	28	305	36.09	36.47
Pressure (Bar)	3	5	0.06	0.06
Mass Vapor Fraction	0	1	0.00	0.03
Mass Liquid Fraction	1	0	1.00	0.97
H2O (kg/sec)	127.78	9.7	51.24	76.00
Mass Fractions	1	1	1	1
H2O (kg/sec)	0.965	1	1	0.94
sailinty	0.035	0	0	0.062
Mass Density (kg/cum)	907.59	1.87	2.00	1.48
Status	Call	Call	Call	Call

Table (7): Validation results of the Multi-Effect Desalination (MED) plant model [15].

Parameters	Referenc	Model	Error (%)
Driving vapor(bar)	5	5	0
Seawater for one cell (ton/h)	460	460	0
Heating vapor in first effect (ton/h)	33	33	0
First effect temperature (°C)	70	70	0
Second effect temperature (°C)	63	64	1.58
Third effect temperature (°C)	57	58	1.75
Fourth effect temperature (°C)	51	51	0
Fifth effect temperature (°C)	45	46	2.22
Sixth effect temperature (°C)	40	42	5
Seventh effect temperature (°C)	35	36	2.85
plant capacity (M^3/Day)	4543	4427.1	2.55

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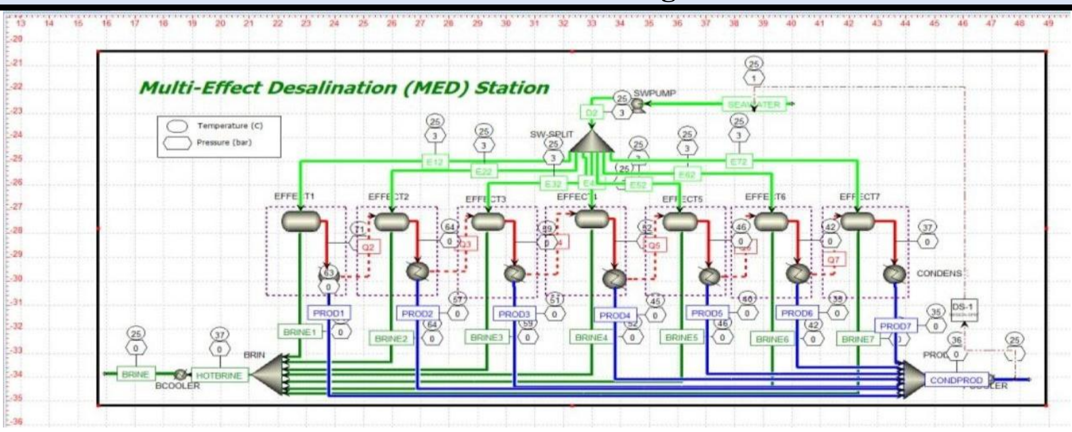

Figure (2): Units used for simulating the (MED) plant effect in (Aspen Plus)

6. Results and Discussion:

6.1 Overall Performance Comparison:

The simulation results obtained using Aspen Plus for both (MED) and (MSF) systems under identical operating conditions and a production capacity of (1,000 m³/h) demonstrate clear differences in thermodynamic and economic performance The (MED) system exhibits a clear advantage in thermal energy utilization efficiency due to the reuse of latent heat across multiple successive effects, whereas the (MSF) system exhibits higher thermal consumption and lower efficiency because of losses associated with the flashing process and thermal irreversibility.

6.2 Effect of Feed water Salinity on Exergy Efficiency and Exergy Destruction Rate of (MED) and (MSF) Desalination Plants:

Figure (3) illustrates the effect of feed water salinity (30 – 40) on exergy efficiency and exergy destruction for the (MED) and (MSF) plants The results show that the exergy efficiency of the (MSF) plant remained nearly constant at approximately 0.0255 (2.55%) whereas that of the (MED) plant was approximately 0.0216 (2.16%) across all investigated salinity values. Conversely, the (MED) plant recorded a higher exergy destruction of approximately 34 MW, compared with approximately 28.5 MW for the (MSF) plant. The stability of these values with increasing salinity indicates that the effect of feedwater salinity within the investigated range is limited, and that the exergy performance of both plants is more strongly dependent on operating and design conditions.

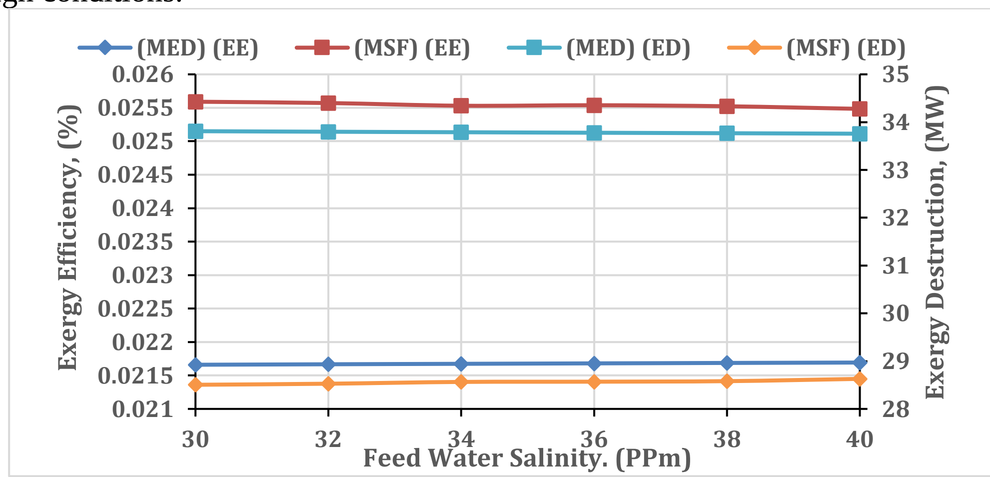

Figure (3): Effect of feed water salinity on exergy efficiency and exergy destruction rate of (MED) and (MSF) desalination plants.

6.3 Effect of Feed water Temperature on Exergy Efficiency and Exergy Destruction Rate of (MED) and (MSF) Desalination Plants:

Figure (4) illustrates the effect of feed water temperature (14 – 30°C) on the exergy efficiency and exergy destruction of the (MED) and (MSF) plants The results demonstrate a positive relationship between feed water temperature and exergy efficiency The exergy efficiency of the (MED) plant increased from approximately 0.018 at 14°C to approximately 0.024 at 30°C, while that of the (MSF) plant increased from approximately 0.020 to 0.028 over the same temperature range This behavior can be attributed to the improvement in the quality of the thermal energy supplied to the system and the reduction in irreversibility associated with heat transfer Consequently, a greater fraction of the available energy can potentially be converted into useful work, while exergy losses within the plant components are reduced Conversely, exergy destruction decreased significantly as the feed water temperature increased. For the (MED) plant, it decreased from approximately 40 MW to approximately 32 MW, while for the (MSF) plant it decreased from approximately 35 MW to approximately 26 MW This reduction indicates that increasing the feed water temperature reduces the temperature differences between the heat-transfer fluids, thereby decreasing entropy generation and consequently reducing exergy destruction in accordance with the fundamental principles of the second law of thermodynamics. As a result, thermal energy utilization is improved and the amount of available exergy contributing to actual desalinated water production increases It is also evident that the (MSF) plant achieved higher exergy efficiency and lower exergy destruction than the (MED) plant at all investigated temperatures This reflects the ability of the (MSF) system to utilize the available thermal energy more effectively as a result of its multi-stage heat-transfer configuration and recovery of a significant portion of the latent heat, thereby limiting thermal losses and improving the overall exergy performance of the system The study also demonstrates of the most important operating variables affecting the performance of thermal desalination plants. Optimal control of this parameter contributes to improving energy utilization efficiency, reducing exergy destruction and enhancing system productivity The present results indicate that the (MSF) plant exhibited a greater response to increasing feed water temperature than the (MED) plant, making it more exergy-efficient under the investigated operating conditions Nevertheless, the selection of optimum operating conditions should also account for economic and operational considerations, including fuel consumption, operating costs, and scaling and corrosion risks at elevated temperatures.

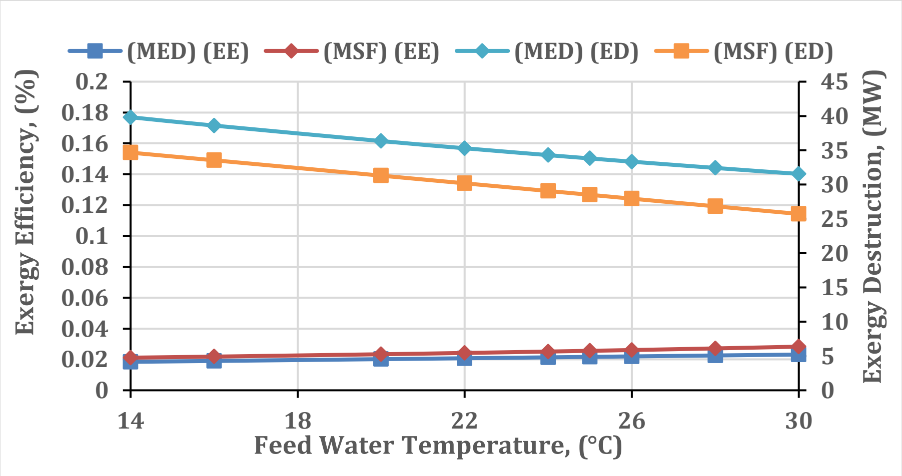

Figure (4): Effect of feed water temperature on exergy efficiency and exergy destruction rate of MED and MSF desalination plants.

6.4 Effect of Feed water Salinity on the Water Recovery Ratio (RR) of (MED) and (MSF):

Figure (5) illustrates the effect of feed water salinity (30 – 40 ppm) on the Water Recovery Ratio (RR) of the (MED) and (MSF) plants. The results show a slight increase in the recovery

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ratio of the (MED) plant from approximately 0.4635 at a salinity of 30 to 0.4655 at a salinity of 40, whereas the recovery ratio of the (MSF) plant decreased from approximately 0.4754 to 0.4730 over the same range Despite this variation, the recovery ratio of the (MSF) system remained higher than that of the (MED)

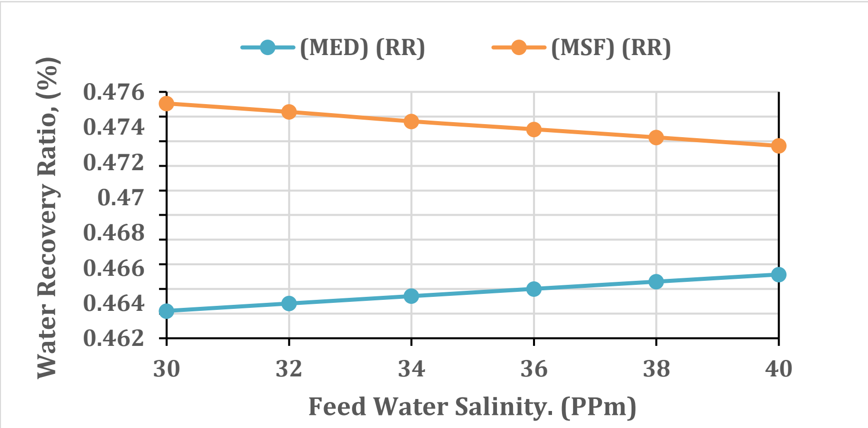

Figure (5): Effect of feed water salinity on the Water Recovery Ratio (RR) of (MED) and (MSF)

6.5 Effect of Feed water Temperature on the Water Recovery Ratio (RR) of (MED) and (MSF):

Figure (6) illustrates the effect of feed water temperature (14 – 30°C) on the Water Recovery Ratio (RR) of the (MED) and (MSF) plants The results show a gradual increase in the recovery ratio of the (MED) plant from approximately 0.40 at 14°C to approximately 0.48 at 30°C, whereas the recovery ratio of the (MSF) plant remained nearly constant at approximately 0.47–0. These results indicate that increasing feed water temperature significantly improves the recovery ratio of the (MED) system, while its effect on the (MSF) system is limited, reflecting the stability of plant performance within the investigated temperature range.

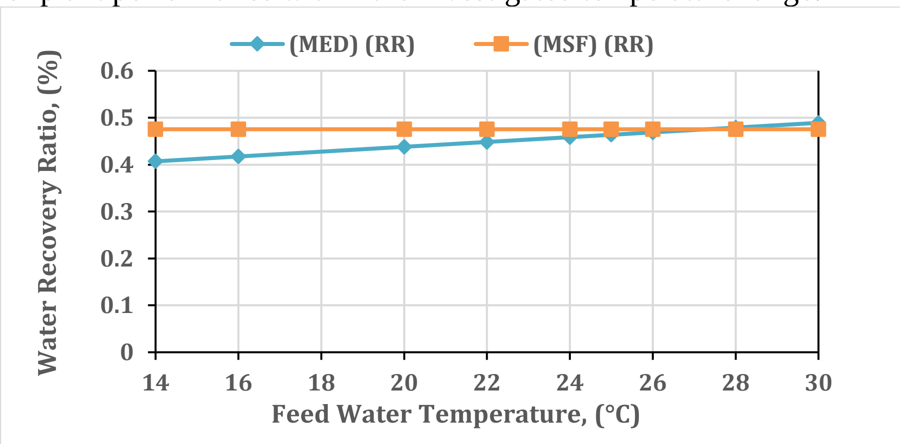

Figure (6): Effect of feed water temperature on the Water Recovery Ratio (RR) of (MED) and (MSF)

6.6 Effect of Increasing Feed water Salinity on Specific Energy Consumption (SER) and Specific Steam Consumption (SSU) of (MSF) and (MED) Desalination Technologies:

Figure (7) illustrates the effect of feed water salinity (30 – 40 ppm) on Specific Energy Consumption (SER) and Specific Steam Consumption (SSU) in the (MED) and (MSF) plants. The results show that increasing salinity did not significantly affect either indicator The (SER) of the (MED) plant remained approximately constant at 0.16 kWh/m³, while that of the (MSF) plant ranged between 1.77 and 1.79 kWh/m³ Similarly, the (SSU) of the (MED) plant remained close to 225 kg/m³, whereas it remained approximately 175 kg/m³ for the (MSF) plant

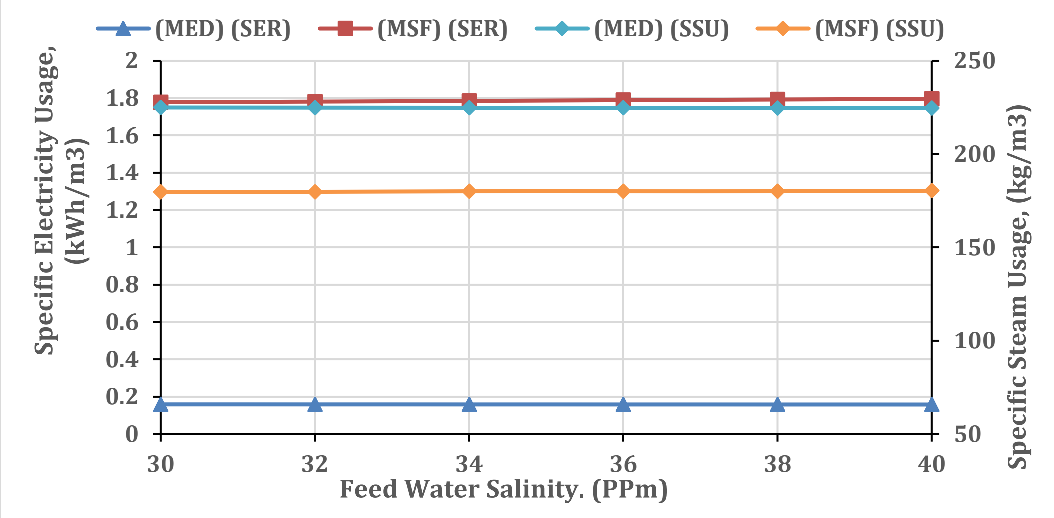

Figure (7): Effect of increasing feed water salinity on Specific Energy Consumption (SER) and Specific Steam Consumption (SSU) of (MSF) and (MED) desalination technologies.

6.7 Effect of Feed water Temperature on Specific Energy Consumption (SER) and Specific Steam Consumption (SSU) of (MED) and (MSF) Desalination Plants:

Figure (8) illustrates the effect of feed water temperature (14 – 30°C) on the energy performance of the (MED) and (MSF) plants using the Specific Energy Consumption (SER) and Specific Steam Consumption (SSU) indicators The results show that specific electricity consumption remained nearly constant for both technologies over the investigated temperature range, indicating that changes in feed water temperature do not directly affect electrical power consumption but have a greater influence on the thermal requirements of the system The (MSF) plant recorded substantially lower electricity consumption, approximately 0.02 kWh/m³, compared with approximately 0.18 kWh/m³ for the (MED) plant, corresponding to a reduction of approximately 88.9% This difference can be attributed to the operational configuration of the two systems The (MSF) plant relies primarily on thermal energy to accomplish the desalination process, whereas the (MED) plant requires a larger number of pumps for circulating seawater, return streams, and condensate, resulting in higher electrical energy consumption Regarding Specific Steam Consumption (SSU), the results showed an approximately linear decrease with increasing feed water temperature in both systems. This reflects improved utilization of the available thermal energy and a reduction in the amount of steam required to produce a unit volume of desalinated water. At a feed water temperature of 14°C, the (MED) plant recorded a steam consumption of 270 kg/m³ compared with 220 kg/m³ for the MSF plant, representing an increase of approximately 22.7%. As the feed water temperature was gradually increased to 30°C, steam consumption decreased to approximately 170 kg/m³ for (MED) and 160 kg/m³ for (MSF), representing reductions of approximately 37% and 27%, respectively. This reduction can be explained by the fact that increasing feed water temperature decreases the amount of heat required to reach the conditions necessary for vaporization. Consequently, the thermal load imposed on the main heater and process units is reduced It also improves heat recovery between the different stages, reduces thermal losses, and increases steam utilization efficiency, directly resulting in lower specific thermal energy consumption. It is also noteworthy that the difference in steam consumption between the two technologies decreased significantly as feed water temperature increased, from 22.7% at 14°C to only approximately 6.25% at 30°C. This indicates that the effect of feed water temperature becomes more pronounced in improving the performance of the (MED) plant compared with the (MSF) plant

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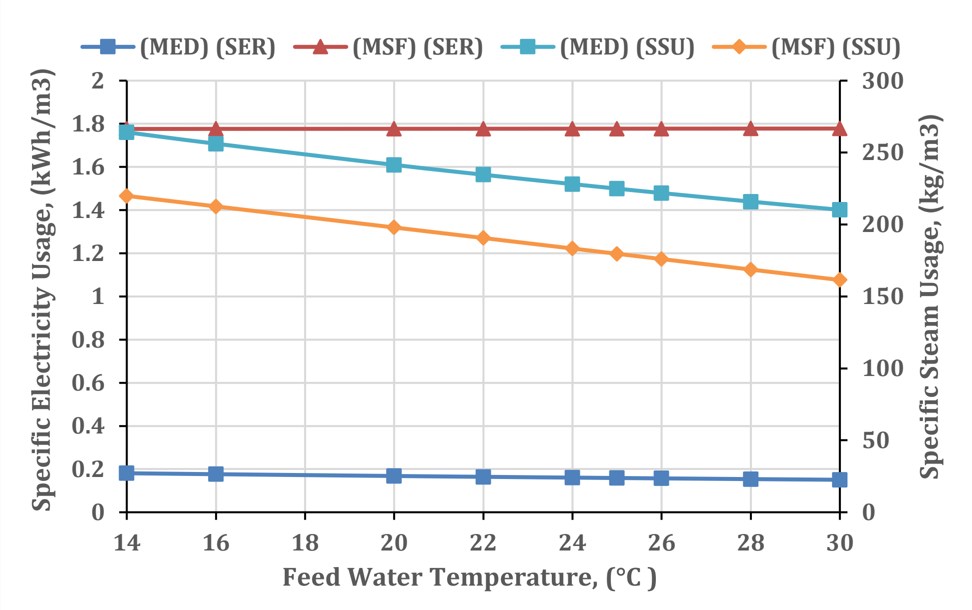

Figure (8): Effect of feed water temperature on Specific Energy Consumption (SER) and Specific Steam Consumption (SSU) of (MED) and (MSF) desalination plants.

7. Economic Analysis (LCOW):

7.1 Analysis of the Effect of Desalinated Water Selling Price on Net Present Value (NPV):

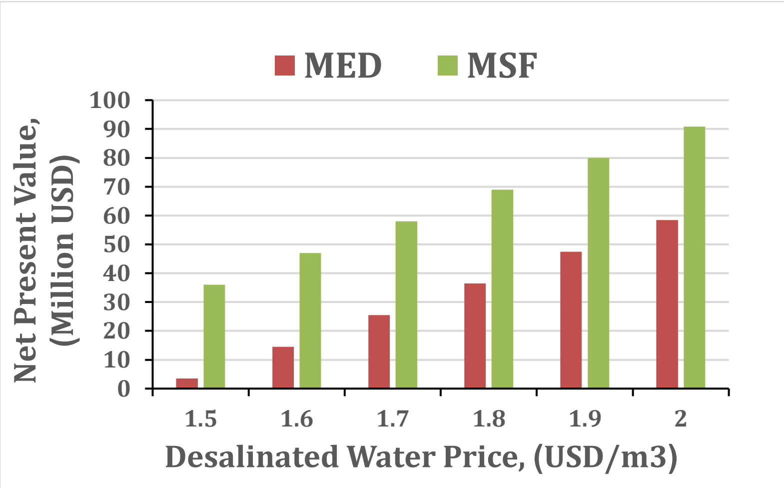

Figure (9): Effect of Desalinated Water Selling Price on Net Present Value (NPV)

Figure (9) presents the economic sensitivity analysis of the (MED) and (MSF) technologies as a function of the selling price of desalinated water The results show that the (NPV) increases linearly for both technologies as the selling price increases from 1.5 to 2.0 USD/m³, confirming improved economic feasibility at higher selling prices. In general, the (MSF) technology outperforms (MED) at all investigated selling-price levels. At the lowest price of 1.5 USD/m³, (MSF) achieves an (NPV) of USD 36 million compared with only USD 3 million for (MED), representing a twelve-fold difference. As the selling price increases to 2.0 USD/m³, the NPV reaches USD 91 million for (MSF) compared with USD 59 million for (MED) This superiority can be attributed to the lower electricity consumption of (MSF) as shown in Figure (9), which reduces operating costs and increases net returns The difference between the two technologies is USD 33 million at 1.5 USD/m³ and USD 32 million at 2.0 USD/m³ However, the percentage superiority of (MSF) decreases from 1100% to 54% because the (MED) (NPV) grows at a faster rate From an economic perspective, (MSF) is more feasible and profitable than (MED) over the investigated price range, particularly at low selling prices, which may not adequately cover the costs of (MED).

7.2 Analysis of the Effect of Desalinated Water Selling Price on Payback Period (PBP):

Figure (10) illustrates the inverse relationship between the water selling price and the capital payback period for the (MED) and (MSF) technologies Increasing the selling price from 1.5 to 2.0 USD/m³ significantly reduces the payback period for both technologies, reflecting improved economic feasibility at higher product prices (MSF) clearly outperforms (MED) in all cases. At a selling price of 1.5 USD/m³, (MSF) requires approximately 10 years to recover the investment cost, whereas (MED) requires approximately 23 years, which is more than twice the duration As the selling price increases to 2.0 USD/m³, the payback period decreases to approximately 6 years for (MSF) compared with 10 years for (MED) This superiority is attributed to the lower operating costs of (MSF) resulting from its lower electricity consumption, as shown in Figure (10), as well as its higher (NPV) It is noteworthy that (MSF) achieves a payback period of less than 10 years even at the lowest selling price, which is an acceptable investment threshold for many infrastructure projects, whereas (MED) reaches this threshold only at a selling price of 2.0 USD/m³ From the perspective of payback period and investment risk, (MSF) represents the better and lower-risk option compared with (MED), particularly under low or fluctuating selling-price conditions.

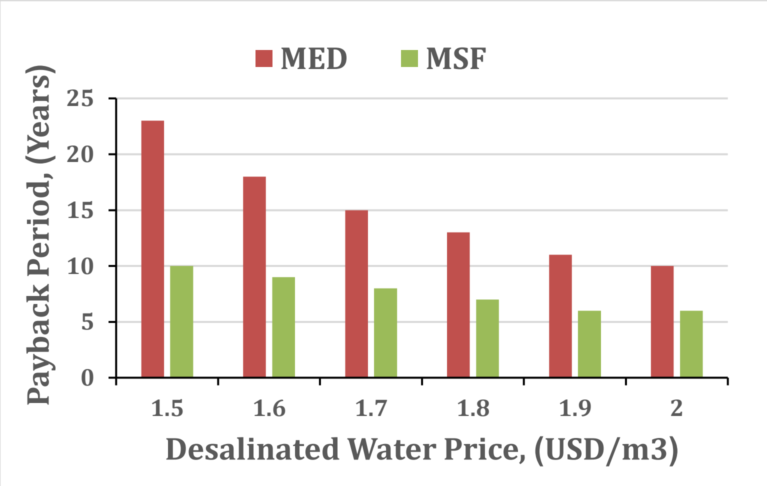

Figure (10): Effect of Desalinated Water Selling Price on Payback Period (PBP)

7.3 Analysis of the Effect of Desalinated Water Selling Price on Annual Rate of Return (ARR):

Figure (11) presents the effect of the desalinated water selling price on the Average Annual Rate of Return (ARR) for the (MED) and (MSF) technologies The (ARR) increases linearly with increasing selling price for both technologies, confirming that project profitability is highly sensitive to the final product price. The results demonstrate the clear superiority of (MSF) over (MED) at all investigated selling-price levels At 1.4 USD/m³, (MSF) achieves a return of 9.7%, compared with only 2.7% for (MED) As the selling price increases to 2.0 USD/m³, the ARR reaches 21.8% for (MSF) compared with 12% for (MED), meaning that (MSF) maintains an average return approximately 1.8 times higher than (MED) This trend is consistent with the (NPV) results presented in Figure (9) and the payback-period results shown in Figure (10) The main reason is the lower operating costs of (MSF) due to its lower electricity consumption It is important to note that (MED) does not exceed the 10% return threshold until the selling price reaches 1.9 USD/m³ or higher, whereas (MSF) exceeds this threshold starting at 1.4 USD/m³ In terms of profitability, (MSF) provides a higher investment return and lower risk, remaining

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economically feasible even at low selling prices at which (MED) does not achieve the minimum acceptable rate of return.

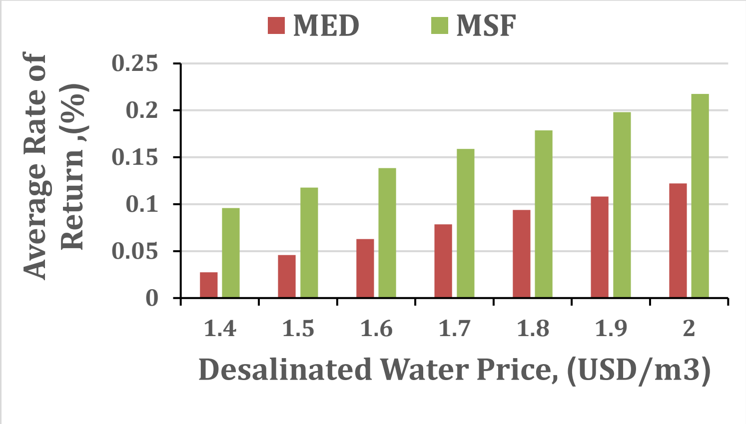

Figure (11): Effect of Desalinated Water Selling Price on Annual Rate of Return (ARR)

7.4 Analysis of the Effect of Desalinated Water Selling Price on Profitability Index (PI):

Figure (12) shows the relationship between the desalinated water selling price and the Profitability Index (PI) for the (MED) and (MSF) technologies The PI increases linearly with increasing selling price for both technologies, while MSF remains significantly superior to (MED) throughout the investigated range At a selling price of 1.4 USD/m³, the PI of (MSF) is approximately 1.65, meaning that each dollar invested generates USD 1.65, whereas (MED) records a PI of only 0.85, indicating that the project is not profitable at this price As the selling price increases to 2.0 USD/m³, the PI reaches 3.4 for (MSF) compared with 2.0 for (MED) Accordingly, (MSF) is more profitable by approximately 94% at 1.4 USD/m³ and 70% at 2.0 USD/m³ This result is consistent with the (NPV), (ARR), and payback-period results presented in the previous figures and is mainly attributed to the lower operating costs of (MSF) resulting from its lower electricity consumption. Therefore, the (PI) criterion confirms that MSF is an economically acceptable investment even at the lowest selling price, whereas (MED) becomes economically feasible only after the selling price exceeds 1.5 USD/m³.

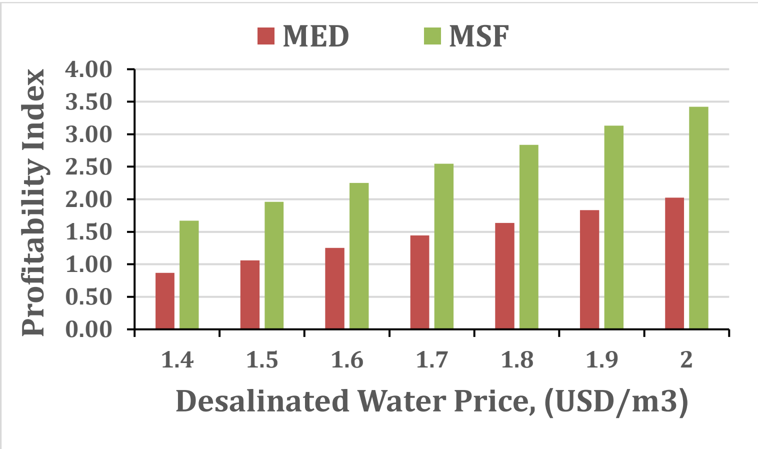

Figure (12): Effect of Desalinated Water Selling Price on Profitability Index (PI)

7. Conclusion:

This study presented a comprehensive comparison between the Multi-Stage Flash (MSF) and Multi-Effect Desalination (MED) thermal desalination systems based on thermal, energy, exergy, and economic analyses, with the aim of identifying differences in performance and evaluating the suitability of each technology under different operating conditions and economic criteria. The results demonstrated that the (MED) system provides superior thermal performance compared with (MSF) This is attributed to its ability to reuse the latent heat of steam between successive effects, thereby improving thermal-energy utilization and reducing thermal-energy demand under the operating conditions investigated. From an exergy perspective, the detailed results showed that (MSF) achieved higher exergy efficiency and lower exergy destruction than (MED) within the investigated feed water-temperature range The results also demonstrated that increasing the feed water temperature improves exergy efficiency and reduces exergy destruction in both systems, with a greater response observed for the (MSF) system. Regarding the water recovery ratio, (MSF) maintained a higher recovery ratio than (MED) as the feed water salinity varied within the investigated range Meanwhile, (MED) showed a notable improvement in recovery ratio as the feed water temperature increased, resulting in convergence between the performances of the two systems at higher temperatures From an economic perspective, the results showed that (MSF) outperformed (MED) under the economic scenario adopted in this study (MSF) achieved a higher (NPV) and a shorter payback period, in addition to a higher annual rate of return and profitability index across the investigated range of water selling prices For example, at a selling price of 2.0 USD/m³, the (NPV) of (MSF) reached approximately USD 91 million compared with USD 59 million for (MED), while the payback period was approximately 6 years for (MSF) compared with 10 years for (MED) Accordingly, neither technology can be considered universally superior; rather, the selection depends on the objective of the project. If thermal efficiency and effective utilization of thermal energy are the priorities, (MED) represents a suitable option However, if exergy performance, economic feasibility, and payback period are the priorities, (MSF) represents the better option according to the results of the present study Future studies are recommended to conduct a more detailed analysis of operation and maintenance costs and to investigate the effects of different energy sources In addition, hybrid systems should be evaluated, together with the integration of thermal desalination technologies with renewable energy sources, with the aim of improving performance and reducing energy consumption and operating costs.

8.Nomenclatur:

Symbol Name	Symbol	Unit
Heat Transfer	(Q)	(kW, kJ)
Work	(W)	(kW)
Enthalpy Change	(ΔH)	(kJ/kg)
Enthalpy	(H)	(kJ/kg)
Entropy Generation Rate	($\dot{S}$ gen)	(kJ/K)
Entropy	(S)	(kJ/kg·K)
Ambient Temperature	(T0)	(K) , (C)
Reference State Properties	(H0, S0)	/
Exergy Input	($\dot{E}$x in)	(kW)
Exergy Output	($\dot{E}$x out)	(kW)
Exergy Destruction Rate	($\dot{E}$ D)	(kW)
Total Exergy Input	(∑ $\dot{E}$ in)	/
Total Exergy Output	(∑ $\dot{E}$ out)	/
Exergy Loss	($\dot{E}$x loss)	(kW)
Exergy Destruction	($\dot{E}$x destruction)	(kW)
Product Exergy	($\dot{E}$x product)	(kW)
Feed Water Exergy	($\dot{E}$x feed)	(kW)
Brine Exergy	($\dot{E}$x brine)	(kW)
Steam Exergy	($\dot{E}$x steam)	(kW)
Physical Exergy	(eph)	(kJ/kg)
Exergy Destruction Rate (MSF)	($\dot{E}$ D,MSF)	(kW)
Exergy Rate	($\dot{E}$x)	(kW)
Mass Flow Rate	($\dot{m}$)	(kg/s)
Thermal Efficiency	(ηth)	(%)
Exergy Efficiency	(ηex)	(%)

Energy Consumption	(E)	(kWh)
Specific Energy Consumption	(SEC)	(kWh/m³)
Specific Steam Consumption	(SSC)	(kg/m³)
Electric Power Consumption	($\dot{W}$ electric)	(kW)
Heat Loss Rate	($\dot{Q}$ loss)	(kW)
Heat Input	($\dot{Q}$ in)	(kW)
Useful Heat	($\dot{Q}$ useful)	(kW)
Steam Heat Rate	($\dot{Q}$ steam)	(kW)
Product Water Flow Rate	($\dot{V}$ product)	(m³/h)
Feed Water Flow Rate	($\dot{V}$ feed)	(m³/h)
Water Recovery Ratio	(WRR)	(%)
Product Water Quantity	($\dot{Q}$ water)	(m³)
Input Heat	($\dot{Q}$ input)	(kW)
Useful Heat	($\dot{Q}$ useful)	(kW)
Evaporation Heat	($\dot{Q}$ evaporation)	(kW)
Heat Loss	($\dot{Q}$ loss)	(kW)
Source Temperature	(T)	(K)
Water Production Cost	(C w)	(USD/M³)
Capital Cost	(C capital)	(USD)
Operation and Maintenance Cost	(C operation)	(USD/year)
Total Capital Investment	(TCI)	(USD)
Equipment Purchase Cost	(EPC i)	(USD)
Equipment Installation Cost	(EIC i)	(USD)
Site Cost	(C site)	(USD)
Capital Recovery Factor	(CRF)	—
Discount Rate	(r)	—
Plant Lifetime	(n)	(Year)
Annualized Capital Cost	(ACC)	(USD/year)
Levelized Cost of Water	(LCOW)	(USD/M³)
Water Production Rate	(WPR)	(m³/h)
Annual Operating Hours	(AOH)	(Hours/Year)
Net Present Value	(NPV)	(USD)
Annual Revenue	(Rt)	(USD)
Annual Cost	(Ct)	(USD)
Internal Rate of Return	(IRR)	(%)
Payback Period	(PBP)	(Year)
Initial Investment	(I0)	(USD)
Annual Cash Flow	(CF annual)	(USD/year)
Discounted Payback Period	(T)	(Year)

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