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Synergizing Cost Optimization and Environmental Engineering in Water Desalination: Best Practices for Sustainable Project Management

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ABSTRACT

This study evaluates desalination technologies' environmental and economic performance by comparing the Ras Al-Khair and Shoaiba desalination plants in Saudi Arabia. The primary objective is to integrate Life Cycle Assessment (LCA) and cost analysis to assess the sustainability of Reverse Osmosis (RO), Multi-Stage Flash (MSF), and hybrid desalination systems. The results reveal significant differences in energy consumption, global warming potential (GWP), brine disposal management, and resource depletion. Using a hybrid RO/MSF system, Ras Al-Khair demonstrates substantially lower energy demands (3–5 kWh/m³) and a reduced carbon footprint, capturing 300,000 tons of CO_2 annually. In contrast, Shoaiba's MSF system, relying on crude oil for power generation, generates higher energy consumption (13–15 kWh/m³) and 8.2 million tons of CO_2 emissions annually. The economic analysis highlights Ras Al-Khair's higher initial capital expenditure (CAPEX) of $7.6 billion but lower operational costs ($0.65/m³) and a faster break-even period (12 years) compared to Shoaiba's $1.60/m³ cost and a break-even period of 18 years. The study emphasizes integrating energy recovery, carbon capture, and renewable energy solutions in sustainable desalination practices to address global water scarcity while minimizing environmental impact and enhancing economic feasibility.

INTRODUCTION

Water scarcity is a growing global crisis, with nearly two-thirds of the population expected to face water stress by 2025 (Ahmed *et al.*, 2019). The situation is particularly severe in arid regions such as the Middle East and North Africa, where over 80% of freshwater resources are exploited unsustainably (Al-Obaidi *et al.*, 2019). With a projected 40% water deficit by 2030, desalination has become a critical solution, offering a climate-independent freshwater source. Over 97.4 million cubic meters of desalinated water are produced daily, securing water supplies for more than 300 million people. Countries such as Saudi Arabia, Israel, and the UAE have integrated desalination into their national water strategies, demonstrating its role as a global necessity rather than just a regional solution (Peng *et al.*, 2018).

In the past decade, the development of desalination technologies such as Reverse Osmosis (RO), Multi-Stage Flash (MSF), and Multi Effect Distillation (MED) methods have been widespread. GWI 2022 report showed that RO represents almost 70% of the global desalination capacity; in particular, RO consumes less energy (3–5 kWh/m³) than MSF (13–15 kWh/m³), so RO is preferred (Do Thi and Tóth, 2023). Plants such as Israel's Sorek facility and the Sydney Desalination Plant have proven that RO technology is efficient. Nevertheless, salt thermal desalination (MSF and MED) continues to be prevalent in areas of cogeneration with power plants, where MSF is used in Kuwait and the UAE, and MED in solar coupled desalination projects (Angelakis *et al.*, 2021).

Despite its advantages, desalination is fraught with major costs and environmental problems. According to reports of IEA 2022, up to 60% of total desalination costs are energy expenses, which makes desalination highly sensitive to fuel price fluctuations. Innovation in energy recovery systems has progressed, but desalination remains two to three times more expensive than conventional water sources (Schär *et al.*, 2023). Moreover, desalination plants add about 76 million tons of CO_2 annually, which is worsening climate change. Solar- and wind-powered hybrid desalination systems developed by countries like the UAE and Spain are aimed to reduce emissions (Ayaz *et al.*, 2022).

There is also a significant environmental risk in brine disposal. Brine is discharged at about 142 million cubic meters per day with salinity levels twice that of seawater, causing alterations in oxygen levels, loss of biodiversity and habitat destruction. Dilution techniques, brine concentration recovery, and zero liquid discharge are being studied for adoption, but the high costs limit their use. To reduce environmental impact, sustainable desalination must advance from energy and improved brine management to cheaper energy prices and more dependence on renewables (Bello *et al.*, 2021, Soliman *et al.*, 2021).

The issue of water scarcity affects more than 40% of the global population, so desalination is an important means to solve this problem. However, due to low energy mass diffusivities in semiconducting sensors, its adoption is hindered by high energy consumption, operating costs, and environmental impacts (Dhakal *et al.*, 2022). The selection of the most sustainable technology depends on

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the efficiency of technologies such as RO, MSF, and MED, each with its efficiency. However, the costs and impacts of many of these desalination plants are still high; for example, they still consume excessive energy (e.g. MSF 13 15 kWh/m³ vs RO 3 5 kWh/m³), produce high CO_2 emission, and have difficulty with brine disposal. The absence of an integrated assessment framework in the decision-making gap of desalination project management regarding cost efficiency and environmental sustainability is promoted by a need for a comprehensive evaluation (Alshail, 2020).

While considerable work exists in the destination field, the overwhelming majority is centred on efficiency, brine disposal or cost analysis with no holistic assessments that integrate Life Cycle Assessment (LCA) with financial metrics. The real-world economic and environmental trade-offs are often ignored when comparing RO, MSF and MED. Furthermore, most cost studies focus on the CAPEX and OPEX, neglecting external costs, such as carbon emissions and brine disposal. It leads to incomplete financial assessment. However, this study combines LCA and cost analysis to address the gap and provide a balanced sustainability comparison of desalination technologies.

This study is significant because it couples cost optimization with environmental sustainability in desalination. It uses a Life Cycle Assessment (LCA) framework to assess energy use, CO_2 emissions, water consumption, resource depletion, and brine disposal, and a detailed cost analysis of CAPEX, OPEX, and break even. The results provide policymakers, engineers, and investors practical guidelines for economically designing sustainable desalination facilities. This research supports the next generation of sustainable desalination infrastructure by identifying best practices in energy recovery, hybrid technologies and brine management.

This study aims to evaluate desalination technologies' environmental and economic performance by integrating Life Cycle Assessment (LCA) and cost analysis. To determine sustainability, it will assess energy consumption, carbon emissions, water use, resource depletion, and brine disposal. A detailed cost analysis will also examine CAPEX, OPEX, cost per cubic meter of water, and break-even periods to compare long-term economic feasibility. The study also explores synergies between cost optimization and environmental sustainability, identifying strategies like energy recovery and hybrid systems to improve efficiency. Finally, it proposes best practices for desalination project management, offering data-driven recommendations for sustainable and cost-effective operations. This study answers the following research questions:

1. What are the environmental impacts of different desalination technologies (RO, MSF, MED) based on Life Cycle Assessment (LCA) criteria such as energy consumption, carbon emissions, and brine disposal?
2. How do the costs of desalination technologies compare in terms of Capital Expenditure (CAPEX), Operational Expenditure (OPEX), and cost per cubic meter of water?
3. What strategies can optimize desalination project management to balance cost efficiency and environmental sustainability?

LITERATURE REVIEW

Environmental Impacts of Desalination

Extensive studies have been conducted regarding desalination's environmental challenges, mainly related to energy consumption, carbon emissions, brine discharge, and resource depletion. Desalination plants impact marine ecosystems severely by changing the salinity, chemical composition and dissolved oxygen conditions in receiving waters due to the brine discharge (Elsaid *et al*., 2020). Almasoudi and Jamoussi (2024) looked further into this issue and found that brine effluents from desalination plants all across the world are nearly 50% more than previously thought, something that truly needs to be addressed in terms of sustainable brine management approaches, either diluting, dispersing, and mineral recovery (Almasoudi & Jamoussi, 2024).

Another main environmental concern is energy consumption, especially for thermal desalination techniques with higher carbon footprints derived from fossil fuel-based energy resources . In a comparative study, Wang *et al*. (2019) have demonstrated that MSF and MED consume more than double the energy used by RO and, in this regard, are less sustainable in an environmental sense (Wang *et al*., 2019). Panagopoulos and Haralambous, (2020) in their study analyzed that Solar-powered and wind-powered RO systems can reduce CO_2 emissions by 30%. Unfortunately, intermittent energy supply and high initial capital costs have limited their large-scale implementation (Panagopoulos & Haralambous, 2020).

LCA has quantified the environmental impacts of desalination well. A comparative LCA study of different desalination technologies was performed by Najid *et al*. (2021), and they concluded that although RO has a lower energy footprint, it still has a considerable environmental burden in terms of membrane fouling, chemical pre-treatment, and disposal of brine (Najid *et al*., 2021). On the other hand, Khoshgoftar Manesh *et al*. (2020) expressed how MSF and MED could integrate power plants through cogeneration, making them more efficient despite their higher energy consumption. Nevertheless, current LCA studies have not completely integrated cost environmental trade-offs, preventing their use for real-world decision-making (Khoshgoftar Manesh *et al*., 2020).

Cost Analysis of Desalination Plants

Economic factors are paramount in desalination feasibility, and economic studies on capital costs (CAPEX), operational costs (OPEX), and externalities are discussed. Saleh and Mezher (2021) examined the desalination costs of various technologies, especially RO, where costs ranged from$0.50 to$0.80 per cubic meter, whereas MSF and MED faced significantly higher energy demand and maintenance burdens resulting in production costs in the range beyond$1.50 per cubic meter (Saleh and Mezher, 2021). In a more recent study, Generous *et al*. (2021) disclosed that energy costs represent about 40–60% of operational expenditures, which is an incentive to employ energy recovery technologies to decrease operational expenditures (Generous *et al*., 2021).

Most existing studies on desalination have addressed direct cost components, but external environmental costs of desalination often have not been touched upon. According to Eke *et al*. (2020), thermal desalination plants become much less economically competitive if carbon taxes and the ecological damage associated with brine disposal are considered (Eke *et al*., 2020). Ahmadi *et al*. (2020) looked instead at the potential of renewable-powered desalination and concluded that solar-aided RO would reduce energy costs by 30%, although high initial CAPEX remains a barrier to adoption (Ahmadi *et al*., 2020).

The long-term financial sustainability of the desalination project also constitutes another cost-related issue. According to Shokri and Fard (2023), hybrid RO-MSF plants show cost parity with standalone MSF ones in 12 years despite their increased initial investment due to increased energy efficiency (Shokri & Fard, 2023). This aligns with the results that Elewa (2024) showed that integrating energy recovery devices (ERDs) can help save up to 40% OPEX, making desalination financially more sustainable (Elewa, 2024).

Synergies between Cost Optimization and Environmental Engineering

Energy efficiency in desalination, brine management innovations and hybrid renewable desalination systems are strategies that have recently attracted attention as part of the efforts to integrate environmental sustainability with cost reduction. Energy recovery technologies are considered promising since they have been demonstrated to reduce operating costs and carbon emissions dramatically (Saboori & Mehrjerdi, 2022). According to Mendoza-Zapata *et al*. (2023), using pressure exchangers in RO plants can increase energy efficiency by up to 50%, decreasing electricity consumption and environmental footprints (Mendoza-Zapata *et al*., 2023).

Hybrid desalination systems are recognized as effective means of improving the economic and environmental results. Abdelaziz *et al*. (2021) state that combining RO with MSF or MED to use the waste heat from the power plants may help optimize energy use by reducing the energy consumed from the outside (Abdelaziz *et al*., 2021). Gomaa *et al*. (2023) further reported that a solar-powered desalination study revealed that solar-aided RO could achieve levelized water costs below $1.00 per cubic meter. Solar-powered desalination is capable of reaching the same as its fossil fuel-fueled competitors. Solar thermal integration encounters some of these as barriers to its large-scale deployment due to intermittency issues and high integration costs (Gomaa *et al*., 2023).

Desalination research has also attracted increased attention in brine management. According to Mogashane *et al*. (2020), profitable salts and minerals could be extracted from brine, offsetting disposal costs (Mogashane *et al*., 2020). On similar grounds, Abdelfattah and El-Shamy (2024) examined zero liquid discharge (ZLD) technologies to eliminate brine discharge and avoid environmental and financial burdens. Despite this, these approaches are still of interest and will become cost-effective on an industrial scale once further technological advancements are made (Abdelfattah and El-Shamy, 2024).

MATERIALS AND METHODS

Selection of Case Study Desalination Plants

This study selects Ras Al-Khair and Shoaiba desalination plants in Saudi Arabia to represent diverse desalination technologies, operational scales, and geographical contexts, focusing on RO, MSF, and hybrid systems. Using a hybrid RO/MSF system, Ras Al-Khair is one of the largest and most energy-efficient plants globally, incorporating energy recovery and carbon capture technologies to reduce environmental impacts and improve operational efficiency. On the other hand, like other traditional oil-based MSF technology, Shoaiba has lower initial capital costs but higher operating costs and CO_2 emissions from crude oil-based plants. The study compares these plants and utilizes this comparison to discuss trade-offs between a plant's technological efficiency, operational costs, and environmental performance, drawing upon knowledge of desalination in places with water scarcity.

Life Cycle Assessment (LCA) Framework

Goal and Scope Definition

This LCA aimed to determine the environmental impacts throughout a desalination plant's life (construction, operation, and decommissioning phases). The focus was on quantifying the ecological burdens of each desalination stage and comparing the performance of different desalination technologies (i.e. RO, MSF). The LCA consists of three phases: construction phase (Examines the materials, energy consumption and emissions associated with the construction of the plant); operational phase (Analyses energy consumption, water production, brine disposal, emissions and resources used during the operation of the plant); and decommissioning phase (Indicates the environmental impacts such as waste, energy use or the potential risk of soil pollution during dismantling of the installation). The motivation is to identify possible ways to reduce the environmental effects and explore trade-offs between sustainable ecological qualities and economic performance.

Functional Unit

To have a fair comparison between different technologies and scales of desalination, the functional unit of LCA is defined as the production of 1000 cubic meters (m^3) of freshwater. This standardizes the measurement to allow plants of any size, capacity, and technology to be compared and a clear measure of the environmental pressure per unit of water produced. This approach enables a valuable understanding of each desalination process's relative energy consumption and emissions for its sustainability, which is important for sustainable development and for comparing the long-term viability.

System Boundaries

The LCA of desalination plants covers the whole life cycle, from construction to decommissioning, and is focused on three key phases. The construction phase also refers to the energy and materials (i.e., raw material extraction, transportation, manufacturing, and assembly) used to construct the plant and the embodied energy and emissions contained in the materials, including concrete and steel, used to build the plant (e.g., mix and place concrete in the formworks, manufacture of reinforcing bars, the foundry process, etc.). The longest and most important phase for both cost-effectiveness and sustainability is the operational phase of desalination, covering lifetime energy consumption for desalination, freshwater production (both quantity and quality), brine disposal, and emission of CO_2 (especially from fossil fuel burning), and resource use including replacement of consumables such as RO membranes. Finally, the decommissioning phase determines how much the plant's dismantling impacts the environment, like how much energy was used while the plant is being taken down, how much waste will be disposed of, what amount of waste will be recycled, and whether the soil was contaminated by the hazardous matter in the plant. The comprehensive nature of such an approach enables a thorough life cycle assessment of the environmental impacts involved in each stage of the life of the desalination plant.

Impact Categories

The environmental impact categories assessed within the LCA of desalination plants include several key categories, which are important in understanding their sustainability. Global Warming Potential (GWP) focuses on the desalination plant's greenhouse gas emissions regarding CO_2 equivalents, addressing how much the desalination plants contribute to climate change. Other important factors are energy consumption, direct energy inputs (for example, electricity for desalination), and indirect inputs (for example, construction energy) a major component of the whole environmental footprint of the plant. The water use category aims to use total water consumption during the plant life cycle (i.e., construction, operation, and maintenance) to qualify the sustainability of the plant. Resource depletion is the amount of non-renewable materials used in construction, such as steel and cement, calculated by the impacts on natural resources. Finally, brine disposal impacts consider the environmental effects of brine discharge, which may drastically damage marine ecosystems if not properly treated. These impact categories convey a detailed environmental performance of desalination plants, allowing for a detailed comparison between different technologies and their relative sustainability in tackling water scarcity.

Cost Analysis Framework

Cost Breakdown

A cost comparison was carried out for the desalination plants that account for the capital cost and the ongoing cost to assess the cost-effectiveness of the plants. All initial costs for infrastructure development, plant equipment, and installation of the desalination plant form part of the CAPEX, which includes the costs of desalination plant construction. This investment was needed to understand the costs of building a desalination facility. On the other hand, operational expenditure refers to the costs incurred in everyday expenses. This included energy consumption, maintenance, labour and the purchase of desalination consumables (membranes and chemicals).

Besides CAPEX and OPEX, External Costs were also considered during the analysis. These environmental costs included brine disposal, emissions control costs, and other costs associated with compliance with environmental regulations. The study integrated these externalities to represent better the total cost of desalination beyond direct money spent into a wider societal and environmental cost.

Cost Calculation

The study then derived several key cost metrics to compare the economic performances of different desalination technologies. One of the main metrics calculated was Cost per m^3 Water, based on dividing total combined operational and capital costs by the volume of freshwater produced annually. This metric was used as a parameter to determine the economic efficiency of the desalination process and the amount it costs to manufacture a unit of Water.

Another important calculation is the Cost per kWh of energy, which was calculated by dividing the energy costs attributed to fuel, electricity, and maintenance of the plant's energy infrastructure by the total energy consumption during operation. The figure compares the energy efficiency and operating energy costs for desalination technologies.

Lastly, the Break-even Analysis determines the period it takes to recover the initial capital investment, assigning the Cost of producing Water and the revenue generation in the plant. The study calculated the time to break even, judging the long-term economic viability of each desalination technology, which facilitates understanding the investment-bearing capacity of the desalination facilities.

With this analysis, direct financial costs are integrated with external environmental costs to view the economic and ecological aspects of desalination technologies comprehensively. What this extensive cost analysis accomplishes is that it allows one to compare and contrast several plants based on their operational characteristics, broad economic impacts, and environmental sustainability.

RESULTS AND DISCUSSIONS

Environmental Impact Results

Overview of LCA Results

A Life Cycle Assessment (LCA) of the Ras Al-Khair and Shoaiba desalination plants shows that there are significant differences between their environmental impacts in the most common ecological categories, such as the global warming potential (GWP), energy and water consumption, resource depletion and brine disposal. Ras Al Khair operates with lower energy demands (3–5 kWh/m³), and since it largely uses Reverse Osmosis (RO) with energy recovery systems, it results in having a much lower GWP and better ecological footprint, which is related to more sustainable use of water. Furthermore, the plant avoids depletion of resources due to the use of advanced materials, and disposal of brine through dilution minimizes environmental risks. Shoaiba is, however, powered by a Multi-Stage Flash (MSF) technology, which uses crude oil combustion to generate power, requiring a gross energy consumption of 13 – 15 kWh/m³ with a GWP of 2473 in 2012 and 8.2 million tons of CO_2 emissions annually. Additionally, Shoaiba's resource depletion rate is greater than that of the other plants as it requires a large volume of concrete and steel, and its brine discharge methods are effective yet do not involve advanced treatment, potentially leading to higher environmental hazards.. Shoaiba, despite the lower initial capital expenditure (CAPEX) and the capability to produce electricity alongside water, is less sustainable than Ras Al-Khair due to the higher operational expenditure (OPEX) and negative environmental impacts.

Comparative Analysis

The comparison between the Shoaiba and Ras Al-Khair projects demonstrates major differences from an environmental impact point of view; Ras Al-Khair is more sustainable and does not harm the environment. The largest difference is in global warming potential (GWP), which is attributable to the energy efficiency of Ras Al-Khair's RO technology and carbon capture systems, allowing it to capture 300,000 tons of CO_2 per year, whereas Shoaiba emits 8,200,000 tons each year. RO is less energy-demanding than the energy-intensive MSF process employed at Shoaiba using oil combustion. Its energy recovery systems make its energy consumption also much lower than Shoaiba: 3–5 kWh/m³ for RO vs 13–15 kWh/m³ for MSF. Regarding brine disposal, brine from Ras Al-Khair is disposed of with dilution channels, minimizing environmental impact; brine from Shoaiba with brine salinity (65–70 g/L) is not high and requires no advanced treatment but carries higher ecological risks. While the environmental footprint is smaller at Ras Al-Khair due to its use of advanced materials, Shoaiba's construction demanded significant amounts of concrete and steel. These differences illustrate how the more efficient and innovative technologies implemented in Ras Al-Khair minimize environmental impacts across several categories (Figure 1).

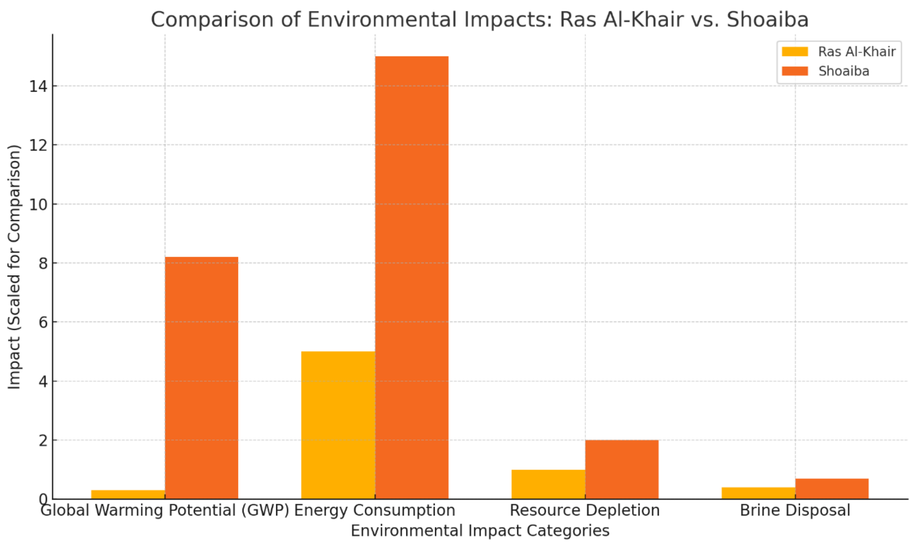

Figure 1: Comparison of Environmental Impacts: Ras Al-Khair vs. Shoaiba

Major Contributors to Environmental Impacts

The energy consumption, brine disposal, emissions, and resource depletion were compared among the Shoaiba and Ras Al-Khair desalination plants. This highlights some of the critical differences, especially on the energy consumption side and demonstrates the advantages of the Ras Al-Khair plant. Using a combined RO / MSF system, Ras Al-Khair largely benefits from a lower energy consumption than Shoaiba. Ras Al-Khair's RO technology also consumes 3 – 5 kWh/m³ specifically, starkly contrasting with Shoaiba's MSF technology, which requires 13 – 15 kWh/m³. Integrating energy recovery systems reduces the total electricity requirements and increases energy efficiency. This made Ras Al-Khair an energy-efficient design with its design a significant key to a low carbon footprint due to its carbon capture system of 300,000 tons of CO_2 reduction per year. In contrast, Shoaiba's use of crude oil combustion for power generation produces 8.2 million tonnes of CO_2 emissions annually, contributing to the environmental damage caused by the plant.

Ras Al-Khair's creative brine disposal approach includes dilution channels, which blend seawater with the contained brine before it is released, making its ecological effect much smaller. Brine with a50–55 g/L salinity in plant brine is less harmful to the marine ecosystem than the Shoaiba brine with 65–70 g/L salinity. Shoaiba has no advanced treatment technologies, and the brine is discharged into the marine environment without sufficient control, resulting in more risks to changing local aquatic life, reefs and fish populations.

Resource depletion constitutes an important factor in the sustainability of desalination plants. Using advanced materials to construct Ras Al-Khair helps reduce the overall demand for non-renewable resources. Through energy recovery and efficient technologies, Ras Al-Khair minimises the amount of raw materials needed, and thus, the plant is constructed and operated more sustainably. However, Shoaiba's development phase entailed using considerable quantities of concrete (1.2 million tons) and steel (85,000 tons), leading to higher resource depletion and a raised environmental footprint associated with the plant's construction.

Through such comparisons, it is evident that adopting modern, low-energy desalination technologies, like the ones used at Ras Al-Khair, provides environmental benefits, reducing energy consumption and environmental impacts like CO_2 emissions and brine discharge. While Shoaiba offers important lessons on the operational viability of conventional desalination technology, a consideration for transitioning to cleaner energy solutions and more sustainable desalination practices in the future are the higher energy and resource demand and fossil fuel reliance, respectively (Figure 2).

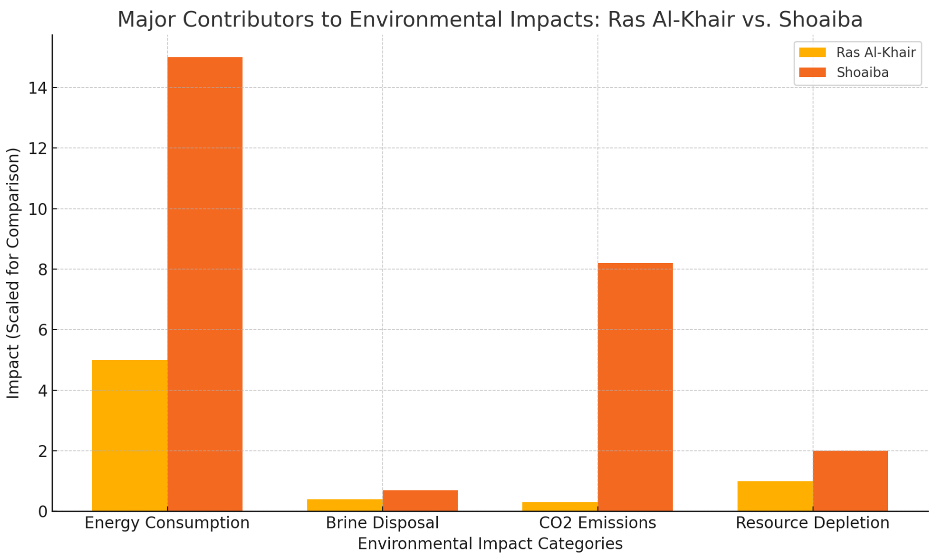

Figure 2: Major Contributors to Environmental Impacts: Ras Al-Khair vs. Shoaiba

Comparison of Desalination Technologies

Reverse Osmosis (RO) and Multi-Stage Flash (MSF) desalination technologies are dissimilar regarding energy efficiency, environmental impact, and sustainability. These differences are even more apparent in hybrid systems, such as At-Khair's combination RO/MSF, which has significant advantages over typical MSFMSF-based stems, such as Shoaiba.

Energy Efficiency

Reverse Osmosis (RO) is widely accepted as the most energy-efficient desalination process among alternatives such as Multi-Stage Flash (MSF). RO requires seawater to travel through semi-permeable membranes to remove salts and impurities, requiring much less energy than the MSF process. Using RO technology, Ras Al-Khair operates at 3–5 kWh/m^3, decreasing the energy demand. Energy recovery systems improve the efficiency of RO by capturing the pressure that is produced during desalination and returning it to the system, thereby minimizing the need for additional energy input. Ras Al-Khair is, therefore, highly energy efficient with a low carbon footprint and reduced operation costs.

On the other hand, MSF uses 13–15 kWh/m^3 of energy. It depends on boiling seawater in steps that reduce the pressure and temperature until freshwater is produced when the vapour condenses. Generally speaking, the heating needed for the process is made by fossil fuel combustion, such as crude oil or natural gas. Due to the high energy demand in MSF systems, the process is less efficient and costlier.

Environmental Impact

The energy consumption in desalination technologies is generally the main factor for its environmental impact in releasing more CO_2 and global warming potential

(GWP). The energy-efficient RO technology used in Ras Al-Khair has a much reduced ecological footprint. The carbon capture system of the plant also helps to capture and repurpose about 300,000 tons of CO_2 per year as part of their environmental impact mitigation. Ras Al-Khair's utilization of renewable energy sources or carbon capture mechanisms reflects a sustainability and ecological conservation pledge, addressing the challenge caused by the high GWP of desalination processes.

However, Shoaiba's production of 8.2 million tons of CO_2 emissions annually is based on the MSF technology driven by crude oil. These emissions directly affect this plant's obtrusive dependence on fossil fuels to generate energy. As a result, Shoaiba's higher energy consumption and associated CO_2 emissions result in much more environmentally harmful options, thereby contributing to climate change and environmental degradation. Through this comparison, the great importance of energy-efficient desalination technology in minimizing ecological impacts will be shown.

Sustainability

Desalination beyond energy efficiency and the reduction of emissions in desalination involves sustainability on a long-term scale in terms of resource use and preservation of the environment. The deployment of a hybrid RO/MSF system at Ras Al-Khair is more sustainable than a conventional MSF system at Shoaiba. Energy recovery features integrated within the RO process and a carbon capture technology significantly reduces the damage caused by resource depletion and the plant's environmental footprint. Furthermore, Ras Al-Khair also controls the brine discharge through dilution channels to minimise the negative ecological effects on the surrounding marine environment, which enables it to be a more sustainable solution for water production.

However, Shoaiba's dependence on crude oil to generate energy makes the plant more resource-heavy but also exposes the plant to the vagaries of fossil fuel markets. The large energy consumption of the plant and the absence of advanced brine management technologies make the MSF system of Shoaiba less sustainable in the long run. Effective brine management and nonuse of nonrenewable energy sources are lacking in the currently available desalination technologies and need to be addressed for sustainable use (Figure 3).

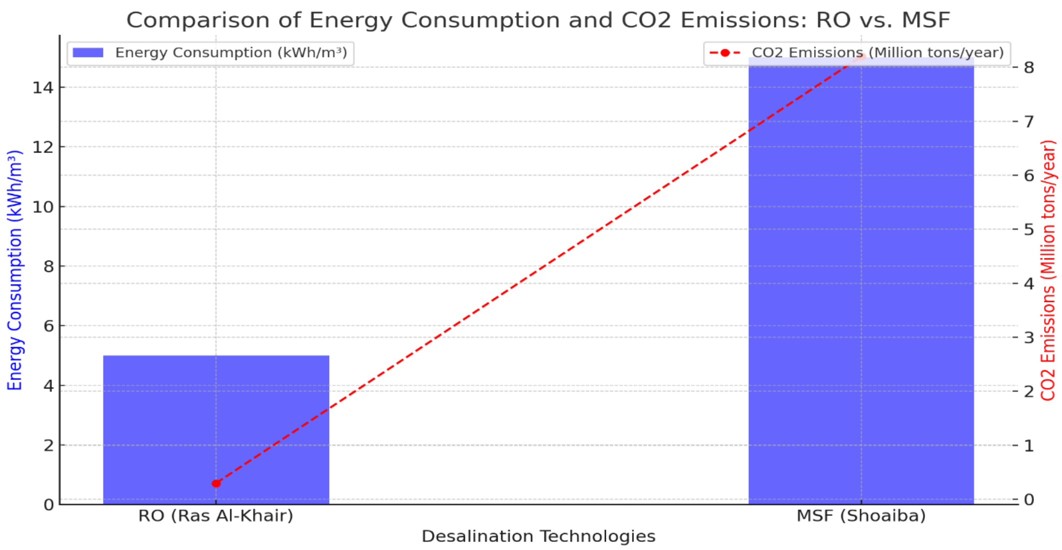

Figure 3: Comparison of Energy Consumption and CO_2 Emissions: RO vs. MSF

Cost Analysis Results

Capital Expenditure (CAPEX)

The Capital Expenditure (CAPEX) analysis provides insight into the financial figure of access between the Ras Al-Khair and Shoaiba desalination plants. With its hybrid Reverse Osmosis (RO) / Multi Stage Flash (MSF) system, the initial investment cost for Ras Al-Khair reached $7.6 billion due to the complex infrastructure and advanced technologies, including energy recovery and carbon capture. However, the higher CAPEX of this solution also means a greater upfront cost for the plant, but the higher energy efficiency and clean air properties that this solution offers present potential long-term financial and environmental benefits. However, Shoaiba turned to a more traditional MSF system with only an initial investment of $5 billion. This is because it has a simpler design, and thus, it relies on oil-fired steam generation, which, though cost-effective at low operational expenditures, is higher than the operational costs due to energy demand and environmental impacts. However, even though Ras Al-Khair has a higher capital investment in the initial stage and higher operational costs in the later stage, it is ready for lower operational costs and environmental sustainability. The comparison illustrates the cost trade-off between more advanced and expensive technologies offering greater long-term economic performance and reduced environmental impact (Figure 4).

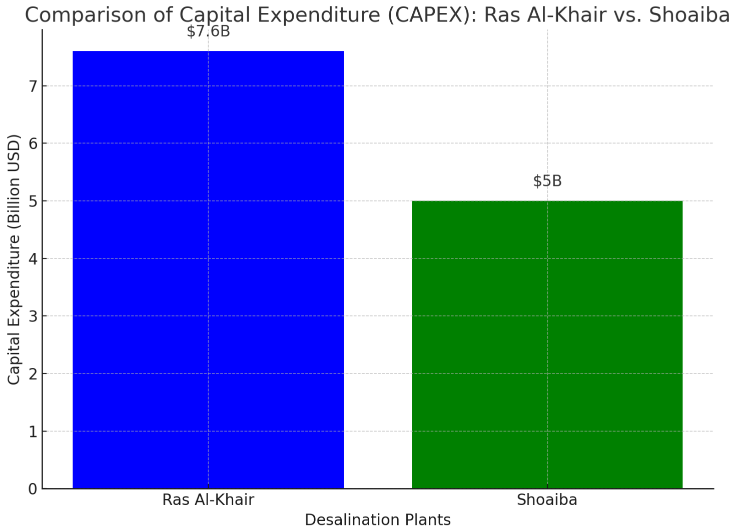

Figure 4: Comparison of Capital Expenditure (CAPEX): Ras Al-Khair vs. Shoaiba

Operational Expenditure (OPEX)

Operational Expenditure (OPEX) analysis allows for the disclosure of valuable insights into the long-term financial sustainability of the Ras Al-Khair and Shoaiba desalination plants by analyzing key cost components such as energy consumption, maintenance, labour, and consumables. Desalination is an energy-intensive process, and energy consumption is the dominant contributor to OPEX for both plants. With energy-efficient Reverse Osmosis (RO) technology, with the help of energy recovery systems, Ras Al-Khair's energy demand is lowered to 3–5 kWh/m³. Its efficient system means you pay less electricity costs, adding to the cost-efficient supply chain. Conversely, Shoaiba relies on Multi Stage Flash (MSF) technology, which has high energy consumption (13–15 kWh/m³) and comes at a high fuel cost due to its dependence on crude oil.

Another major component of OPEX is maintenance cost. At Ras Al-Khair, the energy-efficient design reduces wear and tear on equipment, hence lower maintenance costs ($0.10/m³). Shoaiba's higher maintenance costs ($0.20/m³) are due to more frequent part replacements and a high-energy intense operation. OPEX also includes labour costs, and due to the automation of Ras Al-Khair's operation, its labour requirements are low, and the cost is just $0.15/m³. On the contrary, Shoaiba's utilization of more manual processes leads to higher labour costs at the forklift level ($0.25/m³). Finally, consumables such as chemicals and membranes are an ongoing cost. The cost ($0.30/m³) of the RO system at Ras Al-Khair is estimated with lower consumable use but higher replacement of membranes due to very low energy usage. The MSF system of Shoaiba shows a higher economical consumable cost ($0.50/m³) because of its regular requirements for maintenance.

The Ras Al-Khair OPEX is $0.65/m³ while Shoaiba is $1.10/m³. The stark contrast in this case is attributed to the energy efficiency, automated operations, and high technology of Ras Al-Khair to optimize operational costs directly and indirectly. On the contrary, higher energy consumption and outdated technology in Shoaiba result in higher OPEX and are therefore less competitive in terms of overall cost-effectiveness. The breakdown of the OPEX for both plants is presented in the following graph, which shows the contribution of energy consumption, maintenance, labour, consumables, etc, to the total cost of operation (Figure 5).

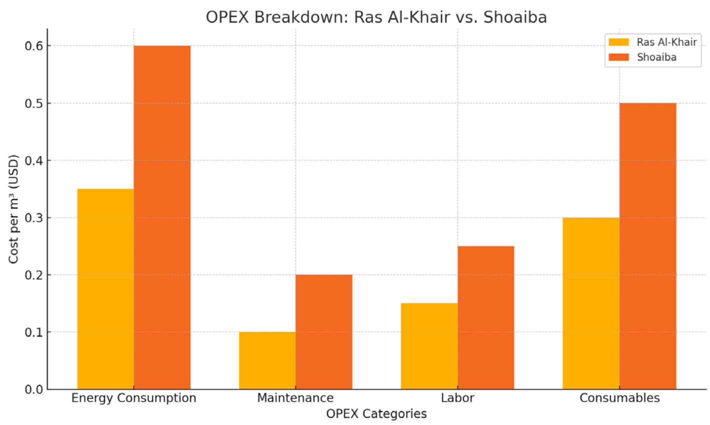

Figure 5: OPEX Breakdown: Ras Al-Khair vs. Shoaiba

Cost Calculation Metrics

Cost per m³ of Water

Freshwater's cost per cubic meter (m³) is a major financial metric of desalination plant economic efficiency. Water Produced Turns Over Total Annual Capital Expenditure and Operational Expenditure To calculate this metric, the total Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) are divided by the annual volume of water produced. It represents the overall costs of producing each cubic meter of freshwater, presenting a transparent image of each plant's economic performance. The plant produces 325 million m³ of water annually at CAPEX of $7.6 billion and OPEX of $0.65/m³ for Ras Al Khair, which has higher but lower OPEX. This means that the cost per m³ of water is relatively low, roughly $1.02/m³, combining the CAPEX and the OPEX in the lifecursive of the plant. Although more expensive to develop in initial capital investment, the operational costs relative to Ras Al-Khair are lower and hence are made economically competitive because of the lower energy consumption associated with energy efficiency and energy recovery systems.

On the other hand, Shoaiba, with a lower CAPEX of $5 billion and higher OPEX of $1.10/m³, produces 150 million m³ of water annually. Furthermore, because the more energy-intensive Multi Stage Flash (MSF) technology prevails, Shoaiba faces a cost of $1.60/m³ of water.. Shoaiba is advantaged in a lower initial investment but suffers from a higher operational expenditure that reduces efficiency in the long term in terms of cost.

Cost per kWh of energy

The other determinant of the energy efficiency of any desalination plant is the cost of energy per kilowatt hour (kWh) consumed during operation. This enables an assessment of the cost to generate each unit of energy consumed by desalination, providing an indicator of each plant's total energy efficiency and cost-effectiveness. Ras Al-Khair enjoys low energy cost per kWh owing to utilizing energy recovery systems in Reverse Osmosis (RO) technology, which are sensitive to natural gas cost variations. The operational efficiency offered by the plant is such that the estimated plant contribution in terms of cost per kWh consumed is $0.12 - $0.18/kWh, even though its energy consumption is 3 – 5 kWh/m³ of capacity. Conversely, energy is produced at a higher cost per kWh using the energy-intensive MSF technology coupled with primary energy such as crude oil. Using fossil fuel, the Shoaiba uses 13–15 kWh/m³ with a significantly higher energy cost per kWh of $0.25–$0.30/kWh.

Break-even Analysis

The break-even period is the time needed to recoup the initial capital investment (CAPEX) in a desalination plant from its water production revenues. It is an important one that dictates whether each desalination technology is financially viable or long-term sustainable. This move was achieved by varying CAPEX, OPEX, and the revenue from selling desalinated water.

The CAPEX of $7.6 billion at Ras Al-Khair also has the break-evenbreak-even analysis to recover its investment in about 12 years. Due to low operations costs and profitability in the long run, this plant's payback period is quite short.

On the other hand, Shoaiba requires only $5 billion for CAPEX, while its break even is set to take about 18 years. However, because Shoaiba has a higher OPEX (mainly high energy cost and maintenance), its payback period is longer than the other two desalination alternatives (Table 1).

Table 1: Cost Summary

Metric	Ras Al-Khair	Shoaiba
CAPEX (Billion USD)	7.6	5.0
OPEX (USD/m³)	0.65	1.10
Annual Water Production (m³)	325 million	150 million
Cost per m³ of Water (USD)	1.02	1.60
Energy Consumption (kWh/m³)	3–5	13–15
Cost per kWh of Energy (USD)	0.12–0.18	0.25–0.30
Break-even Period (Years)	12	18

Discussions

The basis for the environmental analysis is the comparison of energy consumption between the two plants. Having imported water consumption of 3–5 kWh/m³, Ras Al-Khair's water use is significantly lower than Shoaiba's, where consumption is a steep 13–15 kWh/m³; the RO technology with the energy recovery proves to be very efficient. These results align with sGude (2016) and Panagopoulo (2021), who showed that RO systems have a much lower energy demand per produced water than thermal desalination technologies, such as MSF. The integration of the energy recovery system also demonstrates the decreased energy demand of Ras Al-Khair, thereby accentuating the role of energy-saving technologies in combating issues related to high desalination operational costs and environmental impacts (Soliman *et al.*, 2021).

However, Shoaiba is energy-intensive and highly environmentally detrimental due to its power generation based on crude oil. Oil-based desalination systems emit a high global warming potential (GWP) of 8.2 million tons annually due to the Shoaiba MSF process. This aligns with Schär *et al.* found: thermal processes such as MSF are generally more carbon-intensive because they rely on fossil fuels. Furthermore, the carbon capture system in Ras Al-Khair further reduces the amount of CO_2 emissions by 300 000 tons per year, a function that adds to the overall environmental sustainability of the plant and contributes to the transition towards low carbon desalination technologies (Schär *et al*., 2023).

Furthermore, brine disposal is another advantage of Ras Al-Khair over Shoaiba. Shoaiba brine (65-70 g/L) is discharged untreated, while brine dilution techniques are applied in Ras Al-Khair plants to reduce the levels of ecological risk of discharge. High salinity brine discharge is known to deplete oxygen and harm aquatic life, disposing of the risk of marine ecosystem disruption as per literature (Fernández-Torquemada *et al*., 2019). Therefore, a site with less salty brine (50–55 g/L) and less mineral salts is more environmentally responsible as the sustainable option for disposing of brine.

In the cost analysis, an examination of the long-term cost benefits obtained through lower operational expenditure ($0.65/m^3) makes the initial capital expenditure, while the price for the Ras Al-Khair mine project ($7.6b) is comparatively higher than the other two projects, attractive. Shoaiba, with a lower CAPEX of $5 billion, incurs higher OPEX ($1.10/m^3) due to its energy-intensive MSF system. The work Gao *et al*. (2021) presented demonstrates that RO-based desalination facilities will initially be more costly to invest but will cost far less in the long term because of the lower energy requirement. The main difference lies precisely in the huge energy requirement of MSF, as well as the efficiency of Shoaiba's technology, which leads the plant to burn more fuel and to repeat its processes more frequently (Gao *et al*., 2021).

Another factor that enhances the cost advantages of Ras Al-Khair is that the cost of producing one cubic meter of water is only $1.02/m^3, substantially lower than the $1.60/m^3 at Shoaiba. That aligns with findings by Mansour *et al*. (2020), who previously showed that energy recovery systems in RO plants can decrease operational costs by 40% (Mansour *et al*., 2020). Furthermore, the break-even analysis conducted on Ras Al-Khair returns its investments in roughly 12 years, which is consistent with what Sawle *et al* (2018) observe when discussing the research trend on hybrid systems, which initially cost more yet are financially sustainable in the long term because of their efficiency and reduced operating costs (Sawle *et al*., 2018).

The findings of this research show that a synergy between the environment and cost optimization is significant. Improvement of Ras Al-Khair through the combination of energy recovery systems and carbon capture technologies shows that energy-efficient technology increases the economic viability and environmental outputs of the process. The study correlates with the findings of Ghazi *et al*. (2022) who also mentioned that desalination ought to be rendered sustainable by providing energy recovery and use of renewable energy. The Ras Al-Khair characteristics of high sensorial carbon capture and low energy consumption demonstrate the ways of how the advanced technologies can eliminate the environmental harm and maintain the economies low (Ghazi *et al*., 2022).

Moreover, the presence of the hybrid RO/MSF system in Ras Al-Khair confirms that the hybrid desalination systems can be used to facilitate the optimal combination of energy consumption and environmental impact, as stated by Heidary *et al*. (2018), which means that the employment of the hybrid system can utilize the existing waste heat to reduce the external energy input requirements (Heidary *et al*., 2018). This is consistent with Heidary *et al*. (2019), who could increase the cost-effectiveness and reduce greenhouse gas emissions by integrating energy recovery systems into desalination infrastructure (Heidary *et al*., 2019).

CONCLUSION

The environmental and economic environmental performance of desalination technologies at Ras Al-Khair and Shoaiba desalination plants has been comprehensively evaluated for this study. Results indicate that Ras Al-Khair's hybrid RO/MSF system becomes environmentally most sustainable, consuming less energy, creating less carbon emissions and better brine management, versus Shoaiba's traditional MSF system. Also, Ras Al-Khair has lower operational costs and a quicker break-even period, further suggesting the financial benefit of energy-efficient technologies on desalination.

The results reinforce the value of related cost optimization with environmental sustainability in future desalination projects. By incorporating energy recovery systems, renewable energy schemes, and carbon capture technologies, desalination plants can become economically viable in the long term and lower their ecological impact. This study's findings can provide rich insights for policymakers and stakeholders in the desalination sector to adopt more sustainable and cost-effective desalination technologies to mitigate global water scarcity issues.

Limitations and Future Recommendations

Although much can be learned from this study regarding desalination technologies' environmental and economic performance, some limitations should be addressed in the future. A significant limitation is the use of regional energy and emission factor data that do not always cover global parameters of energy sources and emissions profiles. Future studies would need more localized data and more contextualization concerning areas based on the energy grid and environmental regulations. In addition, this research focused primarily on large-scale desalination plants, but further study in the context of scale and decentralized systems powered by renewable energy (which have great potential in supplying water to underserved or off-grid communities whilst dealing with challenges with water scarcity) may be useful for applications to some cases soon.

Other future areas of research include the social and economic impacts of desalination, such as community acceptance, water affordability, and public health effects of large scale desalination projects. A more systemic approach that considers these attributes and environmental and economic dimensions will help provide decision-makers with more informed decisions and promote desalination technologies that benefit the environment, economy, and large. Additionally, integrated models that integrate cost and environmental sustainability metrics are required for development to guide desalination project management in developing a financially viable and environmentally responsible solution.

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