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Innovative Approaches to Seawater Desalination: Balancing Efficiency and Sustainability

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Abstract **– Desalination has long been vital for providing clean water for consumption and agriculture. Recently, seawater desalination has emerged as a sustainable freshwater source, necessitating operational optimization. This project aimed to identify and optimize a suitable seawater desalination technology, selecting Reverse Osmosis (RO). The project involved designing, simulating, and optimizing the plant, followed by economic evaluations. Additionally, the integration of solar energy systems was analyzed for economic viability and CO2 emissions. Four alternatives were simulated to optimize a seawater desalination plant with a capacity of 500,000 m³/day, focusing on maintaining Total Dissolved Solids (TDS) below 300 ppm and specific energy consumption under 5 kWh/m³. The fourth alternative, deemed the best, achieved a TDS of 164.7 ppm and the lowest specific energy consumption of 4.33 kWh/m³. Economic analyses assessed the viability of ultrafiltration and desalination processes with and without 10% reliance on renewable energy. Two approaches were used: one excluding labor and land costs, and another including them. The first approach estimated the cost of producing 1 m³ of drinking water at BD 0.246/m³ without renewables, yielding a Net Present Value (NPV) of 373 million Bahraini Dinars. With renewables, the cost rose to BD 0.331/m³, with an NPV of 232.6 million Bahraini Dinars. The second approach, accounting for land and labor costs, calculated the cost at BD 0.252/m³ without renewables (NPV of 363 million Bahraini Dinars) and BD 0.3374/m³ with 10% renewables (NPV of 231.6 million Bahraini Dinars). Increasing renewable reliance to 20% raised the cost to BD 0.42788/m³ and reduced the NPV to 82 million Bahraini Dinars. Carbon footprint analysis showed lower emissions for the renewable-integrated design, with direct and indirect emissions of 1.6 and 0.72 kg CO2/m³, respectively, compared to the original design's 1.79 and 0.78 kg CO2/m³**.

Keywords—Desalination, Reverse Osmosis, Solar energy, Sustainability

I. INTRODUCTION

Desalination is a crucial process that removes dissolved salts and minerals from saline sources like seawater or brackish water to produce potable water. This technology is essential for providing safe drinking water and supporting agricultural, industrial, and other sectors. The first large-scale desalination facility was built in 1865 in South Australia to meet the growing demand for freshwater driven by population growth and welfare needs [1]. Desalination addresses water scarcity and the limitations of traditional freshwater sources such as rivers, lakes, and wells. Its importance extends beyond immediate water needs, impacting sustainability and global water security.

Historically, desalination relied on thermal technologies, which were cost-effective when fossil fuels were inexpensive. However, rising energy costs have made thermal techniques less viable. To reduce water treatment costs, two main approaches have emerged: improving the energy efficiency of existing technologies and developing new, cost-effective, and energy-efficient desalination methods [2]. Desalination technologies can be broadly classified into three categories: Evaporation and Condensation, Filtration, and Crystallization.

Thermally driven desalination methods have notable environmental impacts, such as high energy consumption resulting in carbon emissions and damage to marine life from brine and chemicals. Filtration-based desalination, though more energy-efficient, still presents similar risks to marine ecosystems. The cost of desalination varies, with reverse osmosis (RO) being the most cost-effective due to its low capital expenses and absence of thermal energy use, while multi-effect distillation (MED) and multistage flash (MSF) are more costly because of their significant steam and electricity needs.

This study aims to develop an optimized seawater desalination process using commercially available technologies, renewable energy sources, and cost-effective methods to create a sustainable freshwater production process. The study involves extensive research into the latest advancements in seawater desalination technologies, comparing thermal [3], [4] such as multistage flash distillation and filtration-based methods [5] such as reverse osmosis in terms of energy consumption, efficiency, cost-effectiveness, and environmental impact. The goal is to simulate an optimized desalination plant for the Gulf region, particularly Bahrain, using advanced software tools. The selected methodology was assessed under various operating conditions to optimize key parameters such as feedwater salinity, salt rejection, efficiency, energy consumption, and recovery rate. The investigation also explores incorporating renewable energy resources to reduce the carbon footprint and operational costs. An economic analysis will evaluate the viability of the optimized desalination process with and without renewable energy, comparing it to traditional freshwater production methods.

II. Methodology

The methodology involved selecting a Reverse Osmosis (RO) system as the optimal desalination unit for Bahrain. The system was modeled and optimized using the Water Application Value Engine (WAVE) which is a systematic approach that integrates value engineering principles to enhance water resource management and allocation [6]. This methodology focuses on optimizing the functionality and cost-effectiveness of water projects, ensuring that socio-economic and environmental factors are adequately addressed. WAVE software relies on empirical equations derived from experimental data. This ensures that the simulation results are highly valuable. A base case and four alternatives were created, each improving Total Dissolved Solids (TDS) and energy consumption. One alternative was chosen for further analysis. An economic evaluation was conducted, considering a pretreatment unit and using data from Lenntec to estimate Bahrain's seawater composition. Ultrafiltration was selected for pretreatment, and chemicals were used within the process to address fouling issues.

The four alternatives were assessed based on energy consumption and TDS, aiming for specific energy consumption below 5 kWh/m³ and TDS levels below 300 ppm. The best option was chosen for its balance of pressure vessels, low energy use, and acceptable TDS levels. Costs for chemicals and electricity were calculated, with chemical costs converted from Indian Rupees (INR) to Bahraini Dinars (BHD) using the exchange rate of 1 INR = 0.0045 BHD. Replacement costs for pressure vessels and elements were considered, with replacements every 10 years for pumps and pressure vessels, and every 5 years for elements.

The potential for integrating solar energy was explored, and an economic analysis was repeated to compare CO2 emissions between a standard SWRO plant and a solar-integrated one. The operating temperatures of the plant do not exceed 45 degrees Celsius, which is lower than Bahrain's summer temperatures that can reach above 50 degrees Celsius. A stream factor of 0.95 was used to account for days when the unit might not be operational due to maintenance and other unexpected events. Finally, chemical costs were entered into the WAVE program for a detailed cost analysis.

III. Simulation and Optimization

The simulation and optimization of the RO system involved several key parameters that were crucial for enhancing system performance and efficiency. One of the primary parameters was the RO pass and stage configuration. Single and double pass systems were compared, with double pass systems providing higher quality water by further treating the permeate from the first pass. This configuration is essential for achieving the desired TDS levels. Another critical parameter was flux, which represents the rate at which water permeates through the RO membrane per unit area. As applied pressure increases, flux typically rises, improving production efficiency but also increasing the risk of fouling and scaling. Therefore, maintaining an optimal flux rate is vital to balance efficiency and mitigate these risks.

The recovery rate, which measures the percentage of feedwater converted into permeate, was another key factor. Higher recovery rates improve salt rejection and reduce brine waste, but they also increase the concentration of salts in the brine, potentially harming marine life. The number of pressure vessels (PVs) was also significant, as more PVs increase system capacity and reduce operating pressure, but they also raise initial costs. Operating pressure, typically between 55 to 82 bars, was tailored based on factors like feedwater salinity and temperature, influencing the system's overall performance.

In the base case, a two-pass system with two stages in the first pass and a single stage in the second pass was designed, using 14,100 PVs in the first pass and 4,730 in the second pass. This configuration resulted in a TDS of 28.5 mg/L and specific energy consumption of 6.42 kWh/m³, indicating a need for further optimization.

Several alternatives were explored to improve the system's performance. Alternative I increased the recovery rate to 43% for the first pass, reducing specific energy consumption to 4.7 kWh/m³ and achieving a TDS of 209 mg/L. Alternative II made adjustments to the bypass and recovery rates, resulting in a specific energy consumption of 4.46 kWh/m³ and a TDS of 130 ppm. Alternative III achieved a specific energy consumption of 4.45 kWh/m³ and a TDS of 209.1 ppm, but at a higher capital cost due to the increased number of PVs. Finally, Alternative IV implemented a bypass stream and concentrate recycle, significantly reducing specific energy consumption to 4.32 kWh/m³ and achieving a TDS of 164.7 ppm, with an overall recovery rate of 36.6%.

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IV. Results

A. Simulated alternatives

Alternative I

In the first alternative (Fig. 1), the concentrate recovery from the second pass to the feed was set at 100%, diluting the high TDS feed with a lower TDS concentrate stream. This reduced osmotic pressure, minimized membrane fouling and scaling, and decreased flow resistance, significantly lowering specific energy consumption. A bypass from the feed of the first pass to the feed for the second pass further reduced energy consumption and load. The recovery rate increased from 30% to 43% for the first pass, with flux rates of 7.6 and 16 LMH for the first and second passes, respectively. The TDS of the product was 209 mg/L, and specific energy consumption was 4.7 kWh/m³.

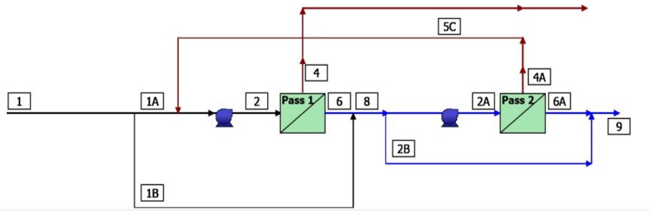

Fig. 1. RO configuration of Alternative I

Alternative II

This alternative retained the configuration of Alternative I but made three key changes: reducing the bypass from the feed to 0.5%, adjusting the recovery rates to 46% for the first pass and 68% for the second pass, and implementing a 7% bypass from the second pass to the final product. These adjustments resulted in a specific energy consumption of 4.46 kWh/m³ and a TDS of 130 ppm. The flux rates were 8.44 LMH for the first pass and 13.9 LMH for the second pass.

Alternative III

The third alternative, shown in Fig. 2, featured a two-pass, two-stage configuration, The element type for the first stage was chosen to be SW30XLE-440i, sacrificing some of the high rejection properties of its counterpart, SW30HRLE-440i, to achieve the lowest energy consumption among the available effective elements for seawater. This sacrifice was acceptable due to the good TDS range achieved, and the usage of this element type maintained the flux above the minimum of 6 LMH. For the second pass, the element type used was BW30HRLE-440i, which helped keep the TDS under the maximum limit while maintaining the flux. Lastly, the recovery percentage of the first pass was kept at 40.1%, which is typical value, for the first pass and 65% for the second pass. The lower percentage of the second pass's recovery is noticeable, nonetheless, it does not cause any design risks at this point, as there is a lack of any design warnings. In addition, keeping the recovery at 65% allows for lower energy consumption, hence, the use of such a low recovery is justified. Furthermore, the overall recovery was calculated as 31.4%, which is a satisfactory value achieving a specific energy consumption of 4.45 kWh/m³ and a TDS of 209.1 ppm. The flux rates were 6.3 LMH for the first pass and 12.1 LMH for the second pass. This configuration required a higher capital cost due to the increased number of pressure vessels, totaling 19,700 for the first pass and 7,000 for the second pass.

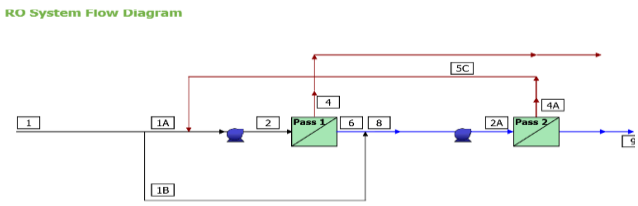

Fig. 2. RO configuration of Alternative III

Alternative IV

The final alternative, shown in Fig. 3, introduced a bypass stream, diverting 2.3% of the feed to the head of the second pass, and recycling 98% of the concentrate stream from the second pass to the head of the first pass. This setup reduced the flux within the first pass to 6.3 LMH and within the second pass to 13.1 LMH, lowering the overall pressure required and specific energy consumption to 4.32 kWh/m³. The TDS of the permeate was 164.7 ppm, with an overall recovery rate of 36.6%. Despite the higher number of pressure vessels (18,900 for the first pass and 6,500 for the second pass), this alternative was the most optimized, balancing capital and operational costs effectively.

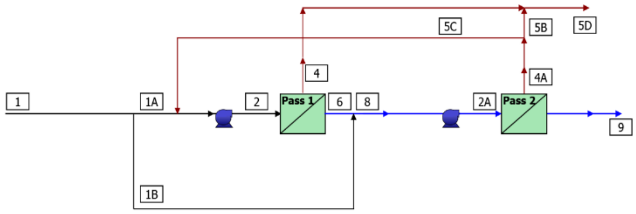

Fig. 3. RO configuration of Alternative IV

B. *Economic analysis*

The economic analysis of the chosen configuration will consider both capital and operating expenses. The plant will have a lifespan of 20 years and will be subject to an interest rate of 10%. Additionally, a 10-year MACRS depreciation will be utilized in this study to assess the financial viability of the selected configuration.

Capital Costs:

Capital costs were divided into direct and indirect costs, focusing on equipment such as the main pump, booster pump, membranes, and pressure vessels. For instance, the cost of an 8-inch RO pressure vessel membrane housing was approximately 76 BD per unit [7]. In the best-case scenario (Alternative IV), 25,400 pressure vessels were used, with seawater and brackish water membranes costing 378.5 BD and 341.1 BD per element, respectively [7]. The costs of the main and booster pumps were estimated based on their power consumption and cost correlations [8].

Operating Costs:

Operating costs included electricity consumption, chemical costs, and replacement costs for pressure vessels, elements, and pumps. Electricity consumption was calculated using local Bahrain tariffs, estimated at 0.029 BD/m³. Chemical costs were challenging to estimate but were minimized by adjusting the chemicals added to the ultrafiltration (UF) unit and the main RO unit. The total annual chemical cost was calculated to be approximately 1,878,056.95 BD. Replacement costs for elements were considered every five years due to wear from exposure to highly saline seawater.

Discounted Cash Flow:

A discounted cash flow diagram was created to estimate the cost of producing 1 m³ of potable water and assess the project's economic viability. The cost was found to be around 0.246 BD/m³. The net present value (NPV) was calculated for two scenarios: one to break even with zero profit or loss, requiring a revenue of approximately 44.9 million BD/year, and another based on Bahrain's water tariffs, resulting in a revenue of 88.7 million BD/year and an NPV of approximately 373.1 million BD/year. The payback period for the second scenario was 1.24 years.

Land and Labor Costs:

Land cost was included in the analysis, with an average capital cost of 600,000 BD [9] and an annual cost of 70,475.77 BD, translating to 0.000386 BD per m³ of potable water. Labor costs were also considered based on the average wages in Bahrain in 2023 [10], [11], [12], with an estimated annual labor cost of approximately 1,063,881 BD based on the average labor wages in Bahrain.

Renewable Energy Integration:

The potential for integrating renewable energy, specifically solar power, was explored. An on-grid solar system was chosen for analysis, supplying 10% of the total energy consumption. The capital cost for this system was estimated at 86,600,000 BD, with an annual maintenance cost of 8,660,000 BD. The economic analysis showed that using solar power to cover 10% and 20% of the energy consumption would be profitable, with the greatest profit achieved without any solar integration. However, covering 10% of the energy was more profitable than covering 20%.

Carbon Footprint:

The carbon footprint analysis compared direct and indirect CO_2 emissions from electricity generation with and without solar energy [13]. Without solar energy, direct and indirect emissions were 1.79 and 0.78 kg CO_2/m^3, respectively. With solar energy, these emissions were reduced to 1.6 and 0.72 kg CO_2/m^3, respectively, indicating that solar energy is more environmentally friendly.

Overall, the economic analysis demonstrated the financial viability and profitability of the optimized RO desalination process, with and without renewable energy integration, while also highlighting the environmental benefits of using solar power.

V. Conclusions

In summary, the comprehensive analysis highlights the superiority of Reverse Osmosis (RO) technology for desalination. Among the various technologies examined, RO was identified as the most cost-effective and energy-efficient, requiring only 2.5 – 4 kWh/m³, in stark contrast to the high energy and carbon emission levels associated with Multi-Stage Flash (MSF) technology. Multi-Effect Distillation (MED) demonstrated a steady performance, positioned between the extremes of RO and MSF. RO emerged as the most efficient, achieving 33% efficiency at an 80% recovery ratio with a minimum work requirement of 1.06 kWh/m³. These findings collectively establish RO as the leading technology in commercial desalination.

Further analysis of the RO system included a detailed evaluation of parameters such as flux, recovery percentage, and the effects of integrating bypass, recycle, and permeate split streams into the design. Through simulation, multiple alternatives were assessed for efficiency, performance, and sustainability, focusing on maintaining TDS under 300 ppm, specific energy consumption below 5 kWh/m³, and appropriate flux ranges for both passes. The optimal design achieved a TDS of 164.7 ppm and a specific energy consumption of 4.33 kWh/m³, with flux values of 6.3 LMH and 13.1 LMH for the first and second passes, respectively. This configuration effectively balanced capital and operational costs, demonstrating a robust and reliable system free of design warnings. Overall, the thorough evaluations confirm that RO technology not only meets but exceeds the requirements for efficient and sustainable desalination.

Additionally, an economic analysis was conducted to assess the viability of the optimized ultrafiltration and desalination process with and without reliance on renewable energy sources. The total cost of producing 1m³ of water without renewable resources amounted to BD 0.246/m³, with a total NPV of 373 million Bahraini Dinars, indicating a profitable project. In contrast, the total cost approached BD 0.331/m³ with renewable resources, with a positive NPV of 232.6 million Bahraini Dinars, also indicating profitability. Furthermore, the carbon footprint of both processes was analyzed. The original design had higher direct and indirect carbon emissions, with values of 1.79 and 0.78 kg CO2/m³, respectively. The renewable integrated design emitted lower values of 1.6 and 0.72 kg CO2/m³, respectively. These findings not only validate the superiority of RO technology but also emphasize the importance of considering economic and environmental factors in the pursuit of sustainable desalination solutions.

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VII. References

[1] N. Voutchkov, *Desalination Engineering - Planning and Design, McGraw Hill, 2012*. 2012.

[2] D. Curto, V. Franzitta, and A. Guercio, "A Review of the Water Desalination Technologies," *Applied Sciences*, vol. 11, no. 2, 2021, doi: 10.3390/app11020670.

[3] M. Rosen and A. Farsi, "Desalination technologies and their working principles," *Sustainable Energy Technologies for Seawater Desalination*, pp. 45–106, Jan. 2022, doi: 10.1016/B978-0-323-99872-7.00009-7.

[4] O. M. A. Al-hotmani, M. A. Al-Obaidi, G. Filippini, F. Manenti, R. Patel, and I. M. Mujtaba, "Optimisation of multi effect distillation based desalination system for minimum production cost for freshwater," *Computer Aided Chemical Engineering*, vol. 46, pp. 169–174, Jan. 2019, doi: 10.1016/B978-0-12-818634-3.50029-1.

[5] J. Kim, K. Park, D. R. Yang, and S. Hong, "A comprehensive review of energy consumption of seawater reverse osmosis desalination plants," *Appl Energy*, vol. 254, p. 113652, Nov. 2019, doi: 10.1016/J.APENERGY.2019.113652.

[6] R. Roopchund, J. Andrew, and B. Sithole, "A Systematic Review of WAVE Water Treatment Design Software and Related Technologies," *SSRN Electronic Journal*, 2023, doi: 10.2139/ssrn.4332839.

[7] "FilmTec™ Reverse Osmosis Membranes Technical Manual," 2023.

[8] R. Turton, R. C. Bailie, W. B. Whiting, J. A. Shaeiwitz, and D. Bhattacharyya, "Analysis, Synthesis, and Design of Chemical Processes Fourth Edition."

[9] P. Droogers *et al.*, "Water resources trends in Middle East and North Africa towards 2050," *Hydrol Earth Syst Sci*, vol. 16, pp. 3101–3114, Nov. 2012, doi: 10.5194/hess-16-3101-2012.

[10] H. Ait Lahoussine Ouali, M. I. Soomro, S. Touili, M. Eltaweel, and A. Alami Merrouni, “Performance investigation of seawater desalination system powered by central receiver concentrated solar thermal plant,” *Appl Therm Eng*, vol. 225, p. 120165, 2023, doi: https://doi.org/10.1016/j.applthermaleng.2023.120165.

[11] R. H. Mohammed *et al.*, “A novel solar-powered thermal desalination unit coupled with a reverse osmosis plant to increase overall water recovery,” *Appl Therm Eng*, vol. 234, p. 121306, 2023, doi: https://doi.org/10.1016/j.applthermaleng.2023.121306.

[12] S. Shalaby, “Reverse osmosis desalination powered by photovoltaic and solar Rankine cycle power systems: A review,” *Renewable and Sustainable Energy Reviews*, vol. 73, pp. 789–797, Dec. 2017, doi: 10.1016/j.rser.2017.01.170.

[13] “U.S. Energy Information Administration (EIA).” Accessed: Nov. 07, 2024. [Online]. Available: https://www.eia.gov/tools/faqs/faq.php?id=74&t=11