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Regional meeting to review guidelines on available treatment technologies for urban wastewater and sludge, industrial pre-treatment, and environmental standards and available desalination treatment technologies

Ankara, 22-23 November 2022

Agenda item 5: Regional standards on desalination technologies

Guideline on Reginal Standards for Discharge from Desalination Plants and Decision Support Systems for Sustainable Desalination Technologies in the Mediterranean

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Note by the Secretariat

Following the adoption by COP 22 (Antalya, Türkiye 7-10 December 2021) of Decision IG.25/19 on UNEP/MAP's Programme of Work and Budget, the Secretariat/MED POL Programme was requested under Output 1.2, Activity 1.2.3 to prepare regional standards on desalination technologies and available environmental standards for discharging brine to the marine environment.

Previously, the Contracting Parties adopted in COP20 Decision IG.23/13 on the "Updated Guidelines on the Management of Desalination Activities." These Guidelines elaborated the impact of desalination activities with a particular focus on the marine environment including recommendation for mitigating those impacts. The Guidelines provided extensive information on the environmental impact assessment process together with monitoring requirements to be established during the construction phase as well as in the long-term.

In comparison, the current Guidelines build on of the notion of sustainable desalination by recommending proven desalination technologies as well as proposing common discharge standards to be established, as appropriate, at the regional level. Moreover, this Guideline provides a greater context for the following three aspects:

a. Available state of the art desalination technologies and their possible implementation in the context of sustainable desalination solutions.
b. Regulatory aspects for seawater desalination including compliance with the amendments to the Annexes of the LBS Protocol; recommended emission limit values; as well as guidance for implementation of regular monitoring programmes for discharges from desalination plants; and
c. Recommendations on Decision Support Systems (DSS) with the aim to assist policy makers/facilities' operators in applying best technologies which are appropriate to achieve sustainable desalination in compliance with national/regional legal frameworks and regulations.

The regulatory aspects for seawater desalination as well as the recommendations on DSS are new aspects included for the first time in the Guidelines for management of desalination activities with the aim to strengthen the decision-making process for sustainable desalination at regional scale in the framework of adopted standards.

In compiling this Guideline, scientific literature on desalination and treatment of discharges from desalination plants were reviewed as detailed in the references section to this report. Special emphasis was given to reviewing up-to-date reports and technical documents that have been developed by scientific institutions and international organizations including the United States Environmental Protection Agency (EPA) and the European Union (EU), as well as to reflecting recent global and regional initiatives in the field of desalination.

This guiding document is presented to the Regional Meeting to review Guidelines on Available Treatment Technologies for Urban Wastewater and Sludge, Industrial Pretreatment, and Environmental Standards and Available Desalination Treatment Technologies for their review with the aim of submission to the MED POL Focal Points Meeting, planned to be held in May 2023, for their approval.

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Abbreviations and Acronyms

AD	Adsorption desalination
BAT	Best Available Techniques
BEP	Best Environmental Practices
BRO	Batch Reverse Osmosis
CDI	Capacitive Deionization
CHD	Clathrate Hydrate Desalination
COP	Conference of the Parties
DSS	Decision Support Systems
ED	Electrodialysis
EEA	European Environmental Agency
EIA	Environmental Impact Assessment
EMPs	Environmental Monitoring Plans
EU	European Union
FD	Freeze Desalination
FEI	Freshwater Ecosystem Impact
FO	Forward Osmosis
FWI	Freshwater Withdrawal Impact
GES	Good Environmental Status
GHG	Emissions Greenhouse Gas Emissions
GWI	Global Water Intelligence
HDH	Humidification Dehumidification
IDA	International Desalination Association
IMAP	Integrated Monitoring and Assessment Programme
LBS	Land Based Sources Protocol
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainable Assessment
LCC	Life Cycle Costing
MCA	Multi Criteria Analysis
MD	Membrane distillation
MED	Multiple Effect Distillation
MSF	Multi-Stage Flash Distillation
MED POL	Mediterranean Pollution Control and Assessment Programme
PRO	Pressure retarded osmosis
RO	Reverse Osmosis
RED	Reverse Electrodialysis
SCWD	Supercritical Water Desalination
SED	Solvent Extraction Desalination
SLCA	Social Life Cycle Assessment
STD	Solar Thermal Desalination
SW	Seawater
UNEP/MAP	United Nations Environment Programme /Mediterranean Action Plan
WFD	Water Framework Directive
ZLD	Zero Liquid Discharge

1. Introduction

2. In their 20th Ordinary Meeting to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean and its Protocols (Tirana, Albania, 17-20 December 2017), the Contracting Parties adopted in their Decision IG.23/13 the “Updated Guidelines on the Management of Desalination Activities.”

3. The aim of the 2017 Updated Guideline was to better describe the desalination efforts around the Mediterranean and to assess their impacts on the coastal and marine environment. The Updated Guideline also served to provide information to the Contracting Parties on conducting Environmental Impact Assessments (EIA) for the implementation of desalination projects including environmental monitoring requirements.

4. Complementing the 2017 guidelines, in this Guideline, the reginal standards for discharge from desalination plants and decision support systems for sustainable desalination technologies in the Mediterranean are presented. This guideline which complements the 2017 Guidelines is built upon the following three pillars:

a. Available state of the art desalination technologies and their possible implementation in the context of sustainable desalination solutions. In this section, designers and operators of desalination plants are provided with information on emerging seawater desalination technologies, factors contributing to sustainable seawater desalination, pillars of sustainable seawater desalination, as well as the technological tools for sustainable desalination of seawater;

b. Regulatory aspects for seawater desalination including compliance with the amendments to the Annexes of the LBS Protocol; recommended emission limit values based on prevailing regional standards for seawater desalination; as well as guidance for implementation of regular monitoring programmes for discharges from desalination plants; and

c. Recommendations on Decision Support Systems (DSS) based on multi criteria analysis (MCA) and life cycle assessment (LCA) with the aim to assist policy makers/facilities’ operators in applying best technologies which are appropriate to achieve sustainable desalination in compliance with national/regional legal frameworks and regulations.

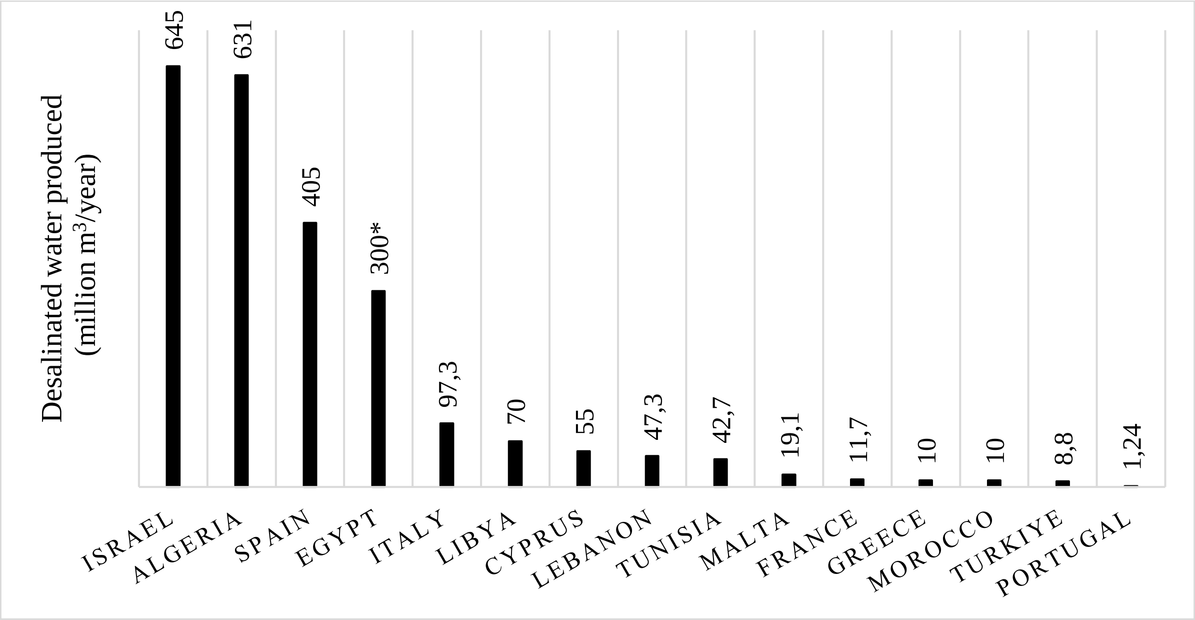
2. Seawater Desalination – Facts and Figures

5. Desalination can be divided into two categories depending on the feedwater source: seawater desalination and brackish water desalination. There are 15,906 working desalination plants worldwide with a total desalination capacity of approximately 95.37 million m^3/day (34.81 billion m^3/year), constituting 81% and 93% of the total number and capacity of desalination plants ever built respectively (Jones et al., 2019). Seawater desalination makes up roughly 61% of the 5328 desalination plants when it comes to capacity and plant count. Brackish and hard river waters account for 8% of 1825 plants, whereas brackish water desalination accounts for 21% of 5960 plants (Elsaid, Kamil, et al., 2020). This document serves as a comprehensive guide to the process of seawater desalination.

6. While brackish water, river water, wastewater, and brine water desalination each produced more than 15.4 million, 6.5 million, 4.4 million, and 110,501 m^3/y of freshwater, respectively, seawater desalination is still the most common method used worldwide, producing over 43.2 million m^3/y in 2018 (GWI, 2018). Since 2010, the global installed desalination capacity has been continuously expanding at a rate of roughly 7% per year through the end of 2019, which is equivalent to an average annual addition of roughly 4.6 million m^3/day of production capacity. In total, 155 new desalination plants were contracted and put into service worldwide from January 2019 to February 2020 alone, adding 5.2 million m^3/day to installed capacity (Eke et al., 2020).

7. Beginning in July 2016, 18,983 plants and projects around the world have a cumulative desalination capacity for freshwater production of 95.6 million m^3/day. By the end of 2017, the overall operating capacity of installed plants was estimated at 93% of the installed capacity, with a cumulative desalination capacity of 99.8 million m^3/day (considering facilities completed since 1965). Global installed and cumulative desalination capabilities for freshwater production as of mid-February 2020 were provided by 20,971 projects, and they were 97.2 million m^3/day and 114.9 million m^3/day, respectively. There were 16,876 installed plants among these 20,971 projects (Eke et al., 2020).

8. The United Nation's Food and Agriculture Organization (FAO 2019) provides the most up-to-date and thorough survey of desalination capacity in the Mediterranean region as depicted in Figure 1 (with the exception of Egypt where the amount of desalinated water is obtained from a study by Elsaie et al. 2022).



** Data for Egypt is obtained from a study by Elsaie et al. 2022*

Figure 1. Production of desalinated water in the Mediterranean (FAO, 2019)

9. A quick glance of the state of desalination in the region shows that Israel, Algeria, Spain and Egypt are the major producers of desalinated water in the Mediterranean region. Israel's annual desalination capacity is about 80% of the total urban water consumption (Miller et al., 2015). In Algeria and Morocco, 85% and 60% of desalination plants use seawater as their source of feed water, respectively (Dhakal et al., 2022). Spain has the most important desalination plants in Europe, located in Torrevieja in the province of Alicante, in the Region of Valencia and El Prat located in the Metropolitan area of Barcelona, which is one of the most heavily populated areas in Spain (Morote et al., 2017). In Libya, desalination technology has been used since the early 1960s, although few desalination plants have been established since then. In total, Libya currently has about 21 operating desalination plants in which thermal processes represent about 95% of production capacity while reverse osmosis membrane technology represents 5% (Brika, 2018). In Egypt, over 90 seawater desalination plants are operational (Elsaie et al., 2022). In Malta, desalinated water constitutes up to 60% of the drinking water supply.

3. Desalination technologies and their possible implementation in the context of sustainable desalination solutions

10. In this section, available state of the art desalination technologies, particularly novel and emerging seawater desalination, is presented with the aim to explore their possible implementation in

the context of sustainable desalination. To this aim, factors contributing to sustainable seawater desalination, the three pillars of sustainable seawater desalination; sustainability indicators for sweater desalination, as well as the technological tools for sustainable desalination of seawater are discussed.

3.1 Common desalination technologies

11. The "Updated Guideline on the Management of Desalination Activities" (2017) provides an overview of the most common thermal and membrane process desalination technologies including Multistage Flash Distillation (MSF), Multiple Effect Distillation (MED); as well as Reverse Osmosis (RO) and Electrodialysis (ED).

12. Reverse Osmosis (RO) is by far the most dominant desalination technology, accounting worldwide for 84% of the total number of operational desalination plants and producing 69% (65.5 million m^3/day) of total global desalinated water. Despite their small number, the two major thermal technologies, Multi-Stage Flash Distillation (MSF) and Multi-Effect Distillation (MED), produce the majority of the remaining desalinated water, with market shares of 18% and 7%, respectively (Jones et al., 2019).

13. It should be noted that hybrid technologies like MSF-MED, MED-adsorption (MED-AD), and RO-MSF are currently being considered to improve the efficiency of desalination plants by combining the advantages of each technology to compensate for the weaknesses of the others.

3.2 Novel and emerging seawater desalination technologies

14. The interest in emerging technologies has increased due to the increasing demand for desalination and the high energy consumption, fouling and brine discharge issues in existing technologies. To overcome the current challenges in RO, MED and MSF technologies, there has been an increased focus on developing processes with low energy requirements. Emerging desalination technologies have the potential to compete with conventional technologies for seawater desalination, or to outperform these technologies in niche areas; however, their transition to full-scale employment depends on further scientific advances to achieve threshold performance and energy efficiency (Ahmed et al., 2021).

15. Membrane Distillation (MD), Forward Osmosis (FO), Adsorption Desalination (AD), Capacitive Deionization (CDI), Freeze Desalination (FD), Humidification Dehumidification (HDH), Clathrate Hydrate Desalination (CHD), and Batch Reverse Osmosis (BRO), Solar Thermal Desalination (STD) , Solvent Extraction Desalination (SED), Supercritical Water Desalination (SCWD) are several emerging desalination technologies that are still largely in the research and development stages. A detailed description of the aforementioned emerging technologies is presented in the Appendix I

16. Pretreatment technologies, such as ultrafiltration (UF), nanofiltration (NF), ionic filtration (IF) and Zero Liquid Discharge (ZLD) have been also explored to increase the efficiency of desalination plants (Eke et al., 2020; Park et al., 2022).

17. Moreover, hybrid systems that combine various energy sources and desalination technologies seem to offer the most promising solutions. Innovative hybrid solar (or wind) energy driven systems coupled with highly effective desalination processes show promise in places with rising water scarcity and high solar radiation. Additionally, research is being done all over the world to increase the effectiveness of currently commonly used desalination processes (such as RO) as well as to find new solutions, such as metal-air desalination batteries and desalination via gas hydrate, as well as new materials, such as 3D printing for membrane separation, carbon nanotubes, Janus composite hollow fiber membrane-based direct contact distillation, single-layer graphene membranes, and nanofibrous membranes (Bundschuh et al., 2021).

18. Brine disposal in seawater desalination is a very important issue due to negative environmental impacts. As a result, an alternative and more sustainable approach to mitigating the

effects of brine discharge has been considered. This method is referred to as zero liquid discharge (ZLD). More detailed information about the ZLD approach is given also in Appendix I.

3.3 Factors contributing to sustainable seawater desalination

3.3.1 Reducing environmental impacts

19. The majority of the environmental impacts of seawater desalination are attributed to brine discharges, which can degrade coastal water quality and harm marine life (Heck et al., 2018; Panagopoulos et al., 2019). However, the impingement and entrainment during seawater intake, the effects of brine and chemical discharge, changes in seawater quality, negative effects on fish resources, the degradation of marine habitats as a result of toxic brine concentrations, air pollutant emissions attributed to the energy demand of the processes are the main environmental impacts of seawater desalination processes (Elsaid, Kamil, et al., 2020). In addition to creating a number of environmental concerns, the seawater desalination industry offers a great deal of potential for using brine to produce some precious resources as a byproduct (Mavukkandy et al., 2019). In light of the desalination industry's expected, rapid growth, chemical composition of brine suggests that it may have both economic and ecological benefits (Ayaz et al., 2022).

20. Significant environmental impacts of sweater desalination are associated with the intake of seawater; brine discharge as well as for emerging contaminants released during the desalination process. These impacts are addressed in the “Updated Guidelines on the Management of Desalination Activities” (2017). In the current guideline, recommendations are provided for reducing impacts of the aforenoted aspects with the aim to achieving sustainable seawater desalination:

21. With regards to the intake of seawater (Kress 2019), and taking into consideration the nature of the local environment at the intake area, intake capacity, intake type, and structure, the following recommendations can be considered:

a. Install intake structure in zones of deep waters and less biological productivity.
b. Install bypass mechanisms to enable the returning of organisms that have been impinged on in the intake site.
c. Decrease the effluent flow velocity; 0.15 m/s is suggested so that fish can resist impingement.
d. Install behavioral barriers, such as horizontal velocity-caps that provide less impingement than vertical velocity-caps, and sound and light-generating equipment to keep organisms outside.
e. Locate the intake at a hydrologically active region with strong currents and waves.
f. Minimize over drafting and draining freshwater from the subsurface reservoir.
g. Appropriate planning and positioning of intake/outfall basin.
h. Use of high quality, corrosion/erosion-resistant material.
i. Apply appropriate and periodic maintenance.

22. Concerning brine discharge (Elsaid, Sayed, et al., 2020), and taking into consideration the various chemicals and different coagulants in use, as well as thermal desalination processes, the following recommendations can be considered:

a. Use iron salts instead of aluminum salt as it is less toxic,
b. Optimize coagulant and flocculant dosage,
c. Use biodegradable green chemicals,
d. Apply predilution with wastewater and cooling water for brine from thermal desalination processes,
e. Perform brine treatment for removal of toxic components.

23. It should be noted that proper plant design may significantly reduce the entrapment of marine organisms at the intake and provide for the rapid dilution of brine released at the outfall; hence, reducing the environmental impacts of a single desalination plant on the local marine ecosystem. However, several desalination plants that discharge to a single body of water with limited circulation will increase the salinity of the water body because of the cumulative effect of multiple desalination plants; thus, increasing the susceptibility of semi-enclosed seas, such as the Mediterranean Sea, to increased salt levels (Gies, 2019).

3.3.2 Sustainable brine management: water, energy and mineral recovery

24. It is currently essential to use a different brine management strategy since disposal of brine strategies, which were once widely used in brine management, have recently been considered unsustainable (Alvarado-Revilla, 2015). It is necessary, in particular, to develop a strategy to decrease the volume of brine while recovering precious resources including water, minerals, salts, metals, and even energy.

25. The methods for recovering minerals can be broadly categorized into four groups based on the driving force that is used: (1) pressure-driven processes like NF and RO, (2) thermal processes like evaporation and membrane distillation (MD), (3) electrochemical potential-driven processes, and (4) physico-chemical processes like adsorption, ion exchange, etc. Currently, extraction of the four metals with the highest concentrations (Na, Mg, Ca, and K) in brine takes the form of Cl- and SO_4^{2-}. Additionally, minor elements including Li, U, Sr, Ru, and Rb among others were specifically isolated from seawater desalination concentrate.

26. Energy recovery (also known as ‘blue energy’ and ‘salinity gradient power’) has also gained attention recently in addition to the recovery of water, metals, and minerals from the brine flow of seawater desalination processes. The interest in energy recovering technologies based on salinity gradient from SWRO concentrate by an energy recovery system has risen steadily in recent years as a means of minimizing energy usage and maximizing the benefits of seawater desalination brine. The total energy consumption of the approximately 308 million kWh/day SWRO plants, which are widely used technique around the world, is estimated to be recoverable up to 40.7 million kWh/day (Wan & Chung, 2016).

3.3.3 Improving energy efficiency

27. Improving energy efficiency of current desalination technologies and development of new approaches for seawater desalination is crucial for the sustainability of the desalination sector. One of the most essential strategies to reduce energy consumption is to improve the efficiency of the process itself. Additionally, seawater desalination has a significant potential to significantly decrease its contribution to pollution by minimizing its dependency on conventional fossil fuels (Ayaz et al., 2022). It is estimated that using renewable energy sources could prevent up to 99% of the carbon dioxide produced by desalination procedures (Elmaadawy et al., 2020). On the global scale, numerous small- to medium-sized desalination facilities have been constructed that are entirely powered by renewable energy sources. However, the capacity of these desalination plants is insignificant when compared to total global production. Although the Global Clean Water Desalination Alliance (GCWDA) has set a target of 20% for all new desalination plants constructed between 2020 and 2025 to be powered by renewable sources, the overall current share of renewable energy used for desalination operations is less than 1% (Ayaz et al., 2022). Currently, solar photovoltaic contributes 43% of the major renewable sources utilized for desalination, followed by solar thermal with 27% and wind with 20% (Khan et al., 2018).

3.3.4 Applying Best Available Technology (BAT) and Implementing Best Environmental Practice (BEP)

28. The criteria for defining Best Available Techniques (BAT) and Best Environmental Practice (BEP) are specified in Annex III of the LBS Protocol as amended in 2021. The priority of the industries and groups of substances listed in Annex I for the broad preventive measures relating to the

use of BAT and the implementation of BEP is also emphasized in Annex III of LBS Protocol as amended in 2021.

29. The LBS Protocol as amended in 2021 emphasizes preventing or minimizing environmental impacts throughout all stages of a product's life cycle, maximizing the value of products, materials, and resources within the economy, and minimizing waste generation. This aspect is equally applicable for desalination plants. With regards to determining the BATs, in general or individual cases, the 2021 amended LBS Protocol makes note of the following special considerations which are equally applicable for desalination plants:

a. the commissioning dates for new or existing installations;
b. the consumption and nature of raw materials used in the process and its energy efficiency;
c. the need to prevent or reduce the overall impact of the releases to the environment and the risks to it;
d. the need to prevent accidents and to minimize their consequences for the environment;
e. the need to ensure occupational health and safety at workplaces;
f. the need to use non-toxic substances in view of facilitating non-toxic waste streams to facilitate recovery and recycling; and
g. the need to keep material and products in use as long as possible.

30. Regarding the selection of BEPs for individual cases, the 2021 amended LBS Protocol promotes the use of eco-labels, eco-design, and eco-innovation to identify environmentally sound products and the establishment of collaboration along the value chain to ensure that the origin and value of raw materials remain traceable when closing the loop are added as aspects. Implementation of the aforementioned BEPs is critical for the sustainable operation of desalination plants.

3.3.5 Meeting the sustainable development goals

31. Desalination directly contributes to the fulfillment of SDG 6 (access to safe drinking water) as well as climate change adaptation (SDG 13). Desalination offers safe drinking water in water-stressed areas, which is a prerequisite for socioeconomic development, industrial activity, and agricultural production. Furthermore, the construction of new desalination capacity can decrease demand on conventional water sources such as underground aquifers, lakes, and rivers. Additionally, desalination can also help to climate change adaptation for the reasons mentioned above (NATIXIS, 2020).

32. Moreover, desalination provides various co-benefits, indirectly contributing to the achievement of several other SDGs. Desalination facilities can be constructed to have an adjacent wind farm or solar power plant, which will help increase the use of clean energy (SDG 7). Desalination, when powered by clean energy, can lead to more sustainable cities and communities (SDG 11) in such areas by providing a reliable supply of drinking water. In addition, long-term policy support for desalination can also encourage innovation and help create local industrial players, which will help with economic growth (SDG 8), as well as industrial development, technological innovation, and infrastructure building (SDG 9) (NATIXIS, 2020).

3.4 Pillars of sustainable seawater desalination

33. The three pillars of sustainable development are addressed in this section with the aim of providing guidance on the achievement of sustainable desalination solutions. These consist of: (i) environmental sustainability; (ii) techno-economic sustainability; and (iii) social sustainability.

3.4.1 Environmental sustainability

34. In recent years, seawater desalination has gained more importance due to the increase in global environmental problems such as climate change and drought. In contrast, traditional desalination techniques increase greenhouse gas (GHG) emissions since they depend heavily on fossil fuels (in some cases, heavy fuel oil), which release carbon dioxide. The average amount of fossil fuel needed to produce 1000 m^3 (or 1 million liters) of water per day using thermal desalination is roughly

10,000 tons per year (Tal, 2018). Even with energy-efficient RO, the desalination of each 1000 m^3 of saltwater results in the potential release of 0.4–6.7 tons of CO_2, depending on the size of the plant and other operational processes (Cornejo et al., 2014). In 2020, global CO_2 emissions from desalination facilities driven by fossil fuels were predicted to be 76 million tons. Additionally, assuming operations continue under the current conditions, the amount of CO_2 can reach 218 million tons by 2040 (Ayaz et al., 2022). Hence, seawater desalination facilities must use renewable energy sources to reduce their environmental impacts.

35. As a result, the main sustainability issues for desalination, such as GHG emissions and energy consumption must be taken into account within appropriate temporal and spatial bounds. Planning, design, construction, commissioning, operation, and decommissioning are all directly related activities that must be considered, as well as indirect ones like the effects of the utilities and service systems that were used, the associated materials' embodied energy, emissions, and impacts.

3.4.2 Techno-economic sustainability of seawater desalination

36. The main concerns of techno-economic sustainability of seawater desalination are the overall unsubsidized cost of the desalted water, covering the rising cost of permitting (which can account for 60% of a major project) and of permitted chemicals (Lior, 2017). A variety of contractual, managerial, and technological factors that affect water production costs with seawater desalination. Besides from technical knowledge, the success of desalination projects requires the optimal selection of funding, risk-sharing, and contractual arrangements for the project's operational lifetime. Due to the high energy requirements of desalination and the complexity of designing, financing, building, and operating desalination infrastructure, the costs of desalinated water remain higher than those of conventional potable water sources. However, desalination must be employed strategically when conventional solutions to water constraint are insufficient (NATIXIS, 2020).

3.4.3 Social sustainability of seawater desalination

37. The social pillar of seawater desalination mainly covers impacts on health, developments, local growth and visual amenity (Lior, 2017). Desalination must be approved by the community; meet their water needs; and is operated and managed within their capacity to be socially sustainable (Werner & Schäfer, 2007). However, the public perceptions about desalination plants are not stable, and statistically proven predictors may change overtime. Furthermore, public support may shift between periods of adequate water supply and drought. Public support may reduce after the perceived threat to the local water supply begins to fade, as it appears to be a substantial predictor of support (Haddad et al., 2018).

3.4.4 Sustainability indicators for seawater desalination

38. For a comprehensive assessment of environmental, techno-economic and social sustainability of seawater desalination, the following indicators and aspects listed in Table 1 are recommended.

Table 1: Environmental, techno-economic and social sustainability aspects and indicators for assessing seawater desalination (Lior 2017)

Environmental sustainability indicators	**Techno-economic sustainability indicators**	**Social sustainability indicators**
a) Water conservation. b) Water resources planning and use, water supply alternatives. c) Water resources impact indices: Water Impact Index, Freshwater Ecosystem Impact (FEI) index, Freshwater Withdrawal Impact (FWI) index, Water Footprint. d) The Carbon Footprint. e) Impacts of construction wastes and excess soil. f) Soil and groundwater pollution (fuels, oils, etc.) g) Air pollution (fugitive dust emission). h) Noise emission. i) Damage to antiquities and heritage. j) Alteration of the seabed. k) Sediment resuspension (impacts on marine water quality and ecology). l) Oil pollution. m) Alteration of the coastal zone and obstruction of passage along the seashore.	a) Cost of water. b) Affordability. c) Pricing policy. d) Capital investment cost (including possible financial incentives). e) Operating cost (including taxes, insurance, warranties). f) Impact on economy; economic growth and development. g) Commercial conflicts (e.g., immediate and surrounding land use and values, water navigation, access to harbors, commercial fishing, Aquaculture). h) Pre-treatment and post-treatment requirements. i) Production reliability. j) Water distribution. k) Water supply alternatives. l) Water conservation. m) Impact on energy use and security. n) Construction materials consumption. o) Consumption of fuel, chemicals. p) Chemicals consumption. q) Corrosion cost and prevention. r) Embodied energy. s) Research and development (R&D) cost.	a) Health and sanitation, e.g., indices of the populations at risk of being affected by the project; product water quality must ensure that unhealthy ingredient levels are kept to a minimum. b) Life quality. c) Effective and equitable employment, local and regional. d) Impact on food (cost, availability, quality). e) Education and training. f) Land footprint. g) Present land-use and planned development activities. h) Visual amenity. i) Equitable water security for all. j) Poverty. k) Trans-border relations. l) Gender effects. m) Demographic development. n) Community structure. o) Recreation. p) Cultural aspects incl. tribal and indigenous people. q) Characteristic landscape and natural scenery. r) National water security.

3.5 Technological tools for sustainable desalination of seawater

39. Table 2 provides a list of technological tools that can be utilized for achieving sustainable solutions for seawater desalination (Ayaz et al., 2022). These include technology to be used, the process to which this technology can be applied, the aim and advantages to be accomplished.

Table 2: Comparison of technological tools for achieving sustainable solutions for seawater desalination (Ayaz et al., 2022)

Technology/ Technique	Target Process	Aim	Advantages
Sensors	Through all processes, including intake and outfall	Monitor a range of parameters (pH, conductivity, turbidity, etc.)	- Providing early detection of any malfunction - Keep the production and efficiency at peak - Expanding the system's life cycle - Decreasing safety risks and resource wastage
AUVs and gliders	Intake and outfall	- Providing proper water quality for intake - Influences of concentration discharge and plume detection - Observe and map the plumes	- Contributing to the reduction of chronic impacts on marine ecosystems - Facilitating accurate navigation - Capable of carrying out week-to-month monitoring tasks
Satellites	- To determine proper location for plant and - Proper intake water quality	- Observing the presence of HABs and other biofouling-causing factors - Ocean color measurement - Tracking the dispersion of effluent - Analyzing ocean salinity	- Providing long-term monitoring, both before and after the installation - Providing spectral and spatial resolution
Models and mapping	The effects of brine discharge, particularly in the far-field	- Analyzing the impact of brine on a large scale - Investigating the impact of wind mixing and tidal currents - Investigating the impact of oscillating tidal flow in both near- and far-field	- Reduce the overall cost of outfall design - Safe disposal of brine discharge - Offering forecasts of the region associated with discharge plumes
Statistical observation	- Typically used for outfall - Design and operation performance of desalination membranes	- Characterization of the environment in which the discharge occurs - Keep track of measurements over time - Providing a precise characterization between data and models	- Analyzing the presence of the discharge along with the impacts of the discharge plume - Facilitating to analysis of various factors when designing the operational performance of a TFC desalination membrane

4. Regulatory aspects for seawater desalination

40. The Contracting Parties to the Barcelona Convention adopted in COP22 (Antalya, Türkiye, 7-10 December 2022) Decision IG.25/5 “Amendments to Annexes I, II, and IV to the Protocol for the Protection of the Mediterranean Sea against Pollution from Land-Based Sources and Activities.”

41. The “desalination of seawater” sector was added to the “Sectors of Activity” under Annex I of the LBS Protocol. With the updated amendment, desalination of seawater is currently primarily

considered when setting priorities for the preparation of action plans, programmes and measures for the elimination of the pollution from land-based sources and activities.

42. Furthermore, “brine” was added as a new substance to the “Characteristics of Substances in the Environment” under Annex I of the LBS Protocol. With this updated amendment, the Parties are requested to take into account when preparing action plans, programmes and measures, the characteristics of “brine.”

43. In this context, and in line with the requirements of the amendments of Annex I of the LBS Protocol, policy officers regulating the desalination sector are recommended to consider implementation of the following measures:

a. Setting emission limit values (ELVs) for brine, also known as "effluent standards" or "discharge quality standards," which refer to numerical values for the constituents of effluent at the site of release with the aim to administer, monitor and enforce.

b. Adopting regulatory measures aiming to avoid spatial conflicts between desalination plants and other activities and the environment. To this aim, the regulations should also enforce procedures to select activities’ site on the basis of the Ecosystem Approach, as well as, where applicable, the Maritime Spatial Planning (MSP).

c. Establish permitting requirements for desalination plants that define the essential conditions for installation and management of activities that ensure good environmental protection. This includes mandatory Environmental Monitoring of biodiversity and non-indigenous species, pollution and marine litter, coast and hydrography, to be based on related IMAP Ecological Objectives and Indicators.

4.1 Emission Limit Values (ELVs) for brine disposal

44. Environmental regulations for brine disposal vary greatly from region to another. In the majority of countries operating seawater desalination plants, the mixing zone concept is employed for brine disposal. The size of the permitted mixing zone ranges from 0 to 500 meters. The ability of mixing zones to regulate the discharge of brine is limited, particularly in environmentally sensitive areas. Recently, a simple-to-implement and -monitor Minimum Return Point Dilution method was proposed to regulate the discharge of brine in sensitive areas (Ahmad & Baddour, 2014).

45. Worldwide, brine discharges have a lack of actual regulations, standards, and guidelines. Though the regulations differ greatly in their specifics, they all include a salinity limit and a point of compliance expressed as a distance from the discharge. Increases in salinity of 1 to 4 parts per thousand above ambient level are typically cited as the upper limit. However, absolute salinity or a minimum dilution level are also typically used to define boundary limits. The salinity compliance point is typically specified as a fixed distance from the discharge, somewhere between 50 and 300 meters, and this boundary is the mixing zone.

46. Further to prevailing standards in the region, the following ELVs for salinity limits, temperature limits and compliance point for temperature listed in Table 3 are recommended.

Table 3: Recommended ELVs for salinity limits, temperature limits and compliance point for temperature for brine (Jenkins et al., 2012)

Parameter	**Recommended ELV**
Salinity limit	Increment ≤ 4 ppt
Salinity limit % increase above ambient	Increment ≤ 5%
Compliance point for salinity (relative to discharge)	50-300 m
Temperature limit (°C), above ambient	<3-10
Compliance point for temperature (relative to discharge)	300 m

4.2 Environmental monitoring

47. Environmental monitoring programs in the case of desalination are primarily focused on determining potential negative impacts associated with brine discharges on the marine environment and implementing appropriate mitigation measures when such impacts are identified. The monitoring and control measures that should be used depend on a variety of factors, including the size of the desalination plant and the quality of the source water, but also the objectives and targets of good environmental status (GES) of marine environment monitoring. In cases where financial resources are limited, operational parameters and monitoring frequencies should be derived from a risk assessment, with potentially hazardous parameters being prioritized based on their level of risk.

48. A routine environmental monitoring program should be implemented following the start of plant operation in compliance with any applicable legislative requirements (e.g. the permit for marine discharge of the concentrate). The monitoring program involves both maritime environmental monitoring that is Integrated Monitoring and Assessment Programme (IMAP) in the framework of the Barcelona Convention, and in-plant pollution monitoring of the intake water and concentrate streams (seawater, sediments and biota).

49. Major tools for monitoring of seawater desalination processes, including compliance and trend monitoring, as well as monitoring plans are presented in Appendix II.

5. Decision Support System for Selection of Technologies for Desalination Plants

50. This section is intended to provide recommendations on Decision Support Systems (DSS) to assist policy makers/facilities' operators in applying best technologies which are appropriate to achieve sustainable desalination in compliance with national/regional legal frameworks and regulations.

51. The starting point for selection of the appropriate desalination technologies is the Environmental Impact Assessment (EIA). It is of utmost importance to conduct an EIA prior to initiation of any desalination project in order to evaluate the potential environmental impacts of desalination and to advocate for the adoption of appropriate countermeasures to prevent or mitigate these impacts (Ihsanullah et al., 2021). A recommended EIA process is presented in Appendix III. In principle, it is necessary to collect and analyze data on the terrestrial and marine ecosystems at the proposed location for the desalination plant, including the intake and discharge zones. Once operations officially start, the collected and/or new data will also serve as a major reference (baseline) for environmental monitoring.

Aspects and issues to be addressed in the EIA report

a) The goal and necessity of the project.
b) Social sustainability.
c) Project description.
d) Technology description.
e) Environmental baseline description.
f) Modeling.
g) Screening for toxicity in discharges.
h) Assessment of potential impacts.
i) Decision between options.
j) Steps to be taken to minimize or reduce adverse effects both during the construction phase and throughout the operational phase
k) Best Available Technique (BAT).
l) Best Environmental Practice (BEP).
m) Application of the precautionary principle.

52. The EIA is a method for assessing and analyzing the environmental impacts of seawater desalination projects, proposing mitigation or prevention measures, and monitoring sites after their construction and operation. It frequently produces massive amounts of complex information, often more than the capacities of decision-makers to process and integrate it. The decision-making process in an EIA can be characterized as a conflict analysis between various value judgments because different decision-makers and stakeholders frequently have differing preferences regarding a project. A formalized decision support tool that allows for the integration

of numerous quantitative and qualitative criteria as well as various value judgments, such as multi criteria analysis (MCA) and life cycle assessment (LCA), can help with the process. Use of MCA and LCA, in seawater desalination is presented below.

5.1 Multi-Criteria Analysis (MCA) in Seawater Desalination

5.1.1 Multi-criteria analysis

53. There are typically a number of technologies/processes available for desalination, including thermal-based technologies, membrane-based processes, and alternative technologies (Subramani & Jacangelo, 2015). When faced with numerous options, it can be difficult for decision makers to choose the best desalination technology. This is because decision makers must consider a variety of factors in the process of selecting desalination technologies, such as production cost, environmental impacts, water quality, energy consumption, and technology reliability, among others. Thus, selection of desalination technologies is a complicated decision-making problem (Wang et al., 2019). MCA is an effective tool in the field of complex decision making that offers solutions to problems involving a wide range of indicators and carefully evaluates several criteria (Yazdani et al., 2017). Additionally, MCA is such a methodology that can assist the EIA in various ways and at various stages (Linkov et al., 2006). Some significant MCA studies applied on desalination from the literature are presented in Appendix IV.

5.1.2 MCA methodology and procedure

54. MCA methodology mainly consists of three stages as shown in Figure 2. The decision problem is identified, input data is obtained, and the alternatives can be ranked based on the input data by using a graphical evaluation in the first stage. Information on all criteria and alternatives, as well as details on individual preferences among specified stakeholder groups, are all included in the input data for an MCA. The alternatives are ranked using MCA in the second stage, which includes selecting an MCA model and standardizing functions, giving weight to the criteria that represent value judgments, and performing sensitivity analysis to determine robustness of ranking. Weighting is a significant technique of MCA and numerical weights can be assigned by using MCA models for each criterion to define the relative valuations of a shift between the top and bottom of the chosen scale. After analyzing the results critically and evaluating the strength of the evidence, an alternative must be selected in the final stage (Latteman, 2010).

5.1.3 MCA models

55. Various MCA models have been developed that synthesize the input data and rank the alternatives using various metrics, each with a different set of advantages and disadvantages (Linkov et al., 2006). Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), multi-attribute utility theory (MAUT), UTA, MACBETH, PROMETHEE, ELECTRE, TOPSIS and VIKOR are the mostly used MCA models for decision problems. MCA models are classified into two groups which are value or utility function-based methods and outranking methods (Linkov et al., 2006). Hybrid models can also be applied by combining two or more MCA models depending on types of decision problem (Communities, 2009).

5.1.4 Sensitivity analysis

56. Sensitivity analysis is a methodology to determine how much vagueness in the inputs or disagreements among individuals affect the final overall results. The selection of weights may be sensitive, particularly for the evaluation of plans or projects that attract public interest. Sensitivity analysis can be applied on the weights assigned to the scenario branches to assess how the scenarios affect the overall ordering of the alternatives. Sensitivity analysis also has the potential to be helpful in resolving disagreements between interest groups (Communities, 2009).

5.2 Life Cycle Assessment in Seawater Desalination

57. The importance of desalination technology is increasing rapidly, which raises concerns about sustainable freshwater supply. Land use change, effects on the marine environment, energy usage, and

noise pollution are only a few of the potential environmental effects of desalination technology. Based on this, it is necessary to incorporate environmental impact measures into the desalination process using a practicable solution and a sensible methodology. In order to assess the environmental performance of products and systems, including desalination technology, the LCA methodology has been widely used and acquired importance to date. Although desalination technology has become one of the most significant sources of water, it also has a number of environmental drawbacks that prevent its broader implementation. Therefore, the LCA approach may be used to propose environmental pollution prevention strategies and enhance the environmental performance of the technology (Aziz & Hanafiah, 2021).

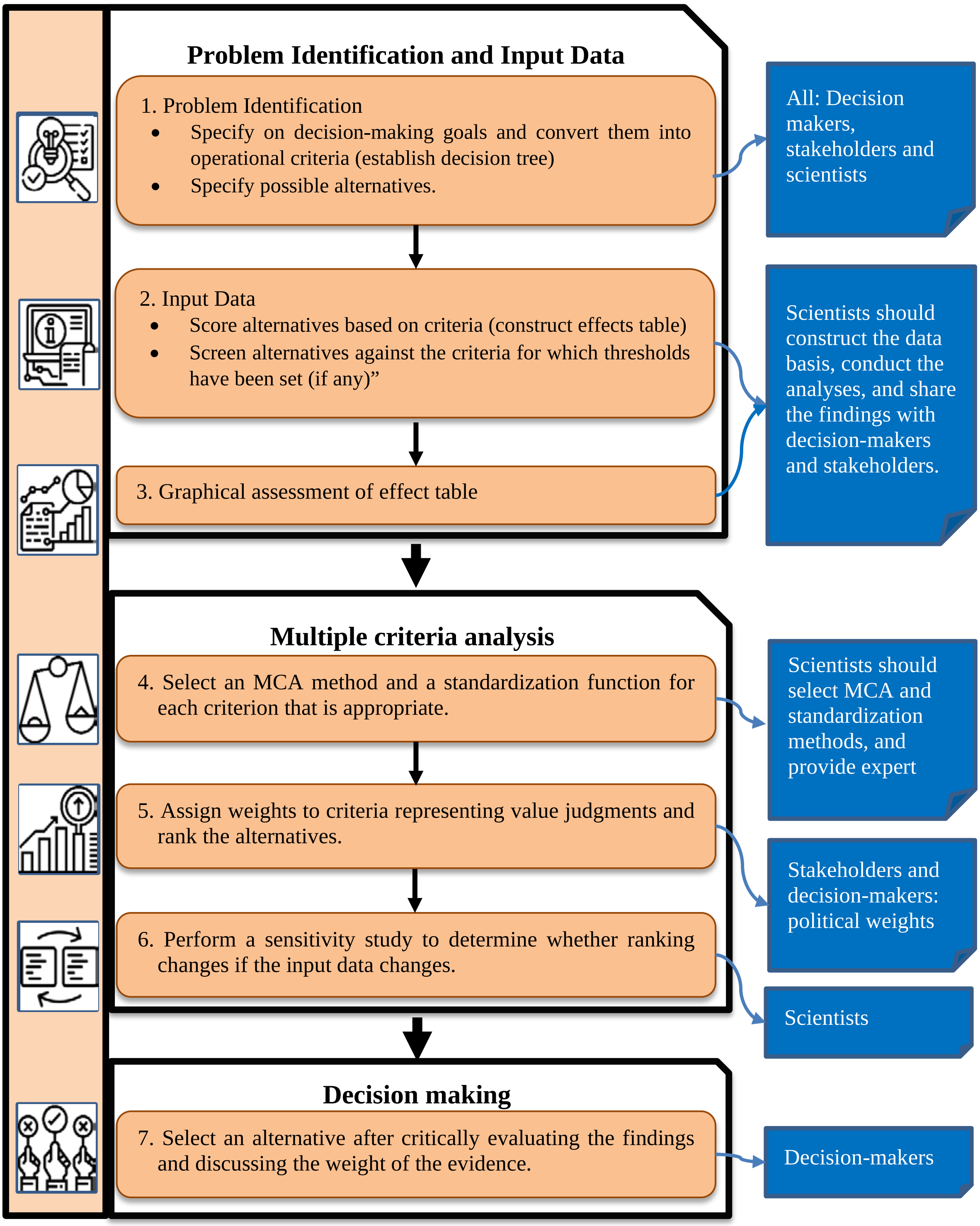


Figure 1. Methodology of MCA for decision making (adapted from Wang et al., 2019))

5.2.1 Life Cycle Assessment in the Context of Decision Making

58. LCA allows for the comprehensive inclusion and comparison of potential environmental impacts throughout the life cycle of a product or system. As a result, LCA enables decision-makers to minimize or select different types of outcomes resulting from products or services that may have an impact on the environment or humans. The decision-making context in the LCA needs to be clarified to avoid using the results out of context (Pryshlakivsky & Searcy, 2021).

59. According to certain definitions, LCA is a decision support tool rather than a device for making scientific measurements. The person making a decision by choosing from a variety of possibilities is given information by the decision-support system. Decisions in LCA are typically presented as either/or choices when considering outcomes. Comparative studies in LCA draw conclusions based on measured differences in the same functional unit. The functional unit is a standardized unit—whether a product or a service—that is made explicit in the scope of the study and defines what is being studied in the LCA. The accuracy of the LCA study is determined by providing exact reference points for the functional unit's inputs and outputs. Despite the fact that the functional unit provides a standardized unit, comparative assertions in LCA are difficult to resolve for basic decisions. Decisions, for example, cannot always be reduced to a single variable, such as whether system A uses less energy than system B. Rather, users of LCA results must choose between options that are incompatible, such as whether waste reduction is preferential over air quality for the users of the results. Bias and preference are naturally introduced into the decision-making process as a result (Pryshlakivsky & Searcy, 2021).

60. LCA research employs scenarios in addition to prospective and retrospective studies. Scenario development tries to map out future situations or solutions. There are several approaches for developing scenarios in LCA, but the two most common are a) what-if scenarios and b) cornerstone scenarios (which use less resources). Because of the significant advancement in the related field, the use of standardized research plans, and the limited time frame in which implications are considered, what-if scenarios tend to be simpler than cornerstone scenarios. On the other hand, cornerstone scenarios, lack development and knowledge within the subject area, are complex, and are intended to broaden the subject area's depth of knowledge. Furthermore, cornerstone scenarios involve strategic planning, which has implications in terms of achieving desired results (Pryshlakivsky & Searcy, 2021). LCA has implications for decision making, but decision making also has consequences for LCA; that is, how the systems are modeled in LCA depends on the purpose of the study. In desalination systems, LCA is very important in decision making and especially in the evaluation and comparison of these systems.

5.2.1.1 LCA definition and principles

61. LCA method is a standardized framework that can enhance our understanding of the effects of a system or product throughout the stages of its manufacturing, utilization, and disposal. The LCA is a technique used to assess how desalination procedures change or effect environmental parameters. LCA is a tool for determining environmental aspects and potential effects throughout the whole life cycle of a product or system, from its raw materials through its disposal. Decision-makers can identify environmental hotspots and develop strategies to reduce harmful environmental impacts by using the LCA method (Lee & Jepson, 2021).

62. The four phases of the LCA, which is a standardized method guided by ISO 14040 and ISO 14044 standards, are goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The context of the LCA research is established in terms of defining the functional unit and system boundary during the goal and scope definition stage. The functional unit explains a system's main objective and makes it possible to treat various systems as functionally equivalent. In desalination LCA studies, the functional unit is often defined as 1 m3 of produced water. The aim of the study, the affected geographic area, the relevant time horizon, etc. all have an impact on how the system boundary is determined. LCI includes the compiling of relevant inputs, outputs, and the activities in the analyzed system. In the interpretation step, the results of the LCI and LCIA are evaluated in accordance with how the LCIA indicates the impacts of the environmental loads quantified in the LCI (Lee & Jepson, 2021; Zhou et al., 2014).

5.2.1.2 System boundary of desalination

63. In LCA studies, four different types of system boundaries are considered: cradle-to-cradle, cradle-to-gate, gate-to-gate, and cradle-to-grave. Only the process of extracting raw materials is covered under cradle-to-cradle. Cradle-to-gate describes the procedure from the extraction of raw materials to the phase of plant operation. Meanwhile, gate-to-gate refers to plant operation activity

only. The desalination system's entire life cycle is covered by cradle-to-grave evaluation, which includes encompassing seawater extraction and processing, treatment, plant infrastructure, transportation, plant operation, distribution and use, dismantling, and final waste disposal. The system boundary of LCA's "cradle-to-grave" principle to desalination is shown in Figure 3. Building materials, equipment materials, and the transportation of construction materials to the plant site are all included in the construction phase. At the plant operation stage, the process consists of electricity generation, chemicals inputs, membranes production, and transportation. Building structure demolition, waste material (brine etc.), and membrane disposal are all included in the dismantling process.

64. Desalination's potential environmental burdens are attributed to the production of potable or non-potable water, which leads to the consumption of natural resources and discharge of pollutant emissions through infrastructure construction, energy generation, chemical production, membrane fabrication, and waste management (Aziz & Hanafiah, 2021; Zhou et al., 2014).

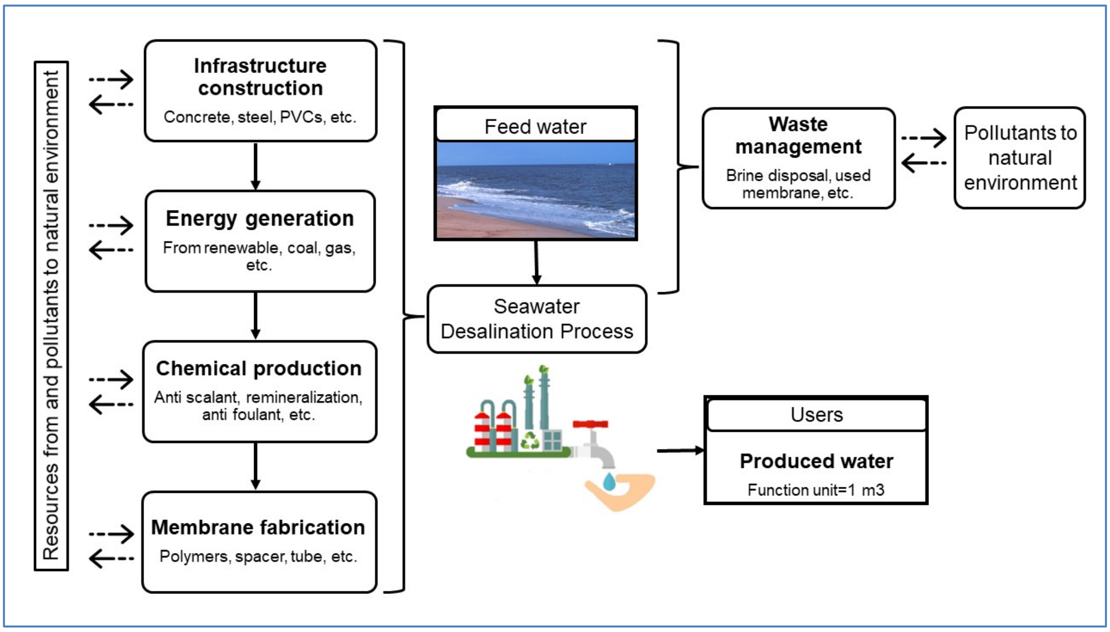


Figure 2. System boundary of LCA's "cradle-to-grave" principle to desalination (Adapted from Zhou et al., 2014)

5.2.1.3 Impact assessment of desalination

65. LCA can be conducted based on two approaches, namely midpoint (problem-oriented) and endpoint (damage-oriented). Midpoint indicators are located somewhere along the impact pathway between emissions and endpoints. A number of impact category indicators were combined into a damage category, also known as an area of protection, at the endpoint level. These indicators included human health, ecosystem quality, and resource availability (Aziz & Hanafiah, 2021).

66. The growth of desalination technology has demonstrated that it has turned into a significant supply of freshwater. This means that desalination must adhere to the principles of sustainable development. A holistic life cycle sustainable assessment (LCSA), as shown in Figure 4, can be completed by combining the well-established environmental life cycle analysis with life cycle costing (LCC) and social life cycle assessment (SLCA). The environmental LCA is performed using a functional unit that defines the product or process. The LCC method is used to calculate all costs associated with the product's or process's life cycle in terms of real monetary flows. In the case of SLCA, the relative social impacts or benefits are evaluated using social criteria and indicators. The three pillars (environment, economy and social) complement each other to achieve the sustainability goal. As a result, desalination has had to be designed and operated in accordance with sustainability pillars in terms of environmental, economic, and social perspectives (Aziz & Hanafiah, 2021).

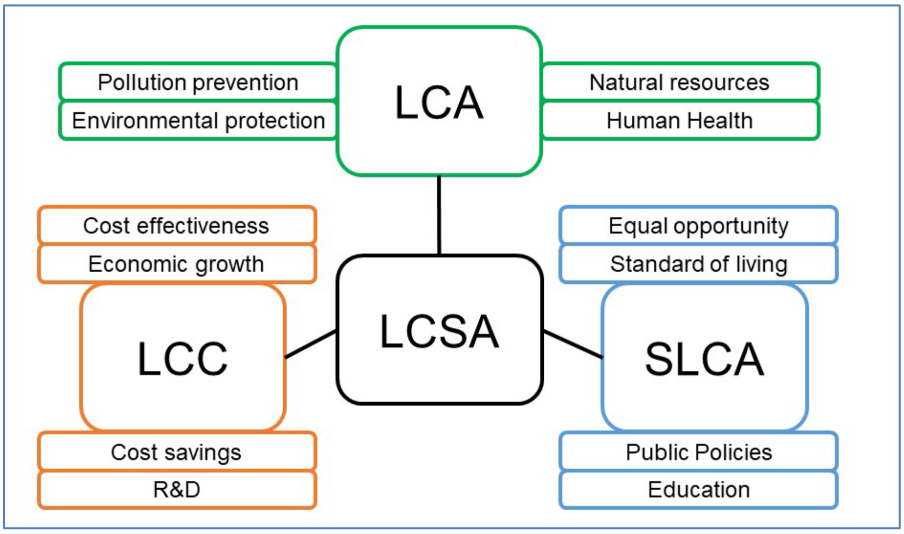


Figure 3. The three pillars of life cycle sustainability assessment (Adapted from Aziz & Hanafiah, 2021)

5.2.2 *Feasibility of applying LCA to desalination*

67. The approach used to make all acquired LCA knowledge easily accessible and usable for desalination studies is referred to as feasibility. Feasibility refers to three components: accounting methods, supporting databases, and approaches to LCIA. The approach used to make all acquired LCA knowledge easily accessible and usable for desalination studies is referred to as feasibility. Feasibility refers to three components: accounting methods, supporting databases, and approaches to life cycle impact assessment. Important considerations for the feasibility application in desalination are listed below (Zhou et al., 2014)

a. The process model is a better accounting method for desalination, whereas the Economic-input output LCA model can be used as a supplement depending on the availability of the economic-input output database and the scope of practitioners' research.

b. Desalination LCA studies, like other LCA efforts, are generally data intensive. To support background processes such as infrastructure construction, energy generation, chemical production, membrane fabrication, and waste management, LCA practitioners can use available databases. However, it is necessary to consider the representativeness of the chosen database.

c. The development of new knowledge can help to improve life cycle impact assessment. Two important features of a desalination system are brine disposal and freshwater savings. Unfortunately, the current assessment models used to translate those characteristics into corresponding impacts are still in development, potentially leading to significant underestimation of environmental impacts.

5.2.3 *Reliability of LCA results for desalination*

68. Another important factor to consider in desalination LCA is reliability. The concerns in this aspect are mainly on the incompleteness of the system boundary, the unrepresentativeness of database, and the omission of uncertainty analysis. Important considerations for the reliability of desalination are listed below (Zhou et al., 2014).

a. It is sometimes necessary to narrow the system boundary by ignoring a number of reference flows from background to foreground. From the perspective of practitioners, this approach is appealing because it can reduce the burdens of primary data collection. However, the exclusion of certain chemicals, construction materials, and membrane materials should be done with caution because they are highly dependent on the study's goal and the impact categories of interest.

b. The temporal and spatial representativeness of a database engaged in desalination LCA is important, as it is for other LCA efforts. Most current databases are based on European data from the late 1990s or early 2000s. To quantify the environmental impacts of newly constructed desalination plants in various geographic locations, regional and up-to-date data may be required to capture technological advancement and local context.
c. Uncertainty estimation can be improved by providing and tracking data quality metrics, such as how the data is acquired, how thoroughly the data is validated, and how well the data captures technological, spatial, and temporal variations. More efforts are needed to provide guidance and "best practices" in uncertainty analysis.

5.2.4 Sensitivity and Uncertainty analysis

69. LCA approach is used to evaluate the environmental impacts and resource consumption associated with the life cycles of products and services. LCA aims to support the development of low impact production systems and to inform decision-makers about the environmental impacts of various options. The results of an LCA study can be influenced by a variety of sources of uncertainty, mainly those related to methodological decisions, initial assumptions made about the allocation rules and system boundaries definition, and the quality of the available data. As a result, LCA supported decisions may be misleading. Uncertainty essentially results from a lack of knowledge regarding the precise value of a quantity. In detail, studies distinguish the following types of uncertainty.

a. Uncertainty in a parameter caused by inaccurate, incomplete, outdated, or missing values of data required for an impact analysis or an inventory analysis.
b. Uncertainty in models is frequently caused by the use of linear models to describe the connections between environmental events and by aggregate data on spatial and temporal aspects.
c. Uncertainty resulting from inescapable methodological decisions made in LCA, such as data collecting techniques, functional unit borders, and cut--off rules.

70. In the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) metrics, there is spatial variability between locations and temporal variability over short and long-time scales.

71. The two main analysis procedures for estimating the uncertainty of LCA results are sensitivity analysis- which assesses the influence of a parameter (the independent variable) on the value of another (the dependent variable) and uncertainty analysis-which determines range of possible results based on data uncertainty (Cellura et al., 2011).

72. Sensitivity analysis evaluates the results' robustness in response to potential changes in each research's underlying assumptions. Selected parameters were used in desalination LCA for sensitivity testing: electricity source and energy mix, energy usage, chemical usage, material life span, distances such as transportation distance, distribution distance, electricity transmission distance, material transportation distance, other variables including water hardness, environmental water requirements, feed water salinity and technology including membrane permeance, water flux, post-treatment process, pre-treatment system, and intake option (Lee & Jepson, 2021).

73. Uncertainty analysis in LCA allows us to calculate the overall uncertainty of the study results and estimate confidence intervals for the results, based on the uncertainties of all the parameters and model selection of the modeled product or system (Bamber et al., 2020).

74. Given the uncertainties that exist during the LCI and LCIA phases, sensitivity and uncertainty analysis should be used to evaluate the final results of an LCA in order to increase their transparency and robustness (Bamber et al., 2020).

5.2.5 Challenges and future perspectives of an LCA of desalination technology

75. Although the LCA is a scientific method for assessing a product's or service's potential environmental effects, it has its limitations and model uncertainties. An LCA requires a large amount of detailed data and information, and it is a time-consuming process. Additionally, a normalization

reference, which represents the entire impact of a reference region for a particular impact category, drives the environmental analysis of LCA. The challenges and some recommendations regarding the application of LCA in desalination are given below (Aziz & Hanafiah, 2021):

a. A normalization reference, which represents the entire impact of a reference region for a particular impact category, drives the environmental analysis of LCA. To ensure that the outcomes of LCA analyses are accurate and practical, it is advised to use local databases.
b. Some of the challenges for LCA implementation will include a holistic consideration of stakeholders, time, and location. More LCI databases and parametric system models of process inventories and product life cycles should be developed urgently in order to overcome these obstacles.
c. Results from LCA should include an analysis of uncertainty, and LCA practitioners should be open and transparent about their limitations. Consequently, in order to implement this intricate and all-encompassing strategy, expert knowledge is required.

76. There are still several obstacles to the sustainable development of the desalination industry. Therefore, the necessary efforts should be contributed by designers, practitioners, utility managers and operators, water stakeholders, and policy or decision-makers. Additionally, education and awareness are crucial for implementing sustainable practices and including environmental performance metrics in decision-making (Aziz & Hanafiah, 2021).

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Appendix I

Description of Emerging and Pre-treatment Technologies

1. **Membrane distillation (MD):** MD is driven by an induced temperature difference between the hot seawater and the cold permeate water. As a result, seawater is heated to between 30–80°C before being transferred to the MD module, and the permeate is then cooled using the cool incoming seawater (< 20°C). An antiscalant is added to the stream prior to heating since the higher operating temperatures encourage scaling on the membrane surface. MD systems have advantages such as low temperature requirement, no pressure required, no limited feed water salinity, and high separation efficiency.

2. MD is now being researched as an alternative to RO and thermal-based desalination processes or as a supplementary technology at lab and pilot scales. Despite its advantages, MD is still not a widely used commercial technique. Pore wetting and low thermal efficiency are regarded as the two main problems for industrial-scale MD systems. The performance of the MD is also significantly impacted by fouling and low water flux (Ahmed et al., 2021; Skuse et al., 2021).

3. **Forward Osmosis (FO):** The natural osmosis phenomenon, by which a solvent moves from a low solute concentration to a high solute concentration, is the basis of osmotically driven processes. In FO, water is drawn into a concentrated draw solution on the permeate side of the membrane from the feed side. FO uses less energy than pressure-driven processes since it is a naturally occurring occurrence, and FO membranes also have a lower tendency to foul. However, FO desalination is a two-step process in which, the osmosis step must be followed by recovery of the draw solution. Desalination by FO depends on both the eventual recovery of the DS as well as the osmotic transport of water molecules through a FO membrane utilizing a concentrated draw solution. Despite being usually overlooked, the recovery step can have a substantial impact on overall energy usage, depending on the procedure used, the choice of draw solution, etc.

4. One of the most substantial FO barriers is the energy consumed during the recovery of the draw solution. Using a solution that does not require recovery, which essentially eliminates the recovery process, is a strategy to reduce the energy consumption of draw solution regeneration. However, this would lead to generation of additional waste through discarded draw solution. Investigating novel materials like ionic liquids (ILs) and magnetic nanoparticles (MNPs) are another strategy. MNPs have demonstrated important advantages over earlier DSs: they are capable of producing extremely high osmotic pressures and can be recovered using low energy magnetic separators. MNPs cannot operate under high enough flux to be commercially feasible, according to earlier studies. Recent studies show that this is being resolved, although long-term stability is still a problem. Since ILs may be recovered using solar energy or waste heat, they are also being looked into as a draw solution for FO desalination. Recent studies investigating ILs have shown improvements in flux and osmotic pressure, but incomplete recovery of the draw solution means that further separation (RO, MD) is needed.(Ahmed et al., 2021; Skuse et al., 2021)

5. **Adsorption Desalination (AD):** As an alternative to desalination methods, a low-temperature and yet low-cost thermal desalination method known as AD has emerged. The adsorption desalination cycle is a novel method that can produce water while using low-temperature waste heat. The two main processes that make up the AD cycle are adsorption-evaporation and desorption-condensation.

6. AD process can be used as hybrids by incorporating them into conventional systems such as MED or MSF, where the water production efficiency of the hybrids can be maximized. In laboratory-scale pilot trials, superior synergistic effects have been confirmed in the MED-AD hybrid system, increasing production up to two to three times over conventional MED (Gude, 2018; Ng et al., 2013).

7. **Freeze Desalination (FD):** The FD process represents a desalination technique involving a phase change from liquid to solid. Liquid, in this case, refers to seawater or saline water (i.e. brine) while solid refers to ice. Theoretically, a major part of ice crystals comprises pure water. Fresh water will be extracted in the form of ice during the freezing process, making the liquid that is left more concentrated. As a result, the FD process has a high separation factor. As it requires lower temperatures to operate, the FD process strongly depends on the use of refrigerants.

8. FD is an emerging technology to overcome limitations of membrane- and thermal-energy-based desalination processes. In contrast to the RO process, the FD method does not necessitate

extensive pretreatment or chemical requirements. Additionally, the environment is harmed by the concentrated brine that is produced by RO. Contrarily, FD has the ability to process concentrated brine produced by the RO process with almost zero liquid discharge. When compared to the thermal desalination process, the FD process has minimum scaling and corrosion issues because of lower operating temperatures. Latent heat of ice fusion has a thermodynamically determined energy need of 333 kJ/kg, whereas water evaporation has a requirement of 2500 kJ/kg. As a result, the energy used for the FD process is approximately one-seventh of what is needed for thermal desalination.

9. In the FD process, large amounts of high-quality energy consumption are required to produce low temperature with the refrigeration cycle. Combining FD with liquefied natural gas regasification plant can solve the problem of energy consumption, thus reducing operating cost and making FD more attractive. Centrifugation, washing, and perspiration are the processes that are suggested to be used following crystallization to improve product quality (Kalista et al., 2018).

10. **Humidification Dehumidification (HDH):** In humidification dehumidification desalination (HDD) method, the saline water is heated, directly or indirectly, turning into water vapor and humidifying the ambient air. After that, it goes through a dehumidifier, producing freshwater condensate. During the humidification process, water diffuses into the air after coming into touch with unsaturated air. The driving force for this diffusion process is the concentration difference between the water–air interface and the water vapour in air.

11. Humidification-dehumidification is one of the most effective desalination procedures to consider for remote regions with a moderate freshwater demand. This is mostly due to the fact that it just needs minor operational and maintenance considerations. Since the heating process, which is an important step in this process, is an energy-intensive process, using sustainable energy sources is a necessity for today's world. The key advantages of HDD, such as its capacity to provide water to remote places, its small-scale rate, and its simplicity in integrating solar energy, make it a potential substitute for conventional desalination systems. When large-scale thermal desalination systems, such as MSF and MED desalination, are unsuitable options because of their cost and size, or when there is insufficient electric power supply to operate RO, HDD technology can be seen as a potential alternative. One of the major disadvantages of HDD systems is the high investment cost (Gude, 2018; Kasaeian et al., 2019; Srithar & Rajaseenivasan, 2018).

12. **Clathrate hydrate desalination (CHD):** In clathrate hydration desalination (CHD), a saline feed is mixed with clathrate-forming gases at low temperatures and high pressures to form clathrate hydrates: networks of hydrogen-bonded frozen water molecules surrounding the gas molecules. Clathrate hydrates, like ice, have a structure that excludes dissolved solids. To recover freshwater and liberate the gas, the solid hydrates can be separated from the remaining liquid and melted. Clathrate hydrates can form above the freezing point of the saline feed stream at sufficiently high pressures. Salts, like FD, adhere to clathrates, necessitating posttreatment (washing, pressing, or gentle melting) to produce low-salinity product water. CHD primarily consumes electricity for refrigeration and pressurization. CHD, like freeze desalination, has been proposed to be co-located with liquefied natural gas regasification, but any integration of LNG with desalination would need to justify that the economic benefits outweigh the opportunity costs of using LNG for other applications.

13. Corrosion, scale formation, and biofouling, which impair conventional desalination methods, are significantly reduced at CHD operating temperatures. CHD, like FD, has poor salt rejection, but it also has extremely slow kinetics and more complex operations, particularly the requirement to recapture clathrate-forming gas. As a result, the technology is unlikely to outperform FD (Shah et al., 2022).

14. **Batch Reverse Osmosis (BRO):** BRO is a transitory process in which the brine that exits the RO module is returned to the feed side without being mixed with fresh feed. The desalination process is extended in time rather than space with a small recovery ratio per pass. Regarding the problems of energy consumption and CO_2 emissions, numerous studies have published new processes and systems to reduce the current level of energy consumption. In order to reduce the RO desalination process' thermodynamically irreversible energy losses, BRO has recently been developed. The irreversible energy loss is significantly decreased in the BRO system because the applied pressure gradually rises

as concentration increases. BRO uses less energy than traditional continuous RO as a consequence, especially at high recovery. Despite the advantage in energy recovery with the BRO system, it cannot easily increase the recovery to a very high value as required for minimal brine disposal because the maximum operating pressure of the RO membrane is limited. For this reason, hybrid systems can be created by integrating BRO systems with systems such as AD, and minimal or zero liquid discharge can be achieved (Cordoba et al., 2021; Park et al., 2022; Wei et al., 2020).

15. **Solar thermal desalination (STD):** Sunlight is converted into heat in solar thermal desalination (STD) to evaporate saltwater. Solar evaporation ponds in conventional desalination, are used to concentrate saline streams but do not produce freshwater. Solar stills are STD devices that also condense the vapor to recover distilled water. Solar stills directly use solar energy, so the technology has the benefits of easy setup and operation, minimal equipment needs, and suitability for deployment in remote areas. Because STD is based on evaporation, it is not constrained by feed salinity and can, in theory, handle hypersaline salt concentrations. Where suitable low-cost land is available, STD can potentially serve as a simple ZLD solution.

16. Despite advances in solar absorption, heat localization, and salt buildup mitigation, STD remains an energy-intensive process. The SEC is, at best, the enthalpy of water vaporization unless the latent heat released by the condensing vapor is recovered (≈667 kWhth/m^3). Furthermore, the water productivity of STD is limited by solar irradiance. A considerable land area would therefore be needed for an operationally viable water production output (Shah et al., 2022).

17. **Solvent extraction desalination (SED):** SED is a thermally driven technique that does not involve the phase-change of water. At extraction temperature, the saline feed is mixed with a low-polarity solvent, where the two liquids are immiscible and thus form a biphasic mixture. However, because the solvent contains hydrophilic functional groups, it draws some water from the feed stream into the solvent phase, whereas salts do not prefer partitioning into the solvent's low dielectric constant environment and remain in the aqueous phase. The water-laden solvent phase is then decanted from the concentrated aqueous phase and brought to disengagement temperature, lowering the solubility limit of water. As a result, the previously extracted water separates from the solvent, yielding a desalinated product stream. Physical separation of the product water occurs, and the regenerated solvent is recycled back into the process. Since 2011, there has been renewed interest in this technology for hypersaline stream desalination and dewatering.

18. SED avoids many of the limitations associated with traditional high-salinity desalination technologies because it is both membrane-free and non-evaporative. Process top temperatures are typically <80 °C, so corrosion is lessened compared to conventional distillation methods.

19. Despite the fact that the solvents used in SED are low polarity, they are not completely insoluble in water. Therefore, a fraction of solvent is lost to both the dewatered raffinate and product water. Additional costs are incurred in recovering the solvent, and any leaked solvent that is not reclaimed must be replenished. Furthermore, residual solvent in the concentrate and product streams may necessitate posttreatment, especially if the solvent is toxic. The identification of solvents that minimize loss while being safe for the environment and human health is critical for technological advancement. Simultaneously, research on new solvents with high water production capabilities will reduce SED's energy consumption (Shah et al., 2022).

20. **Supercritical water desalination (SCWD):** SCWD uses the switch in solvent polarity from polar to nonpolar at supercritical conditions. Water behaves as a nonpolar solvent when it is subjected to supercritical conditions, which are defined as temperatures and pressures greater than 374 °C and 221 bar (≈3200 psi). Salts precipitate out of solution as their solubility in supercritical water decreases significantly, allowing for the easy separation of solid minerals from the fluid product water stream. SCWD is always a ZLD technology because no concentrate waste stream is produced.

21. Different feed stream compositions can be handled and treated with SCWD across the entire salinity range. Additionally, since the method precipitates out even sparingly soluble salts, extensive pretreatment is frequently not needed. The extreme pressures and temperatures required to produce supercritical water result in extremely high energy consumption and initial investment requirements

for SCWD. SCWD materials must be thermally, mechanically, and chemically robust in order to withstand the extremely high temperatures and pressures. Despite the use of long-lasting materials such as stainless steel and titanium, superheated and pressurized high-salt brine is known to cause significant corrosion in equipment.

22. The two main challenges of high material durability requirements and high energy costs to achieve the extreme temperatures and pressures must be resolved for SCWD to be competitive (Shah et al., 2022).

23. **Zero Liquid Discharge (ZLD):** ZLD is a water treatment engineering approach in which the plant does not discharge any liquid effluent into surface water. This results in the complete elimination of the pollution associated with desalination. The ZLD method also eliminates liquid waste, maximizes water usage effectiveness, and reduces potential water quality issues. It also contributes to water conservation by reducing freshwater consumption through wastewater recycling and reuse. The challenges and cost of water recovery are increasing with the rise in salinity, presence of scaling compounds and organics in the wastewater and hence, the need for Zero-Liquid Discharge target is growing. The challenges to consider in ZLD implementation are following.

a. The choice of an appropriate method based on the composition, features, associated corrosion and temperature issues, and target capacity.

b. ZLD's capital and operating costs, which include energy and chemical costs associated with the evaporation and treatment processes, are significantly higher than those of other disposal methods.

c. When considering the ZLD technique, the material compatibility factor is critical. It refers to the material's corrosion resistance, or how it rusts or stains when exposed to chemicals, salt, and other compounds (Soliman et al., 2021).

24. Table A.1 provides a summary on evaluated metrics of energy grade product water salinity (i.e., compatibility with fit-for-purpose applications), technology demonstration status, zero liquid discharge capability, and ability to precipitate solids in bulk aqueous phase for emerging technologies (Shah et al., 2022).

Table A.1: Summary of metrics of energy grade product water salinity, technology demonstration status, zero liquid discharge capability, and ability to precipitate solids in bulk aqueous phase for emerging technologies (Shah et al., 2022)

Criteria	ED	FO	MD	HDD	SED	SCWD	FD	CHD	STD
Primary Energy Input	EC	S/LGH	LGH	S/LGH	LGH	EC+S	EC	EC	LGH
Product Water Salinity	FFP	FFP	DW	DW	FFP	DW	FFP	FFP	DW
Industrial-Scale Demonstration	+[1]	+		+			+[2]		
ZLD demonstrated				+	+	+			+
Precipitation in bulk solid				+[3]	+	+			

EC: Electricity, S: Steam, LGH: Low Grade Heat, +: Demonstrated performance, FFP: Fit-for-purpose, DW: Drinking water
1 ED Demonstrated for brackish water desalination
2 FD Demonstrated for food and beverage industry
3 Precipitation occurs at solution-air interface, away from solid surface

Appendix II

Major tools for monitoring of seawater desalination processes

Introduction

1. Seawater quality is a particularly sensitive subject and has dynamic conditions because it is closely linked to so many environmental issues. Due to the growth of pollution sources, monitoring its quality, particularly during intake and outfall operations, is becoming more difficult. In addition, the operational problems with desalination are heavily linked to the corrosive characteristics of marine organisms and seawater. These characteristics, in turn, might have a detrimental impact on the system, resulting in a facility's partial or occasionally entire closure. Furthermore, any unsuitable occurrence or operation can result in safety risks and resource waste. Thus, the comprehensive monitoring and assessment, and the selection of a suitable location has a significant impact on the entire production process and its efficiency, as well as the plant's overall operating life.

Compliance monitoring (indicator approach)

2. Compliance monitoring usually involves periodic or continuously monitoring of a certain parameter to ensure that legal requirements and environmental quality standards are being maintained. While it is ideal to look at as much as possible in an EIA, it is indeed practically impossible to constantly investigate every organism throughout every environment. Therefore, an indicator strategy is indirectly used in an EIA most often. Salinity and dissolved oxygen concentrations (or temperature for distillation plants) are appropriate physical indicators of desalination plants with the goal of ensuring compliance with regulatory requirements.

Trend monitoring (indicator approach)

3. Trend monitoring of the concentration of pollutants discharging into coastal waters through the effluents of the operations of desalinization needs to be established in order to contribute to the achievement of the targets of the Good Environmental Status (GES) of marine environment as defined in IMAP. Pollution reduction targets of inputs of pollutants should be agreed further to the outcomes of the trend monitoring.

4. Trend monitoring of pollutants discharging into coastal waters needs to include the pollutants emitted through the operations of desalinization by considering the analytical procedures for the sampling, sample preparation and analytical determination of the pollutants as recommended in UNEP/MAP Monitoring Guidelines for IMAP Common Indicators 13. 14 and 17.

5. The maximum permitted level of concentrations of pollutants measured in effluents discharging into coastal waters through the effluents of the operations of desalinization should be set further to a trend analysis of the concentrations of pollutants measured during a period that is not shorter than 5 years in order to guide the appropriate response measures in case of excessive discharges of pollutants.

Environmental monitoring plans

6. Although there is no scarcity of seawater, it is crucial to comprehend, constantly monitor, and take the appropriate steps to reduce the negative effects of seawater desalination, especially raising the prospect of its rapid expansion in the near future. Comprehensive environmental monitoring plans (EMPs) are developed to prevent, predict, and monitor impacts in feasibility, planning, design, construction, and operations of seawater desalination plants. These plans are implemented worldwide to comply with discharge water quality standards and environmental regulations with the aim of protecting the aquatic environment.

7. An environmental monitoring plan is developed to: (i) collect information on the environment during plant construction, installation, and operation as necessary; (ii) monitor the outfalls related to every project stage, including the operation stage; (iii) monitor any substantial changes in the area associated with the plant that may be caused by its activities, such as those that affect the physical,

chemical, or biological properties; and (iv) start mitigating actions before these changes affect the natural processes and become them irreversible.

8. The monitoring plan specifications should include water quality limitations at the sample locations, required dilution of brine discharges (including volume of discharge and salinity), controls for discharge dispersing, controls for local plant and animal species, and mitigation methods to reduce excessive salt concentration.

Appendix III

Process for conducting the Environmental Impact Assessments

Introduction

1. EIA is commonly defined as an assessment of the environmental impact of planned activities, including impacts on biodiversity, vegetation and ecology, water, and air. An EIA is a process for identifying, predicting, and evaluating the likely environmental, socioeconomic, cultural, and other impacts of a proposed project or development to define mitigation actions—not only to lessen negative impacts but also to provide benefits to the natural environment and well-being. A project's potential risks to the environment and human well-being are essentially identified in an EIA, along with steps that can be taken to eliminate and/or at least reduce such risks. This can be done by replacing and/or modifying planned activities to reduce impacts. In this context, an EIA can be seen as an information-gathering activity by the project proponent to outline (and if possible quantify) the risks, impacts and mitigation actions built into the project's whole lifecycle from design to closure so that decision makers are fully informed when approving the project. The most crucial factor in determining whether an EIA is necessary is the degree to which the project would have an adverse impact on both human and environmental health (IISD, 2016).

2. The EIA of projects is a key instrument of European Union environmental policy. It is currently governed by the terms of European Union Directive 2011/92/EU, as amended by Directive 2014/52/EU on the assessment of the effects of certain public and private Projects on the environment (EIA Directive). Since the adoption of the first EIA Directive in 1985 (Directive 85/337/EEC), both the law and EIA practices have evolved. The EIA Directive was amended by Directives 97/11/EC, 2003/35/EC, and 2009/31/EC. The Directive and its three amendments were codified in 2011 by Directive 2011/92/EU. The codified Directive was subsequently amended by Directive 2014/52/EU.

3. The three main stages of the EIA process are project screening and scoping, environmental impact assessment, and decision-making and EIA review. It should be noted that in practice, deviations from the outlined process may occur. Single steps may not necessarily have a defined limit; some may overlap or be used in place of others. Thus, the EIA process should be seen as a continuous and flexible process.

4. In order to assist project designers, consultants, regulators, and decision makers anticipate and address all relevant environmental, socioeconomic, and public health concerns that may arise when undertaking a desalination project for obtaining the highest possible level of beneficial use of the desalinated water in terms of quality, safety, and environmental protection, the United Nations Environment Programme (UNEP) and the World Health Organization (WHO) developed and released a guidance document on desalination. The objective of the guidance document is to identify a wide range of potentially significant challenges that may help in anticipating the pertinent issues of each desalination project individually. EIA process covering three main phases, scoping, screening, impact mitigation and reporting main EIA phases and were subdivided into 10 steps is shown in the following diagram (Figure A.1). UNEP (2008) Desalination Resource and Guidance Manual for Environmental Impact Assessments. United Nations Environment Programme, Regional Office for West Asia, Manama, and World Health Organization, Regional Office for the Eastern Mediterranean, Cairo.

Screening of the project

5. The process of screening determines whether or not an EIA is necessary for a certain project. Thus, screening involves making a quick assessment of the relative importance and anticipated environmental impact of a proposed project. A certain level of basic information about the proposal and its location is required for this purpose (UNEP, 2008).

6. The screening processes can be broadly categorized into two approaches: a standardized approach, where projects are subject to or exempt from EIA as defined by legislation and regulations; and a customized approach, where projects are screened on a case-by-case basis utilizing indicative advice (Lattemann & El-Habr, 2009).

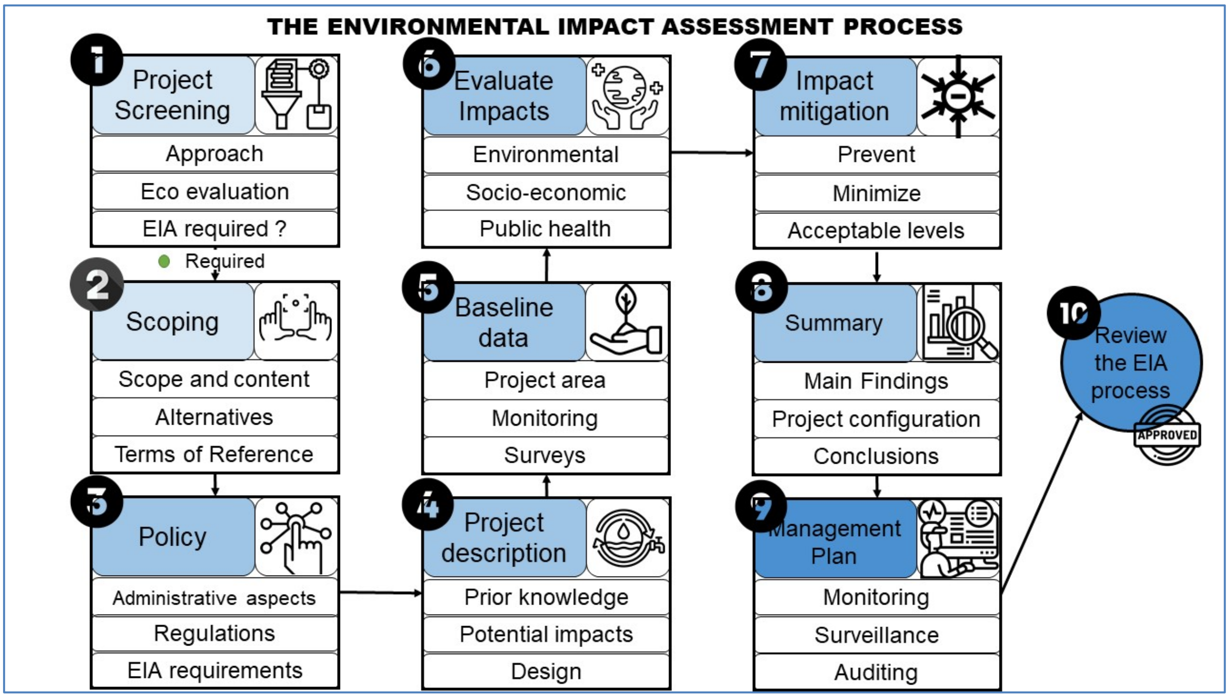

Figure A.1. The Environment Impact Assessment Process
(Adapted from (Lattemann & El-Habr, 2009))

Scoping of the project

7. Scoping is an important step in the preparation of an EIA because it identifies the issues that are likely to be most important during the EIA and eliminates those that are of little concern. Scoping is a systematic process that determines the parameters of your EIA and defines the framework for the studies you will perform at each stage. A quality scoping study reduces the risk of including inappropriate components or excluding components that should be addressed (UNEP, 2008).

8. The scoping procedure follow four basic steps; i) preparation of a scoping document for public dissemination, including project details and a preliminary environmental analysis, ii) organisation of scoping meetings inviting collaborating agencies, stakeholder groups, NGOs, experts and advisers, and announcement of the scoping meeting in public, iii)compilation of a complete list of issues during scoping consultations, which are then evaluated in terms of their relative importance and significance, iv) preparation of the terms of reference for EIA, defining the scope and information requirements of the EIA, study guidelines and methodologies (Lattemann & El-Habr, 2009).

9. The preparation of Terms of Reference (ToR) for an EIA is an important task in concluding the scoping process. The project proponent is given specific instructions for the information that must be submitted to the appropriate authorities for an EIA as well as the studies that must be conducted to gather that information in the Terms of Reference (ToR), which are developed throughout the process (Lattemann & El-Habr, 2009).

a) **Selection of the project site:** Environmental, socio-economic and public health impacts resulting from the construction and operation of a desalination plant are largely dictated by the location of the facility and its associated infrastructure. Therefore, proper site selection for a desalination plant during the planning process is essential for minimizing these impacts. Site selection typically takes place in the early stages of a desalination project and leads to the identification of a preferred site and possibly one or two alternatives.

b) **Project description:** A general description of the purpose and need of the project should be given at the beginning of the EIA document. It should include the following information:
   i. Proposed location of the desalination plant.
   ii. Co-location with other industries (such as power plants).

   - iii. The onshore and offshore components of the plant (buildings, pumps, pipelines, brine outfall), planned construction activities and timeline.
   - iv. Connection to the water supply grid.

c) **Technology selection and characterization of discharges** A detailed technological description of the chosen desalination process should be part of the EIA, including the rational for the choice. It should include the following information:
   - i. The desalination technology chosen and engineering specifications
   - ii. Desalination capacity of the plant and future expansion plans
   - iii. Energy usage and source
   - iv. Area and method of source water intake (open intake, well intake)
   - v. The treatment steps of the source water during the desalination process (among others the pre- treatment, biocide application, anti-scaling measures, cleaning stages, desalinated water treatment)
   - vi. Type of discharges and emissions (marine, terrestrial and atmospheric)
   - vii. Total volume of discharges and emissions (daily, yearly)
   - viii. Area and method of brine discharge (open discharge, co-discharge, marine outfall with or without diffusers)
   - ix. Brine discharge pattern (continuous, intermittent, variable)
   - x. Physio-chemical characteristics of the brine (salinity, temperature, etc...)
   - xi. Concentrations and loads of discharged substances and their environmental characterization (such as persistent, toxicity, bioaccumulation).

Modeling

10. A model is a conceptual or mathematical simplification that is used to investigate a real natural system, a risk assessment problem, and/or a decision-making process, among other things. Modeling is a common requirement for an EIA process and a fundamental component of informed regulatory and decision-making processes. Modeling is a common requirement for an EIA process and a fundamental component of informed regulatory and decision-making processes (Kress, 2019).

Identification and description of policy and administrative aspects

11. An EIA typically takes place within the specific legal frameworks created by the nation in which the project will be located as well as those set by international organizations. As a result, it is advised to get a greater awareness of any national or international rules that might be relevant to the EIA process. Additionally, all thematically relevant laws and policies must be found, such as those pertaining to the preservation of the environment and biological diversity, the prevention and control of pollution, the management of water resources, or land-use and regional planning. To realize a desalination project, more than one permit will often be needed in several jurisdictions. The main approval process, which authorizes the construction and operation of a desalination plant, will not necessarily replace other existing statutory provisions, and permits. It is significant to identify the permits that must be secured early in the project planning process and to get in touch with the competent authorities. By designating a "lead" agency, which coordinates the process by involving other agencies and by notifying the project proponent about regulatory requirements, the permitting procedure may be made easier.

Investigation and description of the proposed desalination project

12. The many life-cycle stages of constructing, commissioning, operating, maintaining, and decommissioning the desalination plant should be covered in the project description. It should be brief, include all the elements required for an impact evaluation, and not included any unnecessary or distracting material. It should include an estimate of every resource used during the various project operations, including the amount of land needed for building, the amount of chemicals used during plant upkeep, and the amount of energy used. It should furthermore include a characterization of all waste products in terms of quantity and composition, including emissions into air, water, and soils, as

well as solid and liquid waste products transported to a landfill or discharged into the municipal sewer or stormwater system (Lattemann & El-Habr, 2009).

Investigation and evaluation of environmental baseline

13. It is possible to choose a reference region with comparable features, for which baseline data is established in the same manner as for the project site. This allows for a comparison between the reference site and the project site during project monitoring in order to detect any changes caused by construction and operation of the project. It is especially helpful to identify natural changes or other anthropogenic impacts unrelated to the desalination project using reference data from a site with similar environmental features (Lattemann & El-Habr, 2009).

Investigation and evaluation of potential impacts of the project

14. The prediction of impact in an EIA is typically based on conceptual models and tests, such as field and laboratory experimental methods (e.g. whole effluent toxicity tests), small-scale models to study effects in miniature (e.g. different outfall designs), analogue models which make predictions based on analogies to similar existing projects (e.g. other desalination plants) or mathematical models (e.g. hydrodynamic modelling of the discharges). Each of these models only covers a small portion of the range of impacts; therefore, they are frequently utilized in conjunction with one another, leading to a variety of studies being conducted by different experts. The relative importance of the anticipated impact should be assessed using factors like:

a) Is the impact direct or indirect, positive or negative?
b) What is its scope in terms of the impacted population's size or the geographic area?
c) How severe is the effect, how likely is it to happen, and is it reversible or can it be mitigated?

15. Identification of secondary effects, potential cumulative effects with other development initiatives on the project site, trans-boundary (far-distance) effects, and growth-inducing effects should be done whenever possible and suitable (Lattemann & El-Habr, 2009).

Mitigation of negative effects

In order to avoid, minimize, or correct major negative consequences to levels acceptable to the regulatory agencies and the affected community, impact mitigation step should identify the most feasible and cost-effective alternatives. According to various national, regional, or local standards, which depend on the social, ideological, and cultural values of a society or community, as well as on economic potential and politics, the definition of acceptable will change (Lattemann & El-Habr, 2009).

16. A hierarchy of actions is used to organize the mitigation components. Usually, impact prevention through appropriate actions and alternatives is given highest priority. Impacts should be reduced to the least extent practicable if prevention is impossible. All remaining major but unavoidable consequences that cannot be further minimized should be compensated for or remedied following the project's decommissioning (Latteman, 2009).

17. Mitigation can involve structural measures (e.g. design or location changes, technical modifications, waste treatment) and non-structural measures (e.g. economic incentives, policy instruments, provision of community services, capacity building).

18. Restoration of the impacted site during the project's lifespan or after demolition is complete is one option for remediation and compensation, as is the improvement of resource values elsewhere, such as through habitat improvement, reforestation, or restocking of a particular species (Lattemann & El-Habr, 2009).

Summary and conclusions

19. For this aim, a summary of the major implications (possibly in the form of a table) should be supplied, distinguishing between substantial impacts that can be avoided or mitigated and those that

cannot. Both direct and indirect effects, positive and negative effects, and the potential of cumulative effects should be examined.

20. Whenever possible, choices to mitigation or avoid major effects should be provided. A systematic comparison of the original project proposal to different project configurations in terms of negative and positive impacts and the efficacy of mitigation strategies is essential. The final step is to identify the "best practicable environmental option," which is the ideal project design according to environmental, social, cultural, and public health criteria. It is important to make sure this choice is both financially and technologically viable. The decision should be transparent and supported by arguments (Lattemann & El-Habr, 2009).

Establishment of an environmental management plan

21. During the construction, commissioning, operation, maintenance, and decommissioning of the proposed desalination project, an environmental management plan should be developed to ensure the continual monitoring and review of the project's effects. Its purpose is to determine the actual consequences of the project and to confirm that the observed impacts are within the range indicated by the EIA. In addition, the goal of environmental management is to ensure that the mitigation measures or other requirements linked to the project permit are appropriately executed and effective. If not, or if unanticipated effects emerge, the measures and conditions must be modified in light of the new information. The management plan should outline any plans for planned monitoring, surveillance, and auditing activities, including methodology, timetables, and management processes for unanticipated occurrences (Lattemann & El-Habr, 2009).

Review of the EIA and decision-making process

22. The goal of review is to confirm the completeness and quality of the EIA data collected. This final phase ensures that the material supplied in the report conforms to the Terms of Reference as defined during scoping and is sufficient for decision making.

23. Review is a formal phase in the EIA procedure that serves as a final review of the EIA report before it is submitted for project approval. The review may be conducted by the relevant authority, another government agency, or an independent organization. Participation of collaborating and advising agencies in the review process is strongly advised, as is the participation of the public and important stakeholders in public hearings regarding the EIA's results.

24. The review should adhere to a systematic methodology. This will involve an appraisal and validation of the EIA methodology and technique, as well as a verification of the consistency, plausibility, and exhaustiveness of the discovered impacts, offered alternatives, and suggested mitigation actions.

25. The review process may adhere to specified norms and review criteria. If these are unavailable, the committee may rely on broad principles, objectives, and terms of reference, or use the questions below:

a) Does the EIA report address the Terms of Reference?
b) Is the requested information provided for each major component of the EIA report?
c) Is the information correct and technically sound?
d) Have the views and concerns of affected and interested parties been considered?
e) Is the statement of the key findings complete and satisfactory, e.g. for significant impacts, proposed mitigation measures, etc.?
f) Is the information clearly presented and understandable?
g) Is the information sufficient for the purpose of decision-making and condition setting?

26. The response to the last question is the most important and will essentially determine whether or not the EIA may be submitted to the competent authority as-is or with minor adjustments for decision-making.

27. On the basis of the EIA report, the analysis of stakeholder interests, and comments from collaborating agencies, the competent authority will make its own evaluation of the proposed project

and decide on its approval or rejection. If the project is accepted, the competent authority will often impose conditions, such as mitigation measures, emission limitations, or environmental standards to be observed. (Lattemann & El-Habr, 2009).

<u>Outline of an EIA report should incorporate</u>

The outcome of the EIA process should include documented information pertaining to the following:

a) The goal and necessity of the project, including the accessibility and affordability of alternative water sources (water treatment and reuse, water conservation, water waste prevention).
b) Social sustainability: Impacts on human health (quality of desalinated water), land use, population growth, infrastructure, trust in the availability of desalinated water, impact on recreational activities, or other acceptable uses of the sea and shoreline.
c) Project description: The plant's onshore and offshore physical components (structures, pumps, pipelines, intake, and brine disposal systems), planned construction processes, and timeframe, as well as the intended location, co-located with other industries or marine applications.
d) Technology description: Engineering requirements, production capacity, energy source and use, intake and discharge systems, pretreatment of source water (coagulation, biocide application, anti-scaling measures, cleaning stages, desalinated water treatment), and type, volume, and composition of water discharge and emission levels (marine, terrestrial and atmospheric) are all factors in the desalination process.
e) Environmental baseline description: Compilation and analysis of current information on the terrestrial and aquatic environments nearby, as well as baseline monitoring assessments conducted before the construction.
f) Modeling: Loss of organism entrainment, impingement, and entrapment at intake systems, regional (near and far field) hydrography and brine dispersion, transboundary transport, and effects on seawater quality and sea organisms are the issues that need to be addressed.
g) Screening for toxicity in discharges.
h) Assessment of potential impacts.
i) Decision between options: Tools for defining and selecting the best alternative and establishing mitigation measures include environmental risk assessment and multicriteria decision assessment.
j) Describe the steps that will be taken to minimize or reduce adverse effects both during the construction phase and throughout the operational phase of the desalination plant, taking the following factors into account:
k) Best Available Technique (BAT): A measure's practical suitability for reducing discharges, emissions, and waste is indicated by its most recent stage of development (state of the art) of its processes, facilities, or methods of operation.
l) Best Environmental Practice (BEP): The use of the best possible set of environmental control techniques and methods.
m) The precautionary principle: Even if there is merely suggestive evidence of an influence, action should be taken to avoid major negative effects. 146 Seawater Desalination's Marine Impacts: Science, Administration, and Policy Recently, it has been proposed to add a phase to the EIA to account for the impact of climate change. Increased freshwater demand, rising seawater temperatures and salinities, and rising phytoplankton blooms are all potential factors in desalination (Kress, 2019).

Appendix IV

Example MCA studies applied on desalination

1. García-Bartolomei et al. (2022) used a GIS-based Multi-Criteria Analysis (GIS-MCA) approach to investigate and evaluate probable locations fit for the development and operation of desalination facilities in Chile. Using the Analytic Hierarchy Process (AHP) methodology, various environmental, social, and technical criteria were evaluated and weighted. Only 4.54% of the territory analyzed (114,450 km^2) was classified as highly suitable, proving the scarcity of space available to meet the industry's growth expectations. These findings indicate that GIS-based analysis provides a practical solution for selecting optimal areas for developing desalination plants, emphasizing the importance of defining priority areas for the long-term development of the desalination industry (García-Bartolomei et al., 2022).

2. Do Thi et al. (2021) studied on desalination procedure of saltwater using several technologies, including RO, MED, and MSF, with several energy sources (fossil energy, solar energy, wind energy, nuclear energy). In this study, the three assessment methods, which are LCA, PESTLE, and multicriteria decision analysis (MCDA) were studied at individually with the purpose of comparing the efficiency of the various desalination systems with that of the energy sources as given in Table 4. In MCDA part of the study, Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) method was used to assess the desalination technologies. In this study, the environmental factors were found as the most important with highest weight followed by the social and economic factors. The results indicates that RO is the best technology while MSF-based technologies are worst (Do Thi et al., 2021) as can be inferred from Table A.2 below.

Table A.2: Comparison of desalination techniques from several aspects (Abdelkareem et al., 2018; Al-Karaghouli & Kazmerski, 2013; Al Washahi & Gopinath, 2017; Cherif & Belhadj, 2018)

Type of Technology	**Thermal Technology**				**Membrane Technology**	
	MSF	**MED**	**MVC**	**TVC**	**ED**	**RO**
Type of Water	Seawater, Brackish	Seawater, Brackish	Seawater, Brackish	Seawater, Brackish	Brackish	Seawater, Brackish
Operation temperature (°C)	90–110	70	70–100	63–70	Ambient	Ambient
Typical unit size (m^3/day)	50,000–70,000	5000–15,000	100–3000	10,000–30,000	2–145,000	24,000
Electrical energy consumption (kWh/m^3)	4–6	1.5–2.5	7–12	1.8–1.6	2.6–5.5	5–9
Thermal energy consumption (KJ/kg)	190–390	230–390	None	145–390	none	None
Electrical equivalent for thermal energy (kWh/m^3)	9.5–19.5	5–8.5	none	9.5–25.5	none	none
Total electric equivalent (kWh/m^3)	13.5–25.5	6.5–11	7–12	11–28	2.6–5.5	5–9
Maximum value of CO$_2$ emissions (kg CO$_2$/m^3)	24	19.2	11.5	21	5.3	8.6
Distillate quality TDS (ppm)	~10	~10	~10	~10	150–500	<500
Unit product cost (USD/m^3)	0.52–1.75	0.52–1.01	2–2.6	0.827	0.6–1.05	0.52–0.56

3. In order to rank desalination plant location criteria in the United Arab Emirates (UAE), Dweiri et al. (2018) created a multi-criteria decision support system (DSS) by taking into account social, environmental, economic, technical, and operational factors. Their results show that the most

significant aspects of desalination plant location criteria are technical (21.9%) and economical (20.9%). Additionally, the most important sub-criteria of environmental, social, economic, technical, and operational aspects are wastewater discharge (22.2%), life species (13.3%), real cost of water and government subsidy (18%), quality and quantity of fresh water (12.4%), and water supply network (9%) respectively (Dweiri et al., 2018).