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Environmental Impact Management and Monitoring in Desalination Processes: A Case Study of Bandar Lengeh (Persian Gulf) Based on ISO 14040/14044 Standards

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Abstract

In the context of escalating water stress in coastal and arid regions, seawater desalination has become a key pillar of freshwater supply. However, the high energy dependence of this process, particularly in hot and saline regions such as the Persian Gulf coasts, has made environmental impact assessment a managerial necessity. This study presents a framework for managing and monitoring the environmental impacts of desalination technologies in Bandar Lengeh, based on ISO 14040 and ISO 14044 standards. A cradle-to-grave life cycle assessment (LCA) was conducted using the production of 1 m³ of potable-quality freshwater as the functional unit. The analysis shows that, in fossil-fuel-based systems, the operation stage accounts for more than 90% of greenhouse gas emissions; therefore, specific energy consumption and grid carbon intensity are the most influential determinants of the carbon footprint. A comparative assessment of desalination technologies further indicates that reverse osmosis performs more favorably from an environmental perspective than thermal technologies such as MED and MSF. Scenario analysis also demonstrates that integrating renewable energy sources, especially solar and wind power, can significantly reduce carbon emissions. Finally, by introducing key environmental performance indicators and a continuous monitoring framework, this paper provides a practical decision-making model for managing desalination facilities in Bandar Lengeh and other similar sites across the Persian Gulf region.

Keywords Desalination, Life Cycle Assessment, Carbon Footprint, Persian Gulf, Environmental Management

1. Introduction

Water scarcity in many arid and semi-arid regions of the world, particularly in coastal areas, has made desalination technologies one of the primary options for freshwater supply [1]. In Iran, the southern coastal zones, especially areas adjacent to the Persian Gulf, have become increasingly dependent on the expansion of desalination systems due to limited surface and groundwater resources, grow-

ing urban and industrial demand, and mounting pressures associated with climate change. In this context, Bandar Lengeh, as one of the country's important southern coastal locations, provides a suitable case for examining the technical and environmental challenges and requirements of desalination processes.

Although desalination plays a significant role in enhancing water security, it is also associated with major envi-



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ronmental challenges. High energy consumption, greenhouse gas emissions, chemical use, brine disposal, and equipment degradation in high-salinity environments are among the key impacts that must be considered when assessing the sustainability of these systems [2]. In the Persian Gulf region, this issue becomes even more critical due to the higher salinity of seawater, elevated ambient temperatures, and the sensitivity of coastal ecosystems. Under such conditions, evaluating desalination performance solely on the basis of production capacity or economic cost is insufficient; its environmental burden must also be assessed throughout the entire life cycle [3, 4]. Life cycle assessment (LCA) is one of the most widely recognized analytical tools for evaluating the environmental impacts of products and processes across all stages of their life cycle [4]. ISO 14040 and ISO 14044 provide a scientific and systematic framework for goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation of results [5, 6]. Applying this approach to desalination makes it possible to identify major emission hotspots, determine the contribution of each life cycle stage, and more accurately evaluate the effectiveness of emission reduction scenarios [3].

Despite the growing number of LCA studies on desalination, many focus mainly on comparisons between technologies. Less attention has been given to management frameworks for the continuous monitoring of environmental impacts [4, 7]. This study therefore aims to develop a management and monitoring model for desalination systems in Bandar Lengeh. The model follows the principles of ISO 14040 and ISO 14044 [5, 6] and considers local conditions, including high feedwater salinity, hot climatic conditions, and dependence on the regional electricity mix.

This study addresses three questions: (i) Which life-cycle stage contributes most to greenhouse gas emissions from desalination systems? (ii) Which desalination technology is more suitable for Bandar Lengeh in terms of emission intensity? and (iii) How can continuous monitoring of operational and energy-related indicators support a low-carbon management strategy? The findings can support water-sector managers, energy planners, and environmental policymakers in southern Iran.

2. Methodology

This study was developed based on the life cycle assessment framework established in ISO 14040:2006 and ISO 14044:2006 [5, 6]. The research approach was designed not only to support environmental analysis, but also to provide practical value for operational management and continuous monitoring of desalination systems [7]. Accordingly, the methodology was structured into four main

stages: goal and scope definition, life cycle inventory compilation, impact assessment, and interpretation of results [2].

In the first stage, the objective of the study was defined as the quantification of the carbon footprint and the identification of environmental hotspots in desalination processes applied in Bandar Lengeh. Given the climatic conditions and the characteristics of seawater in the Persian Gulf [9], the functional unit was defined as the production of 1m³ of potable freshwater at the point of operation. The selection of this functional unit enables direct comparison among different desalination technologies and energy supply scenarios. The system boundary was defined as cradle-to-grave, meaning that raw material extraction and production, equipment and infrastructure manufacturing, operation, maintenance, chemical consumption, and end-of-life treatment of equipment were all included in the assessment [4].

In the second stage, the life cycle inventory (LCI) was compiled. At this stage, input and output flows, including energy, materials, equipment, and waste streams, were identified and categorized. The main data considered included specific electricity consumption per cubic meter of produced water, consumption of chemicals used for pretreatment and membrane cleaning, water recovery rate, feedwater characteristics, and the general characteristics of the energy supply network [3]. Because this study focuses on Bandar Lengeh, the analytical framework considers the local characteristics of Persian Gulf seawater and the regional electricity supply. Feedwater conditions were characterized by a total dissolved solids (TDS) range of 39,000-44,000 mg/L and seasonal operating temperatures of 20-34 °C. High salinity and elevated temperatures can increase the likelihood of scaling [4]. Scaling may require higher operating pressure, increase energy consumption, and lead to more frequent maintenance. These effects can increase the carbon footprint of the desalination process. To represent the regional energy context, the carbon intensity of the electricity grid was estimated at 0.58-0.62 kg CO₂-eq/kWh, reflecting the dominance of thermal power generation [10].

In the third stage, the life cycle impact assessment was carried out with a focus on the global warming potential (GWP) indicator. This indicator is expressed as kilograms of CO₂ equivalent per m³ of produced freshwater and was adopted as the key environmental performance indicator in the proposed management framework. GWP was selected because, in desalination systems, the dominant environmental burden is generally associated with energy consumption and the resulting greenhouse gas emissions [8]. Therefore, this indicator provides managers with a clear and comparable basis for evaluating different tech-

Table 1. Comparative analysis of carbon footprint across major desalination technologies [3, 9]

Technology	Process Type	Carbon Footprint Range (kg CO ₂ -eq/m ³)	Representative value (kg CO ₂ -eq/m ³)	References
RO	Membrane	0.4-7.3	3.85	[3, 9]
MED	Thermal	7.0-17.6	12.30	[3, 9]
MSF	Thermal	6.7-25.0	15.85	[3, 9]
NF & Hybrid (e.g., NF-RO)	Membrane/Hybrid	< 2.0	Not reported	[3, 9]
Solar-RO	Solar-powered RO	0.4-0.6	0.50	[3, 9]
Note: The typical values represent the midpoint of the reported carbon-footprint ranges and are provided for comparative purposes only. The ranges and representative values were compiled from the cited sources.				

nological and energy options.

In the fourth stage, sensitivity analysis and a continuous monitoring framework were incorporated into the methodology in order to increase the practical applicability of the results at the operational level. In this part, variables such as specific electricity consumption, grid carbon intensity, feedwater salinity, recovery rate, and the use of energy recovery devices were considered as sensitive parameters. In addition, different energy supply scenarios, including fossil-fuel-based electricity and renewable energy options, particularly solar and wind, were included in the analysis. The purpose of this stage was to move life cycle assessment beyond a static analytical tool and transform it into a system capable of supporting dynamic decision-making in the management of desalination facilities [11].

Accordingly, the proposed model in this study is not limited to presenting a general estimate of the carbon footprint; rather, it provides a platform for the periodic monitoring of environmental performance in Bandar Lengeh. Within this framework, monthly or seasonal operational data can be updated, and trends in key indicators, particularly GWP and specific energy consumption, can be continuously assessed. Such an approach enables timely managerial intervention in response to changes in salinity, temperature, or electricity source.

2.1. Life-cycle inventory data and software

The life-cycle assessment was performed using SimaPro 9.1. Background life-cycle inventory data for energy, materials, transportation, and waste-management processes were obtained from the Ecoinvent database (version 3.9.1). Primary inventory data were collected from laboratory experiments and relevant operational records, whereas secondary background data were obtained from Ecoinvent version 3.9.1. The methodology and inventory compilation were conducted in accordance with the prin-

ciples and requirements of ISO 14040 and ISO 14044.

3. Results and discussion

Published LCA studies indicate that the operation stage is the main source of greenhouse gas emissions in desalination systems powered by fossil-based energy [3, 4]. In many cases, this stage accounts for more than 90% of the total carbon footprint. Plant construction generally makes a smaller contribution, whereas chemical consumption has an intermediate contribution [4]. These findings show that environmental performance is driven primarily by energy use during operation. In Bandar Lengeh, management efforts should therefore focus on reducing specific electricity consumption and improving the electricity supply mix.

This issue is particularly important in Bandar Lengeh. The relatively high salinity of Persian Gulf water and hot ambient conditions may increase the required operating pressure and energy demand. Consequently, the operation stage is likely to be the principal environmental hotspot in local desalination facilities. Continuous or periodic monitoring of specific energy consumption is therefore recommended.

Published evidence generally indicates that reverse osmosis (RO) has a lower carbon footprint than thermal desalination technologies, such as multi-effect distillation (MED) and multi-stage flash distillation (MSF) [3, 9]. Table 1 summarizes carbon-footprint ranges reported for these technologies. The reported range for RO is approximately 0.4-7.3 kg CO₂-eq/m³ of freshwater, compared with 7.0-17.6 kg CO₂-eq/m³ for MED and 6.7-25.0 kg CO₂-eq/m³ for MSF [3, 9].

These values should not be interpreted as directly comparable site-specific estimates. They vary with system boundaries, energy and heat sources, plant scale, feedwater salinity, recovery ratio, and infrastructure assumptions. Nevertheless, the available evidence suggests that

Table 2. Relative contribution of life-cycle stages under two energy supply scenarios [4, 9]

Emission source	Fossil-based electricity supply: approximate contribution (%)	High-renewable/wind-based electricity supply: approximate contribution (%)
Direct electricity consumption during operation	80-95	30-60
Chemical consumption during operation	2-10	10-30
Construction of plant facilities and energy infrastructure	2-8	15-35
Upstream supply-chain emissions	1-5	5-20
Note: The percentages represent approximate ranges compiled from the cited literature [4, 9] for desalination systems with comparable process configurations. They are intended to illustrate the relative redistribution of environmental burdens between energy-supply scenarios and should not be interpreted as exact measurements for the Bandar Lengeh case study. The contribution ranges may overlap and may not sum to exactly 100% because they depend on the technology, system boundary, operational conditions, infrastructure lifetime, and electricity mix.		

RO and hybrid membrane systems may better support emission-reduction objectives in Bandar Lengeh. Their performance can be further improved through energy-recovery devices and optimized operating pressure.

Technology selection alone does not determine the final carbon footprint. The electricity supply mix is equally important [7, 12]. For an RO system with a specific energy consumption of approximately 3.5 kWh/m³, emissions can vary substantially with the electricity source. The carbon footprint is lower in low-carbon electricity systems and higher in grids dominated by fossil fuels. Therefore, environmental assessments in Bandar Lengeh should consider both desalination technology and electricity carbon intensity. The proposed management framework should monitor these two indicators in parallel.

Renewable energy can substantially reduce the carbon footprint of desalination [13]. Literature-based scenarios indicate that powering RO systems with solar or wind energy can reduce greenhouse gas emissions by more than 50%. In some solar-powered RO configurations, the carbon footprint may decline to approximately 0.4-0.6 kg CO₂-eq/m³ [14]. This option is relevant to Bandar Lengeh because southern Iran has high solar-energy potential. Therefore, emission reduction should address both process efficiency and the electricity supply system. As electricity-related emissions decrease, other life-cycle components become relatively more important. These components include chemical consumption, equipment manufacturing, and infrastructure [2, 4]. This shift highlights the need to avoid transferring environmental burdens from electricity use to other life-cycle stages. Table 2 presents illustrative ranges derived from comparable

desalination studies. These ranges show how the relative contributions of electricity, chemicals, infrastructure, and upstream processes may change under fossil-based and high-renewable electricity-supply scenarios. They are not direct measurements from a desalination facility in Bandar Lengeh.

The sensitivity analysis highlights the importance of energy management during operation. The estimates indicate that a 10% reduction in electricity consumption could reduce GWP by approximately 5%. This reduction depends on the relative contribution of electricity to total life-cycle emissions. Energy-recovery devices, high-efficiency pumps, optimized operating pressure, and appropriate recovery rates can reduce specific energy consumption. Higher feedwater salinity can also increase the required pressure and energy demand. Seasonal and local variations in seawater quality should therefore be included in the monitoring framework.

From a strategic perspective, the findings of the present study suggest that the environmental management model for Bandar Lengeh should be structured around three levels. The first level is the selection of appropriate technology, with priority given to low-carbon options such as reverse osmosis. The second level is operational optimization through continuous monitoring of indicators such as specific energy consumption, recovery rate, feedwater salinity, and the performance of energy recovery equipment. The third level is the gradual transformation of the energy mix through increasing the share of renewable energy sources. The integration of these three levels can transform desalination management from a purely technical activity into an environmentally informed deci-

sion-support system.

Accordingly, global warming potential, expressed as kg CO₂-eq per m³ of produced water, can be defined as the primary key performance indicator (KPI) within the environmental monitoring framework of desalination sites in Bandar Lengeh [3, 4]. In parallel, complementary indicators such as specific energy consumption, electricity carbon intensity, chemical consumption, and water recovery rate should also be measured and analyzed on a regular basis. The main advantage of this framework is that it enables performance comparisons across different time periods and supports the evaluation of the effectiveness of both technical and managerial interventions.

4. Study Limitations

This study should be interpreted in light of several limitations. First, the proposed framework is case-oriented and based primarily on published evidence and scenario interpretation rather than on a full plant-specific life cycle inventory derived from measured operational data in Bandar Lengeh. Second, the assessment focuses mainly on global warming potential and does not quantify other relevant impact categories such as marine ecotoxicity, eutrophication, or brine-related ecological effects. Third, the reported carbon footprint ranges are drawn from studies with different methodological assumptions, system boundaries, and regional settings. Future research should therefore apply the proposed framework to site-specific inventory data from desalination facilities in Bandar Lengeh in order to strengthen empirical accuracy and improve environmental benchmarking.

Other environmentally critical categories, such as marine ecotoxicity, freshwater eutrophication, and localized brine-discharge impacts, were excluded at this stage primarily due to the scarcity of high-resolution, site-specific background characterization factors and long-term marine biological monitoring data in the Bandar Lengeh coastal zone. Future research should expand this single-indicator framework into a multi-criteria life cycle impact assessment (LCIA). It should integrate localized hydrodynamic-dispersion models and field-based marine ecotoxicity metrics to provide a more comprehensive environmental profile.

5. Conclusion

Applying the ISO 14040 and ISO 14044 life cycle assessment framework, this study developed an operational monitoring model for seawater desalination in Bandar Lengeh. The results indicate that the operational stage dominates total greenhouse gas emissions under fossil-based energy regimes. Reverse osmosis (RO) demonstrates superior environmental performance compared to

thermal alternatives (MED and MSF); however, maximizing this advantage requires coupling technology selection with low-carbon energy transition and operational optimization. While solar and wind integration substantially mitigates emissions, life-cycle burdens associated with chemical consumption, membrane degradation, and infrastructure must not be overlooked.

To operationalize these findings, facility managers in Bandar Lengeh should adopt global warming potential (kg CO₂-eq/m³) as the primary environmental key performance indicator (KPI). Specifically, practical plant management should include: (i) daily tracking of specific energy consumption and membrane differential pressure to promptly detect fouling under elevated summer salinities; (ii) monthly carbon-footprint accounting to evaluate grid emission dependencies; (iii) quarterly calibration of energy recovery devices (ERDs) and chemical dosing protocols; and (iv) phased integration of on-site solar photovoltaic (PV) systems. This integrated framework provides a dynamic, transferable decision-making model for sustainable coastal desalination across the Persian Gulf.

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Declarations

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Not applicable.

Consent for publication

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Competing interests

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