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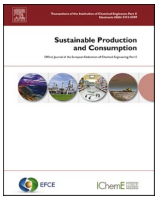

# A value-sensitive approach for integrated seawater desalination and brine treatment

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## ABSTRACT

The transition to seawater desalination integrated with resource recovery, particularly in water- and energy-scarce regions, requires innovative approaches that consider societal benefits and costs. This study goes beyond traditional techno-economic evaluations by employing a Value-Sensitive Design (VSD) approach, which guides the selection of performance indicators and informs the design of technical scenarios for integrated seawater desalination and brine treatment systems. VSD ensures that the scenarios are socially relevant by directly incorporating stakeholder values into the design and assessment process. Four technical scenarios (Sc) were used to evaluate the VSD approach: Sc1) maximum water recovery, Sc2) and Sc3) integrated desalination with brine treatment for maximum resource recovery (using different configurations) and Sc4) electricity-based desalination for chemical recovery. Techno-economic models are implemented using Python to analyse the feasibility and performance of these scenarios. The modelling results indicate that all scenarios achieve zero brine production. However, the trade-offs between resource recovery and greenhouse gas emissions are evident. Increased salt recovery leads to higher $CO_2$ emissions (locally) due to electricity consumption. Scenario 1 minimized electrical energy consumption and emissions while maximizing water production. Scenarios 2 and 3 performed best in water and high-quality salt production. Despite its higher $CO_2$ emissions, Scenario 4 proved most profitable due to the production of chemicals. These findings highlight the importance of tailoring plant designs to regional needs. By providing a comprehensive understanding of trade-offs, the VSD approach fosters stakeholder dialogue and serves as a valuable decision-making tool for designing sustainable desalination systems.

## 1. Introduction

Desalination is a crucial water treatment technology that provides solutions to water-stressed regions, but the high energy consumption and disposal of the saline by-product, brine, pose significant environmental and social challenges. Zero liquid discharge (ZLD) and Minimal liquid discharge (MLD) systems have been developed to increase water recovery and minimize brine discharge by treating brine streams, and recovering water and salts (Mansour et al., 2018). While ZLD presents an attractive solution, its practical implementation faces challenges, including high energy requirements, high operational costs, the management of solid wastes and the need for advanced technologies capable of handling diverse brine compositions (Date et al., 2022).

Seawater is a rich source of valuable and scarce materials, which are lost when they end up in brine discharged from desalination plants (Ogunbiyi et al., 2021). Developments are moving from minimizing brine disposal to recovering valuable resources beyond water, presenting economic and environmental opportunities (Xevgenos et al., 2024). Numerous studies have explored technologies for recovering salts like magnesium, calcium, sodium, and metals (Mavukkandy et al., 2019; Bello et al., 2021; Cipolletta et al., 2021; Morgante et al., 2024). However, no single technology can recover all valuable materials effectively.

Integrating multiple technologies is necessary for effective multiple-product recovery and improved technological and economic performance (Ogunbiyi et al., 2021), but introduces complexity. The transition to resource recovery also introduces societal benefits and costs, as additional processing steps can increase energy use and capital costs,

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**Acronyms**

| | |
|---|---|
| ED | Electrodialysis |
| EDBM | Electrodialysis With Bipolar Membranes |
| EFC | Eutectic Freeze Crystallization |
| GHG | Greenhouse Gas |
| MED | Multi-Effect Distillation |
| MF-PFR | Multiple Feed Plug Flow Reactor |
| MLD | Minimal Liquid Discharge |
| NF | Nanofiltration |
| RES | Renewable Energy Sources |
| RO | Reverse Osmosis |
| Sc | Scenario |
| SWRO | Seawater Reverse Osmosis |
| TCr | Thermal Crystallizer |
| VSD | Value Sensitive Design |
| ZLD | Zero Liquid Discharge |

though they may offer economic gains depending on the recovered resources (Palmeros et al., 2023). Evaluating these integrated systems requires approaches that go beyond technical and economic performance (Rustum et al., 2020). There is no fixed approach to evaluating integrating technologies as it is context-dependent, as goals, target product quality, and quantity (Cipolletta et al., 2021). Thus, integrated systems should be designed to meet market demand and meet local requirements, ensuring solutions are technically efficient and socially relevant.

Although sustainability assessments in desalination often address environmental, economic, and social dimensions (Ibrahim et al., 2018; Lior and Kim, 2018; Wang et al., 2019), there remains a gap in existing frameworks related to the oversight of brine and resource recovery. ZLD studies typically focus on water and salt recovery from brine using a techno-economic approach, often neglecting social aspects, while the environmental assessments primarily center on energy-related emissions (Micari et al., 2020; Panagopoulos, 2021; Morgante et al., 2022b). To advance holistic solutions, existing frameworks need to be revised to incorporate societal context, encourage stakeholder participation, and evaluate whether the technological configurations are desirable in specific contexts (Ktori et al., 2025).

Value-sensitive design (VSD) addresses this gap by explicitly integrating societal values into the design and assessment of technological systems. Incorporating social aspects through stakeholders' values, VSD ensures that technological solutions are tailored to the community's specific needs. This alignment enhances both social acceptability and the likelihood of successful implementation (Ktori et al., 2025). Additionally, recognizing that technical systems cannot be fully understood or designed without considering the stakeholders involved, VSD bridges the gap between technical solutions and social perspectives (de Bruijn and Herder, 2009). Thus, unlike conventional methodologies such as Multi-criteria assessment (MCA) or techno-economic assessments, which focus predominantly on technical and economic parameters, VSD provides a more holistic evaluation by incorporating social, ethical, and environmental dimensions into the process (Borning and Kahn, 2004; van den Hoven et al., 2015; Parada et al., 2021). This contrasts with state-of-the-art methods that often marginalize these societal concerns or include them as secondary considerations (Ktori et al., 2025).

The VSD approach is especially effective in co-designing technical scenarios because it engages stakeholders early in the processes, allowing their values to shape key technical variables. For example, prioritizing resource security could lead to scenarios that focus on brine concentration and resource recovery, aligning technical configurations with both community needs and sustainability goals (Friedman et al., 2015; Parada et al., 2017). This differs from MCA, which typically involves stakeholders only at the final stage to validate pre-selected alternatives. This co-design approach addresses a key gap in existing sustainability assessments, which often lack clear reasoning behind the selection of alternatives or technical scenarios (Lindfors, 2021). In addition, stakeholder values are translated into measurable objectives and performance indicators, making the assessment process transparent and aligned with community priorities.

Given the rapid advancements in seawater desalination and the need to resolve value tensions between societal, environmental, economic and technical goals, this study applies elements of VSD to fill gaps in existing assessment methods and offer insights for the design of socially relevant desalination systems. The study addresses the following key question:

> *What are the benefits and drawbacks of different technical configurations in integrated resource recovery desalination, vis-à-vis identified values, and how do they apply to different societal contexts?*

To answer the questions, we investigate different technical configurations using some of the elements of the VSD approach. Indicators were selected based on values identified in prior research by Palmeros et al. (2023) and technical scenarios were designed to reflect stakeholders' values. Process and economic models were developed to provide the required data for the alternative scenarios. Finally, the alternative technical scenarios were analysed in the context of societal values and placed in relative social contexts. This work provides a novel integration of VSD and soft MCA methodology (Mendoza and Martins, 2006) in the desalination field, offering a valuable decision-support tool.

## 2. Methods

The framework, as previously outlined by Ktori et al. (2025), consists of six steps: 1) Problem definition, 2) Indicator definition, 3) Design of alternative scenarios, 4) Data acquisition, 5) Assessment indicators quantification, and 6) Performance analysis. In this study, we implement steps 2–6 of the comprehensive methodology illustrated in Fig. 1. This section describes the methodology and adjustments that followed. It is worth noting that this work does not evaluate the treatment chains in a specific societal context, but the example of Lampedusa and the identified stakeholders' values in that context are used to implement the framework (see Section 2.1). Then generalized outcomes and useful insights are used in the discussion (see Sections 3.3 and 0). For this reason, a detailed and specific definition of the problem (step 1) is left out.

### 2.1. Problem definition

This work focuses on seawater desalination integrated with a power plant (different owner) on an island or coastal area that depends on external fossil resources for its energy production. The integration aims to increase water availability with the same or similar energy use by capturing waste heat and recovering salts. In particular, the example of Lampedusa, a small island in the Mediterranean Sea, is used to identify the stakeholders' values. The island covers 100 % of its water demand through desalination, which can account for around 30 % of the total electricity usage for small islands Palmeros et al. (2023). Building upon prior research by Palmeros et al. (2023) and Palmeros and Gamboa (2021), we incorporate valuable insights into stakeholder values and tensions related to seawater desalination in island contexts. This study did not involve direct interviews or surveys with new stakeholders; instead, it builds on previously published research that identified key stakeholder values. The main identified stakeholder values are:

- Resource security
- Water security
- Energy security
- Affordability

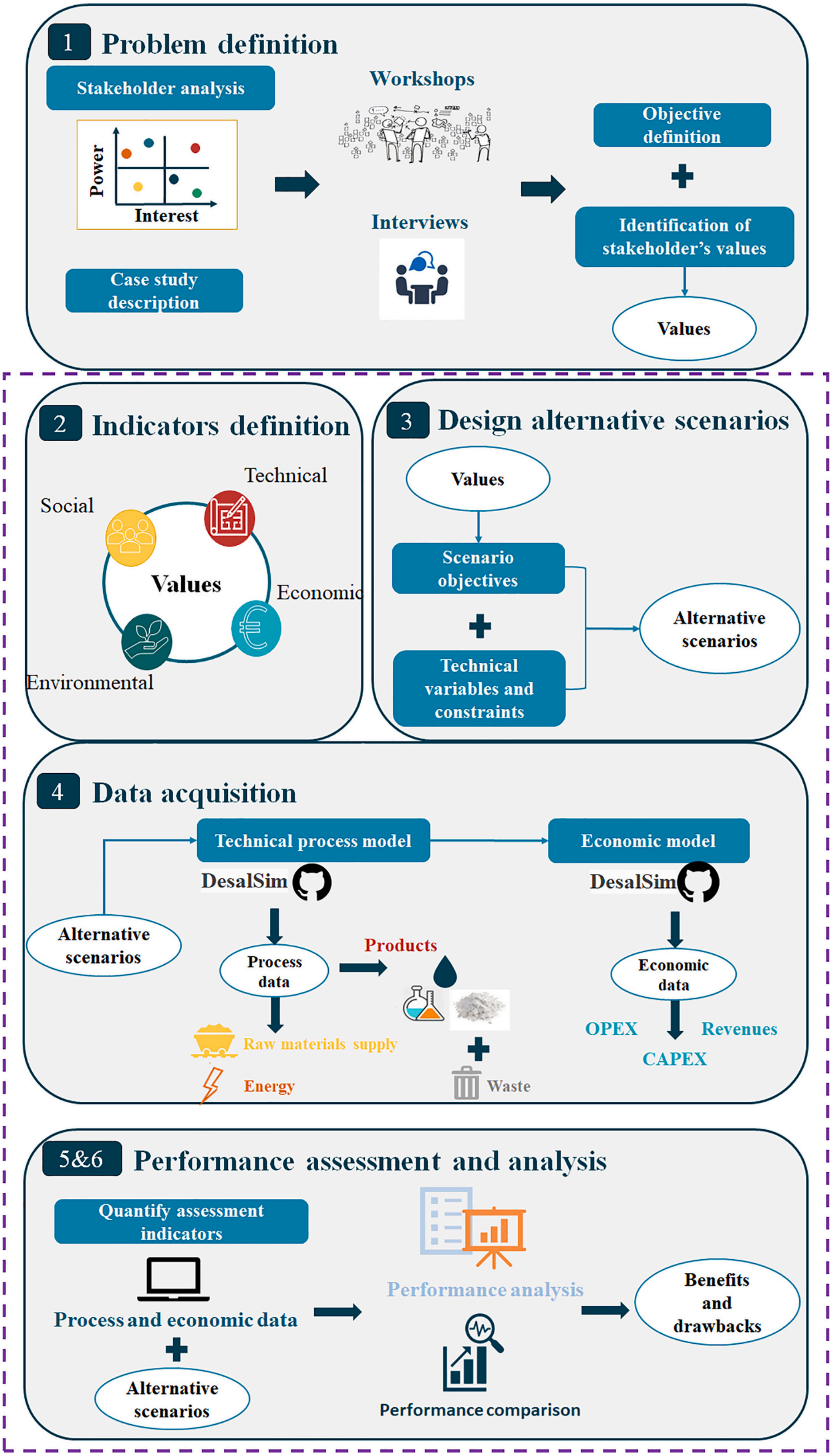


**Fig. 1.** Schematic representation of the followed methodology. The dashed line shows the steps followed in this work.

- Protection of the environment, including marine life
- Climate change mitigation
- Efficiency
- Safety

Systems in this societal problem statement present several tensions that need to be considered. Fig. 2 summarises the identified sustainability tensions for integrated desalination and brine treatment systems in islands or coastal areas. A tension arises between water security, energy security, and sustainability. While the system would enhance water availability and self-resilience, it would increase the need for energy imports and compromise energy security. Furthermore, the system's impacts on sustainability aspects, such as brine discharge reduction and increased greenhouse gas emissions due to higher energy use, as well as uncertainties regarding the cost of water, must be assessed. Therefore, a tension arises between water, resource security, and affordability. While brine minimization and water and salts/chemicals recovery will increase, it will also increase the production costs. In this way, how costs are distributed will affect the competitiveness of resource recovery and the affordability of water in a water-scarce region. Although recovery of valuable products will result in extra revenue from selling products, there is a risk of how competitive the solution is. Finally, a tension exists between efficiency and long-term sustainability. Although integrating waste heat promotes energy efficiency, there is a risk of sustaining dependence on fossil fuels, preventing the adoption of renewable energy sources. Limited renewable energy source areas in islands contribute to the reliance on fossil resources, although local planning considers expanding renewable energy. These tensions require further investigation and discussion with stakeholders to ensure sustainable outcomes.

Finally, in the problem definition step, the analysis boundaries need to be defined (Ktori et al., 2025). This study aimed to design and identify suitable alternatives for various societal contexts, assessing their compatibility and exploring how the development of an integrated system can address identified value tensions. A soft MCA (Mendoza and Martins, 2006) is applied to provide valuable insights and structure knowledge for decision support in desalination projects. Therefore, the analysis boundaries will be limited to technical system evaluation using selected indicators. In this work, we adopt a system-level approach, evaluating technical alternatives as a collective system rather than individual components. By focusing on these specific aspects, we aim to shed light on the potential benefits and challenges of an integrated system and contribute to informed decision-making in the field of desalination.

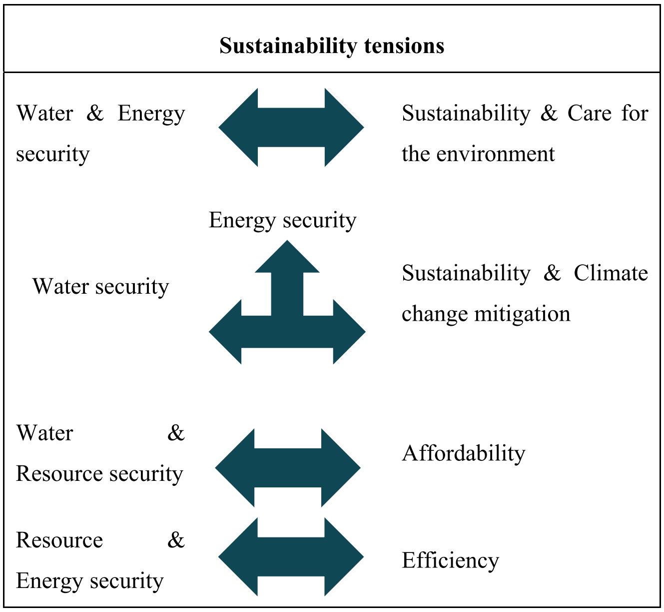


**Fig. 2.** Identified sustainability tensions for integrated desalination and brine treatment systems in islands or coastal areas.

### 2.2. *Define performance indicators*

This methodological step outlines how sustainability issues and identified values are transformed into performance indicators. Firstly, the identified values from (Palmeros et al., 2023) (see Section 2.1) were translated into objectives and then performance indicators. The connection between values, objectives, and indicators can be explained as follows: values guide the selection of the objective used to assess different scenarios, and indicators act as the measurements that evaluate how well those scenarios align with the chosen objective (Ktori et al., 2025). The indicator database in Ktori et al. (2025) was used as inspiration for the selection of indicators in this work. To ensure the indicators' relevance and importance in this context, they were shared with a small group of stakeholders consisting of researchers specializing in sustainability, desalination, and resource recovery. This engagement provided valuable input to refine the indicator selection and ensure alignment with stakeholder expectations.

While social indicators are typically crucial, in sustainability assessments, the social dimension is embedded within the VSD approach rather than through separate social indicators, as the analysis is not focused on a specific societal context. This approach allows us to integrate social considerations holistically throughout the scenario assessment without limiting them to specific quantifiable indicators.

### 2.3. *Design of alternative scenarios*

This section outlines the approach for developing technical scenarios that incorporate stakeholder values identified in the problem definition. While value tensions are acknowledged as a critical aspect of this study (as highlighted in the problem definition), the primary emphasis during scenario development is placed on aligning with these values. This emphasis on alignment stems from the high complexity of the issue. Value tensions will play a crucial role in the subsequent analysis of our results. Therefore, the scenarios are designed to address the value of water, resource, and energy security, climate change mitigation, and environmental protection, particularly concerning marine life and efficiency, while also indirectly considering affordability and safety. Fig. 3 presents the following procedure for the design of the alternative technical scenarios. The design of these scenarios was made on the basis of the Value sensitive design (VSD) approach. The detailed methodology for VSD can be found in (Palmeros Parada et al., 2017; Palmeros Parada et al., 2020).

The development of technical scenarios is organised around three main technical scenario variables: process and technology, product and by-products, and raw materials and utilities. The main variables used in this study to generate the scenarios are the intensity of recovery (water focus vs. intense resource recovery) and the type of energy source (thermal or electrical). In particular:

- The intensity of recovery variable represents the degree of resource recovery within the scenarios, ranging from a focus on maximizing water recovery to intense resource recovery encompassing elements like salts, chemicals, and critical raw materials.
- Energy Source Variable declares the source of energy used within the scenarios, distinguishing between thermal-based technologies and electricity-based technologies, with a potential focus on renewable energy sources.

These key variables are essential in shaping the technical scenarios, but they are intricately linked to the stakeholder values identified in the problem definition. The main identified stakeholder values include:

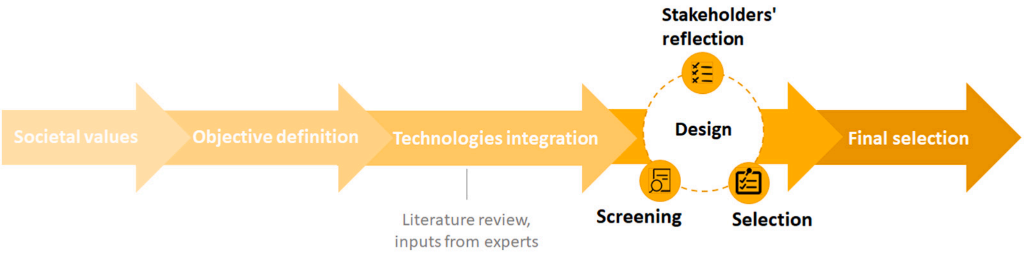


**Fig. 3.** Followed procedure for the design of alternative technical scenarios.

- Resource security is closely related to the intensity of recovery variable. A higher intensity of resource recovery aligns with resource security by reducing dependence on external resources and enhancing self-sufficiency.
- Water security is directly tied to the intensity of the recovery variable. Greater water recovery ensures water availability, which is crucial for human well-being and economic activities.
- Energy security can be linked to both the energy source variable and the intensity of recovery variable. Integrating thermal-based technologies with waste heat or using renewable energy sources contributes to energy security.
- Affordability is influenced by the intensity of the recovery variable, particularly in scenarios with intense resource recovery, which may affect production costs, revenue, and affordability.
- Protection of the Environment, Including Marine Life, aligns with scenarios that aim for minimal brine discharge, reducing the negative environmental impact and benefiting marine life.
- Climate Change Mitigation is associated with the energy source variable, with scenarios using renewable energy sources contributing to reducing greenhouse gas emissions.
- Efficiency is promoted by scenarios with higher energy and water/production efficiency, which both variables can influence.
- Safety considerations should be integrated into scenarios regardless of the variables, ensuring the well-being of individuals involved in the process.

Additionally, a literature review on technology integration for desalination and brine treatment was carried out to identify the advantages and limitations of the integration. Specifically, studies where at least two technologies were combined to treat seawater or brine streams were selected and analysed. For a comprehensive overview of the integration of technology, including the main products, scale, advantages, and limitations of each study, please refer to Table S2 in the Supplementary Material. The performance of technologies in the systems was studied, and data regarding energy consumption and economics were collected and analysed. Note that lab-scale technologies were excluded, focusing exclusively on well-developed technologies with practical relevance. The selected studies were analysed further in terms of the following values:

- Socio-economic values such as development opportunities, energy security, economic value-sharing
- Human-nature interaction such as protection and recovery, efficiency and circularity

Considering the identified values (see problem definition, Section 2.1), the objectives, and the insights from the literature review, the technical scenarios were developed. After the preliminary design of the technical scenarios, they were shared with a group of stakeholders in a workshop to ensure the practicality and feasibility of the scenarios. During this workshop, the objective and the technical aspects of each scenario were discussed. Their feedback was incorporated, and changes were made. The technical scenarios are described in Section 3.

### 2.4. Data acquisition and quantification of assessment indicators

One of the most important steps in the proposed framework is data acquisition because it is directly related to the accuracy, reliability, and quality of the results. In this work, data will be provided by technical and economic models. The mathematical description, the details of the modelling, the main assumptions, and references are given in the Supplementary Materials (see Section S3) since the modelling of desalination and brine treatment processes is not the main objective of this work, and it has been studied extensively in the literature. Interested readers can refer to the GitHub repository for the technical process and economic models (https://github.com/rodoulak/Desalination-and-Brine-Treatment-Simulation-.git) developed in the context of this study.

In this section, an overview of the main inputs and outputs for each process unit in the integrated system is given (see Table 1). These parameters were selected based on their direct relevance to the system's techno-economic and environmental performance. Additional parameters and assumptions are provided in the Supplementary Materials (see Section S3). All technical process models were implemented in Python. The feed flow rate is the same for all the scenarios, and it is equal to $3000m^3/d$. The technical process models were validated with experimental pilot-scale results from the Water Mining project (Morgante et al., 2024) (see Supplementary Materials, Section S5). Furthermore, the results of this study align with those of previous research in the literature (Cipolletta et al., 2021; Morgante et al., 2022b). Especially with work from (Morgante et al., 2022b) that was carried out within the Zero Brine project and previous works (Xevgenos et al., 2015a) sharing the same objective as this work, which is technological integration for recovering valuable materials from brine.

In this study, we have made key assumptions to create a clear framework for our analysis, which are essential for understanding our results and conclusions. It is important to note that the validity and robustness of our findings are contingent upon these assumptions. Variations or deviations from these assumptions could impact the outcomes of our analysis. The key assumptions for our analysis are the following:

i. Waste heat availability at zero economic cost: Given its status as a by-product of electricity generation, we assume waste heat from integrated power and desalination plants is available at zero economic cost.
ii. Negligible emissions from waste heat: In our analysis, we do not consider emissions arising from waste heat. Waste heat, a by-product of electricity generation, is primarily intended for electricity generation, and any emissions associated with it are deemed negligible.
iii. Exclusive use of grid electricity or direct power plant output: we exclusively consider two electricity sources, the grid and direct power plant output for combined facilities, facilitating clear source differentiation in our assessment.
iv. European Union (EU) average emission factor for electricity: we consider the EU average emission factor for electricity as a standardized basis for our $CO_2$ emissions calculations.

**Table 1**
Main inputs and outputs of each process unit in the integrated system.

| Process | Input | Output |
|---|---|---|
| Nanofiltration | Feed flow rate [$m^3/h$] | Permeate flow rate and composition [g/L] |
| | Ion concentration [g/L] | Concentrate flow rate and composition [g/L] |
| | Osmotic pressure [bar] | Electrical requirements [$kWh_{el}$] |
| | Water recovery [%] | Chemicals consumption [L/h] |
| | Ion rejection [−] | |
| Multi-effect distillation | Feed flow rate [$m^3/h$] | Flow rate of water [$m^3/h$] |
| | Ion concentration [g/L] | Effluent flow rate and composition [g/L] |
| | Feed temperature [°C] | Electrical [$kWh_{el}$] and thermal [$kWh_{th}$] requirements |
| | Steam temperature [°C] | Cooling water flow rate [$m^3/h$] |
| Thermal crystallizer | Feed flow rate [$m^3/h$] | Flow rate of water [kg/h] |
| | Ion concentration [g/L] | Flow rate of NaCl [kg/h] |
| | Feed temperature [°C] | Cooling water flow rate [$m^3/h$] |
| | Steam temperature [°C] | Electrical [$kWh_{el}$] and thermal [$kWh_{th}$] requirements |
| Multi-plug flow reactor | Feed flow rate [$m^3/h$] | Alkaline solution flow rate [L/h] |
| | Ion concentration [g/L] | Flow rate of $Mg(OH)_2$ [kg/h] |
| | Concentration of the alkaline solution (NaOH) [M] | Flow rate of $Ca(OH)_2$ [kg/h] |
| | Concentration of the acid solution (HCl) [M] | Acid solution flow rate [L/h] |
| | | Effluent flow rate [$m^3/h$] and composition [g/L] |
| | | Electricity requirements [$kWh_{el}$] |
| Eutectic freeze crystallizer | Feed flow rate [$m^3/h$] | Flow rate of $Na_2SO_4$ [kg/h] |
| | Ion concentration [g/L] | Flow rate of ice [kg/h] |
| | Feed temperature [°C] | Effluent flow rate [$m^3/h$] and composition [g/L] |
| | | Electricity requirements [$kWh_{el}$] |
| Electrodialysis with bipolar membranes | Feed flow rate [$m^3/h$] | Flow rate of acid [$m^3/h$] and composition [g/L] |
| | Ion concentration [g/L] | Flow rate of base [$m^3/h$] and composition [g/L] |
| | Electric density | Flow rate of salt [$m^3/h$] and composition [g/L] |
| | | Electricity requirements [$kWh_{el}$] |
| Electrodialysis | Feed flow rate [$m^3/h$] | Flow rate of diluted stream [$m^3/h$] and composition [g/L] |
| | Ion concentration [g/L] | Flow rate of concentrate stream [$m^3/h$] and composition [g/L] |
| | Electric density | Electricity requirements [$kWh_{el}$] |

Note: The mathematical description, modelling details, and relevant references for the inputs and outputs of each process unit are provided in the Supplementary Materials (see Section S3).

Economic models were developed in order to evaluate the economic performance of the alternative scenarios. The economic model consists mainly of capital expenditure (CAPEX) and operating expenditure (OPEX). Specifically, CAPEX consists of fixed-capital investment and working capital, and OPEX refers to expenditure directly generated by operating the plant (Peters et al., 2003). The main inputs of the economic models are:

- Equipment cost
- Mass flow rates (from technical models)
- Energy and utility consumption (from technical models)
- Selling price of products (from literature)
- Price of energy and utilities (from literature)

Note that in the assessment of economic viability for scenarios, we assumed established market demand and potential off-takers for the recovered salts and chemicals, as their profitability hinges on market uptake. A detailed explanation of the economic models and the assumptions that were made, as well as the input data from the literature, are given in the Supplementary Material (see Sections S4 and S5). All economic models were implemented in Python (see GitHub repository). The two models were coupled, and the main outputs of the technical models for each scenario became the inputs for the respective economic model of the scenario. Finally, the selected indicators are determined using data from technical and economic models. These models provide the necessary input parameters, such as mass flow rates, energy consumption, equipment costs, and product selling prices, which are essential for accurately assessing each indicator. This ensures that the indicators, initially defined in the indicator selection step (see Sections 2.2 and 3.1), are grounded in robust and comprehensive data. After the quantification of the selected indicators, the performance analysis can carried out where the benefits and drawbacks of the different technical configurations relative to the identified values are evaluated (see Fig. 1).

## 3. Results and discussion

### 3.1. Define performance indicators

Following the methodology described in Section 2.2, the performance indicators are defined below, and they are summarized in Table 2. The detailed description (and mathematical formulation) of these indicators is provided in the Supplementary Material (see Section S1).

The value of water security is quantified through the system's water production quantity, emphasizing the importance of measuring product outputs and recovery efficiency. Energy consumption, critical for energy security considerations, is evaluated using indicators for electrical and thermal energy consumption. The value of resource security is quantified through the system's salt production quantity. System efficiency,

**Table 2**
The main values identified and the indicators used to operationalize them in view of sustainability assessment.

| Value | Objective | Indicator | Units |
|---|---|---|---|
| Energy security | Improve energy performance | Energy consumption | kWh |
| Water security | Increase water recovery | Quantity of water produced | $m^3$/year |
| Resource security | Increase resource recovery | Quantity of salt produced[a] | Ton/year |
| Efficiency | Increase efficiency | Resource efficiency | % |
| | | Brine production | ton/year |
| Affordability | Increase the economic viability of the plant | CAPEX | € |
| | | OPEX | €/year |
| | Increase profitability | Production efficiency | €/€ |
| Climate change mitigation | Minimize climate change impact | Carbon dioxide emission | kg $CO_2$-Equ |
| Care for the environment | Minimize resource utilization | Water footprint | $m^3$/year |
| | Minimize the aquatic eco-toxic impact of brine disposal | Eco-toxicity | kg of brine/kg of seawater |
| Safety | Use of chemicals | Human toxicity | – |

[a] In this paper, the term "Salt produced" refers to various types of salts (NaCl, $Mg(OH)_2$, $Na_2SO_4$ etc.) recovered through the integrated seawater desalination and brine treatment processes.

crucial for overall effectiveness and the value of efficiency, is assessed through two specific indicators: overall brine production and resource efficiency.

This study used indicators to evaluate the affordability of integrated systems comprehensively, considering the entire integrated process rather than evaluating each individual component separately. Production efficiency measures the monetary value of all the recovered products relative to the total annual cost of the integrated system. The production efficiency indicator can accommodate different metric units, which is particularly important in multi-product systems. This indicator, along with the selected CAPEX and OPEX indicators, provides a comprehensive assessment of the economic dimension, ensuring that affordability is sufficiently addressed.

To evaluate climate change mitigation and the carbon footprint resulting from energy consumption, we have selected $CO_2$ emissions as an indicator for this specific stage of the analysis. It's important to note that in this phase, we focus solely on operational $CO_2$ emissions and do not consider the broader life cycle impacts of the system. Specifically, we use the average $CO_2$ emission rate from electricity use in the European Union for our calculations. At this stage, renewable energy sources are not included in electricity production, but they will be considered in a subsequent phase of the analysis. In terms of care for the environment and specifically related to brine disposal, aquatic eco-toxicity was selected to quantify the potential impacts of brine discharge on the marine environment. It was calculated based on the final concentration (concentration of salt ions, chemicals, metals) of the brine stream (Zhou et al., 2013). Water footprint is an indicator of resource efficiency. This indicator provides insights into the system's efficiency in utilizing water resources, aligning with the value of care for the environment and resource conservation. Finally, to assess the environmental impact and ensure safety from chemical use in the system, human toxicity was chosen as an indicator.

### 3.2. Description of alternative scenarios

While all scenarios share the common goal of increasing water recovery and reducing brine discharge (compared to typical seawater desalination), they do so differently. Note that the mainstream entering all the treatment chains is seawater (same flow rate and concentration), and all the scenarios aim for either zero-liquid discharge or minimal-liquid discharge. In this way, the scenarios address the value of protection of the environment regarding marine life. The scenarios are summarized in Table 3 and a detailed description of the design of each scenario is given below and in Supplementary Materials (see Section S6).

**Table 3**
Overview of alternative technical scenarios.

| Scenario | Objective | Technologies | Recovered products |
|---|---|---|---|
| 1 | Maximize water recovery and minimize brine discharge | NF, MED, ThCryst | Water, Mixed salts |
| 2 | Desalination and brine treatment for recovery of water and valuable products and minimizing brine discharge | NF, MED, ThCryst, MFPR, EFC, EDBM | $Ca(OH)_2$, HCl, Ice, $Mg(OH)_2$, NaCl, NaOH, $Na_2SO_4$, Water |
| 3 | Integrated RO plant with brine treatment for recovery of water and valuable products and minimizing brine discharge | RO, NF, MED, ThCryst, MFPPR, EFC, EDBM | $Ca(OH)_2$, HCl, Ice, $Mg(OH)_2$, NaCl, NaOH, $Na_2SO_4$, Water |
| 4 | Integrated RO plant with brine treatment focusing on chemical recovery, using only electricity-based desalination | RO, NF, ED, MFPR, EDBM | $Ca(OH)_2$, HCl, $Mg(OH)_2$, NaOH, Water |

ED: Electrodialysis; EDBM: Electrodialysis with bipolar membranes; EFC: Eutectic freeze crystallization; MED: Multi-effect distillation; MFPR: Plug-flow reactor; NF: Nanofiltration; RO: Reverse Osmosis, ThCryst: Thermal crystallizer.

#### 3.2.1. Scenario 1: water recovery

Scenario 1 focuses on water security and energy security values by maximizing water recovery while minimizing energy requirements by using waste heat from a nearby power plant. This scenario does not focus on recovering salts or chemicals but rather on ensuring water availability through the recovery of water. The brine discharge is expected to be zero. This scenario generates a mixed salt stream, which cannot be used and is considered a solid waste that must be disposed of properly. Scenario 1 is a typical Zero liquid discharge system that was reported and assessed several times in the literature (see Section S2; Table S2 in Supplementary Materials). Nanofiltration (NF) is used as pre-treatment to Multi-Effect Distillation (MED) to increase the efficiency of the desalination process, avoid scaling, and further concentrate the NaCl stream. Energy security is ensured by integrating thermal-based technologies such as MED and Thermal Crystallizer (TCr) with available waste heat, which can be sourced from a nearby power plant. While it is true that thermal desalination processes like MED are generally more energy-intensive compared to membrane-based technologies like Reverse Osmosis (RO), their advantage lies in their compatibility with the utilization of excess heat energy.

Based on these considerations, Scenario 1 consists of three process units: NF, MED and TCr (see Fig. 4). The seawater stream first goes to the NF unit and is separated into two different streams: one high in monovalent ions and one in multivalent ions. The former is directed to a process line of conventional units, including the MED unit that obtains water from the evaporation process. The NF unit is used as pre-treatment for MED to increase the performance of the unit. Following this unit, the stream goes to the thermal crystallizer and is mixed with the latter stream from NF, which is high in multi-valent ions, to finally obtain water and mixed salt (low-purity NaCl crystals).

#### 3.2.2. Scenario 2: desalination and resource recovery

Scenario 2 focuses on water security and resource security values by recovering multiple high-value materials. For this reason, the NF concentrate treatment line from scenario 1 is extended by integrating various technologies. The integration of technologies will affect the efficiency of the system. Literature showed that NF can be used as a pre-treatment step to separate the monovalent ions and multivalent ions from brine and increase the efficiency of the MED unit (see Section S2; Table S2 in Supplementary Materials). Another advantage of this separation is the recovery of the multi-valent ions in the form of salt or chemicals. The use of multiple technologies is required to achieve high recovery of valuable products, including Magnesium (Mg), which is one of the Critical Raw Materials (CRMs) defined by the European Union (EU) (Morgante et al., 2022b). Mg precipitation and crystallization from brine streams have been studied in the literature, and pilot-scale plants have been tested (Reig et al., 2016a; Morgante et al., 2022a; Xevgenos et al., 2022). This crystallization step can be combined with Electrodialysis with Bi-polar Membrane (EDBM) to recover chemicals (HCl, NaOH) from the brine feed, contributing to the economic feasibility and circularity of the plant (innovative circular economy). Additionally, the effectiveness of using Eutectic Freeze Crystallization (EFC) as pre-treatment to EDBM has been studied to recover more products ($Na_2SO_4$ and water) and concentrate further the effluent from the precipitation process to increase EDBM efficiency (Culcasi et al., 2022), The recovery of Mg and Ca will also increase the efficiency of EFC, the quality of the products, and, therefore, their affordability.

The main desalination and brine concentration technology used in Scenario 2 is MED, while NF is used as a pre-treatment. MED can be used to recover water and concentrate the brine solution further and it is commonly combined with a thermal crystallizer in ZLD or MLD systems to recover the remaining amount of water and salt crystals (Xevgenos

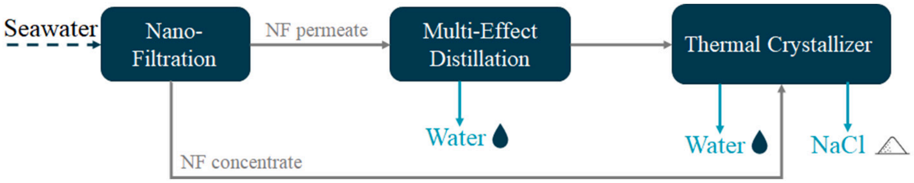


**Fig. 4.** Process flow diagram of Scenario 1.

et al., 2015b; Chen et al., 2021). Besides water and resource security, Scenario 2 aims to ensure energy security by integrating thermal-based technologies such as MED and TCr with waste heat (from power plants) to cover the thermal energy requirements.

Based on the above information, Scenario 2 consists of six process units (see Fig. 5). The seawater stream first goes to the NF unit and is separated into two different streams: one high in monovalent ions and one high in multivalent ions. The former is directed to a process line of conventional units, including the MED unit that obtains water from the evaporation process. Following this unit, the stream goes to a thermal crystallizer to finally obtain NaCl crystals and water. The latter stream from NF, high in multivalent ions, is directed to a treatment line comprising three innovative units for the recovery of magnesium and calcium in the form of hydroxide, $Na_2SO_4$ and water in the form of ice, and HCl and NaOH from the remaining NaCl-rich solution The recovered HCl and NaOH are reused in the treatment chain.

### 3.2.3. *Scenario 3: integrated RO and brine treatment plant*

Scenario 3 aims to ensure water availability and resource security by recovering multiple high-value materials. Specifically, in Scenario 3, the objective is to maximize water and resource recovery from seawater brine by integrating various technologies with a typical desalination plant that uses RO. Unlike Scenario 2, which is integrated with a MED plant, Scenario 3 is designed to be integrated with an existing RO plant (with 40 % recovery). RO brine contains a large amount of water, this water can be recovered in a MED unit. All other aspects of Scenario 3 remain identical to those in Scenario 2 (see Fig. 6).

### 3.2.4. *Scenario 4: electricity-based desalination and chemical recovery*

The objective of Scenario 4 is to balance water and resource recovery. Specifically, this scenario focused only on the recovery of high-value materials such as Mg to increase the economic feasibility and long-term sustainability of the plant. Additionally, the internal production and consumption of chemicals from seawater brine could also contribute to those values and enhance the circularity of the plant. Electrodialysis (ED) can be used as pre-treatment to the EDBM unit to increase efficiency by concentrating the feed stream (Reig et al., 2016b). Additionally, Culcasi et al. (2022) showed that the presence of sulphate ions does not significantly affect the purity of the obtained products but significantly reduces the specific energy consumption of EDBM. Overall, there is no brine discharge from the system since the exit flow streams from ED and EDBM are low salinity streams (diluted brines), and they could be recycled back into the system or discharged. Regarding the energy aspect, in this scenario, only electricity is used to cover the energy requirements of the treatment chain. This scenario addresses the values of energy security and climate change mitigation by using renewable energy and maybe the lack of waste heat (long-term sustainability). Therefore, only electricity-based technologies are used in the design of this scenario (see Fig. 7).

Based on these, Scenario 4 consists of five process units (see Fig. 7) and it represents an MLD system aiming to maximize water and valuable resources recovery from brine. The seawater stream first goes to the RO unit that recovers 40 % of the water, followed by the NF unit that separates monovalent and multi-valent ions. The monovalent-rich stream is further concentrated using ED, while the multivalent stream is processed to recover magnesium and calcium as hydroxide precipitates. The remaining solution, combined with the NaCl-rich stream from ED, is fed into the EDBM unit to recover valuable chemicals such as HCl and NaOH. Additionally, the low-concentration saline solution can be recycled back into the treatment chain.

## 3.3. *Performance assessment*

In this section, we present a critical analysis of the performance of the four designed scenarios, each developed to enhance water recovery and reduce brine discharge compared to typical seawater desalination processes (see Section 2.3). The performance analysis is oriented around the identified value tensions (see Section 2.1, Fig. 2). All scenarios were designed to achieve '*zero brine production*', effectively eliminating concentrated brine discharge (see Table 4), and the modelling results confirm that this was achieved in all cases, resulting also in zero marine eco-toxicity potential. Scenarios 2, 3 and 4 produce a low-salinity solution of Na, Cl, and K, which it is possible to recycle this low-salinity stream back into the system or safely discharge it. For the sake of simplicity in this study, we have not considered the recirculation of these streams. Human toxicity potential due to chemical consumption is negligible across all scenarios, as only antiscalants, HCl, and NaOH are used. Note that other valuable trace elements, such as lithium or rare earth elements, are excluded from the analysis due to their low concentrations and the additional complexity required for recovery, which

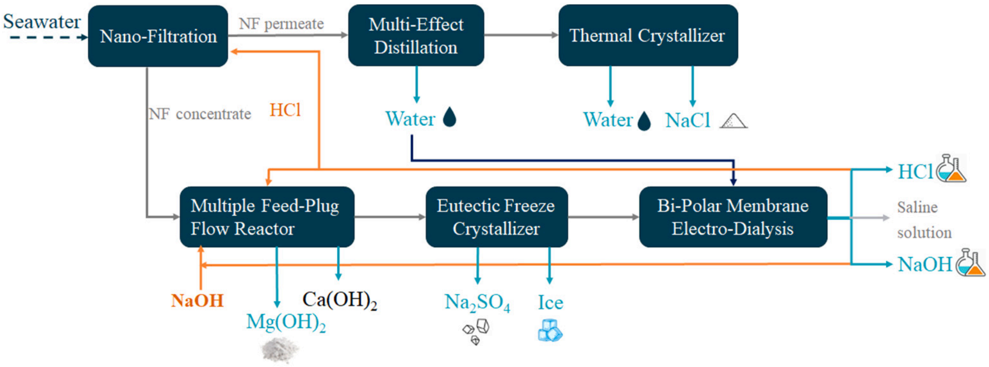


**Fig. 5.** Process flow diagram of Scenario 2.

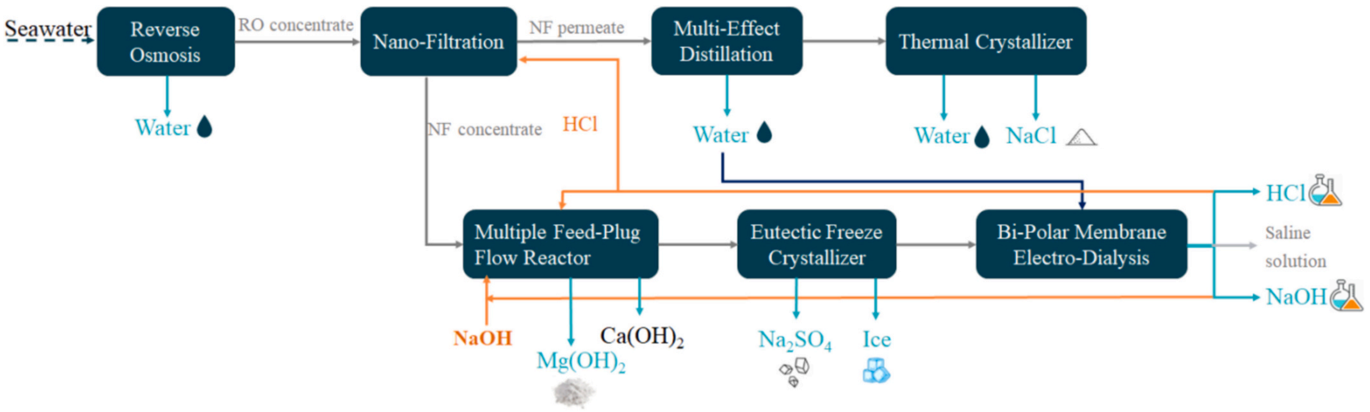


**Fig. 6.** Process flow diagram of Scenario 3.

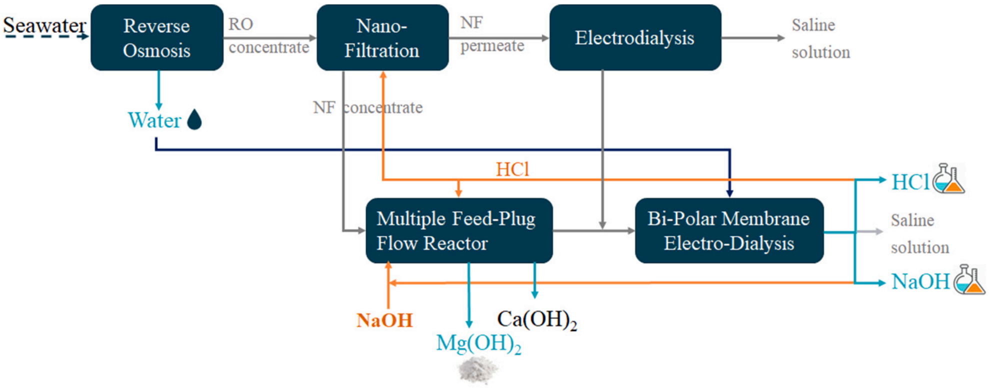


**Fig. 7.** Process flow diagram of Scenario 4.

is beyond the scope of this study.

Fig. 8 illustrates the trade-off between avoiding the environmental impacts of brine discharge and GHG emissions associated with the energy requirements of ZLD systems (see assumptions, Section 2.4). The increased salt recovery in Scenarios 2 and 3 results in 71 % higher $CO_2$ emissions than Scenario 1 (water recovery scenario). This means that recovering multiple products and enhancing resource security value comes with different environmental costs and potential conflicts with values related to climate change mitigation and environmental protection. Additionally, the use of thermal-based technologies and available waste heat sources, like Scenario 1, leads to lower $CO_2$ emissions. In contrast, Scenario 4 focuses on chemical production (lower water and salt production) with only electricity-based technologies that consume higher amounts of electricity and zero amounts of thermal energy, which implies 86 % higher $CO_2$ emissions than Scenario 1 and 52 % higher than Scenarios 2 and 3. This comparison is based on specific assumptions. Scenario 4 exclusively relies on grid electricity, and the emissions will largely depend on the local energy mix used to generate electricity. These emissions could be mitigated by integrating renewable energy sources, which will be considered in future studies.

Fig. 9 illustrates the results for water, recovery and overall resource efficiency versus electrical and thermal energy consumption. Resource efficiency in this context refers to the ratio of mass of valuable materials output, such as water, salts, and chemicals, to material input (see Table 3 and Section S1.3 in Supplementary Materials). The comparison reflects the tension between the values of water, overall resource security and energy security. While the systems would enhance water availability and self-resilience, they increase the energy requirements, compromising energy security. Scenario 1, designed to align with stakeholder values of energy efficiency and security, achieves the lowest electrical energy requirements by utilizing waste heat (Fig. 9A and B). However, it doesn't perform the best in water production (9 % lower than Scenario 3), which is the main objective of this scenario. Regarding the overall resource recovery, Fig. 9 shows that the production of high-quality products in Scenarios 2 and 3 comes with high energy costs. Waste heat use reduces electricity intensity by 86 % and 52 %, compared to Scenario 4, which only uses electricity-based technologies. From an energy efficiency point of view, Scenario 1 performed better in terms of electrical energy consumption and water production, but Scenario 1 is less self-resilient. The use of available waste heat by coupling the desalination plant with a power plant to cover the thermal energy requirements and fewer electricity-dependent technologies can decrease the dependency on energy imports or additional energy sources. Although integrating waste heat promotes energy efficiency, there is a risk of sustaining dependence on fossil fuels, preventing the adoption of renewable energy sources.

The tension between resource recovery for water and resource security and associated costs is illustrated in Fig. 10. Scenarios 1–3 achieve high resource efficiency (86 %–95 %), which comes with high economic costs. Contrarily, Scenario 4, with a focus on chemical production and the use of only electrical-based technologies, has the highest OPEX because of the high electrical energy consumption and the low resource efficiency. The OPEX in scenario 4 is 40–59 % higher than in the other scenarios. The integration of technologies to recover multiple valuable products effectively results in a high investment cost, specifically for Scenarios 2 and 3 (Sc2: 49 % higher than Sc1, 22 % higher than Sc3, 45 % higher than Sc4, Sc3: 35 % higher than Sc1 and 29 % higher than Sc4). An opportunity to deal with this tension is to consider alternative energy sources to decrease energy costs and, therefore, the OPEX. Regarding CAPEX, alternative approaches or designs for the production of the same products could be explored. These technologies will become more cost-effective without compromising resource efficiency as designs evolve,

**Table 4**
Summary of results of the evaluation of technical scenarios.

| Indicator | Scenarios | | | |
|---|---|---|---|---|
| | Scenario 1: Water Recovery | Scenario 2: Desalination and resource recovery | Scenario 3: Integrate RO plant with brine treatment | Scenario 4: Electricity-based desalination and chemical recovery |
| Energy consumption (GWh) | 3.9 | 13.3 | 13.4 | 27.5 |
| Quantity of water produced (1000 $m^3$/year) | 881.7 | 738.8 | 972.9 | 369.7 |
| Quantity of salt produced (Ton/year) | 0.0 | 0.3 | 0.2 | 0.1 |
| Resource efficiency (%) | 95.4 | 87.1 | 86.0 | 24.4 |
| Brine production (ton/year) | 0.0 | 0.0 | 0.0 | 0.0 |
| CAPEX (M€) | 20.0 | 39.2 | 30.6 | 21.7 |
| OPEX (M€/year) | 5.9 | 7.3 | 5.0 | 12.2 |
| Production efficiency (€/€) | 0.3 | 2.0 | 3.4 | 9.7 |
| Carbon dioxide emission (MTon $CO_2$-Equ) | 7.7 | 26.3 | 26.5 | 54.5 |
| Water footprint (1000 $m^3$/year) | 0.0 | 267.1 | 248.0 | 688.5 |
| Eco-toxicity (kg of brine/kg of seawater) | 0.0 | 0.0 | 0.0 | 0.0 |
| Human toxicity (−) | 0.0 | 0.0 | 0.0 | 0.0 |

and advancements reduce initial high costs. Scenario 3 offers an additional benefit compared to Scenario 2 by integrating the brine treatment system with an existing RO plant. This integration enhances the system's overall efficiency and resource utilization. It enables the utilization of existing infrastructure, which means lower investment costs.

The tension between water, resource security, and profitability is given in Fig. 11, which displays resource recovery efficiency and production efficiency for the four scenarios. The production efficiency reveals the monetary value of all the recovered products relative to the total annual cost and, therefore, provides insights into the affordability of the production of multiple products. The higher the production efficiency, the more profitable and competitive the solution. Despite the high resource efficiency and the low OPEX of Scenario 1, its low revenue relegates it to the least profitable. This is because water is the only product of the system. The high resource efficiency of Scenario 1 means that most of the compounds are recovered but in the form of mixed salt, which means low product quality and, thus, low economic value. Scenario 4 presents the largest OPEX, and despite the high investments required, this scenario is potentially more profitable and has higher production efficiency thanks to the possibility of recovering and selling Mg and chemicals (NaOH, HCl). Scenario 3, while having a similar OPEX to Scenario 1, offers higher profitability due to revenue from selling salts and chemicals, offsetting production costs. Scenarios 2 and 3 have the most affordable water.

In resource recovery, Scenarios 2 and 3 excel in water and high-quality salt production. Scenario 3 yields a 9 % increase in water production compared to Scenario 1. Although Scenarios 2 and 3 have similar designs, they differ in water and salt recovery. Scenario 3 produces the most desalinated water (24 % more than Scenario 2), while Scenario 2 has the highest number of high-quality salts and chemicals. Scenario 4 prioritises chemical recovery, resulting in low water and salt recovery and overall resource efficiency compared to the other scenarios (only 24 % resource efficiency). To accurately reflect Scenario 4's performance in its target area (chemical recovery), the output-specific resource efficiency metric (see Supplementary Material, Section S1) is applied. This metric focuses on the recovery efficiency of the targeted chemicals such as NaOH, HCl, and $Mg(OH)_2$, rather than water or general salt recovery. Using this indicator, Scenario 4 achieves an output-specific resource efficiency of 92 %, reflecting its high performance in recovering valuable chemicals, despite its lower overall resource recovery rate (measured in terms of water and salts).

This distinction highlights that while Scenario 4 performs less effectively in general resource efficiency compared to Scenarios 1, 2 and 3, its focus on chemical recovery makes it a strong candidate for regions or industries where chemicals like NaOH and HCl are of primary importance. Thus, Scenario 4's lower overall resource efficiency is offset by its high efficiency in producing specific valuable products tailored to meet specific industrial demands.

Fig. 12 summarises the alignment of the four designed scenarios against stakeholder values, including water security, resource security,

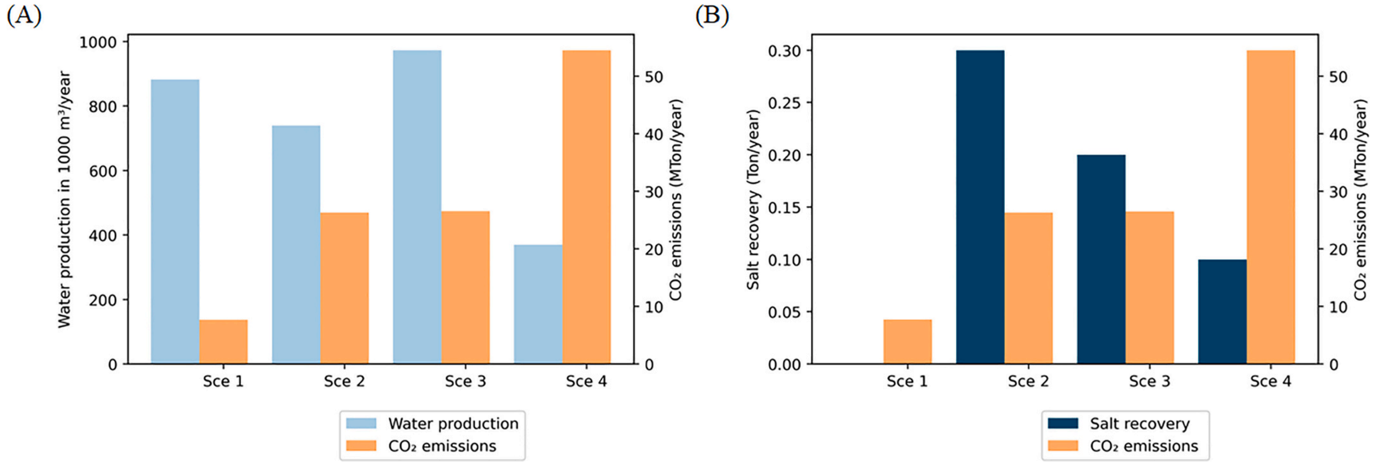


**Fig. 8.** Performance of integrated desalination and brine treatment systems in relation to $CO_2$ emissions from electricity consumption and (A) Water production, (B) Salt recovery.

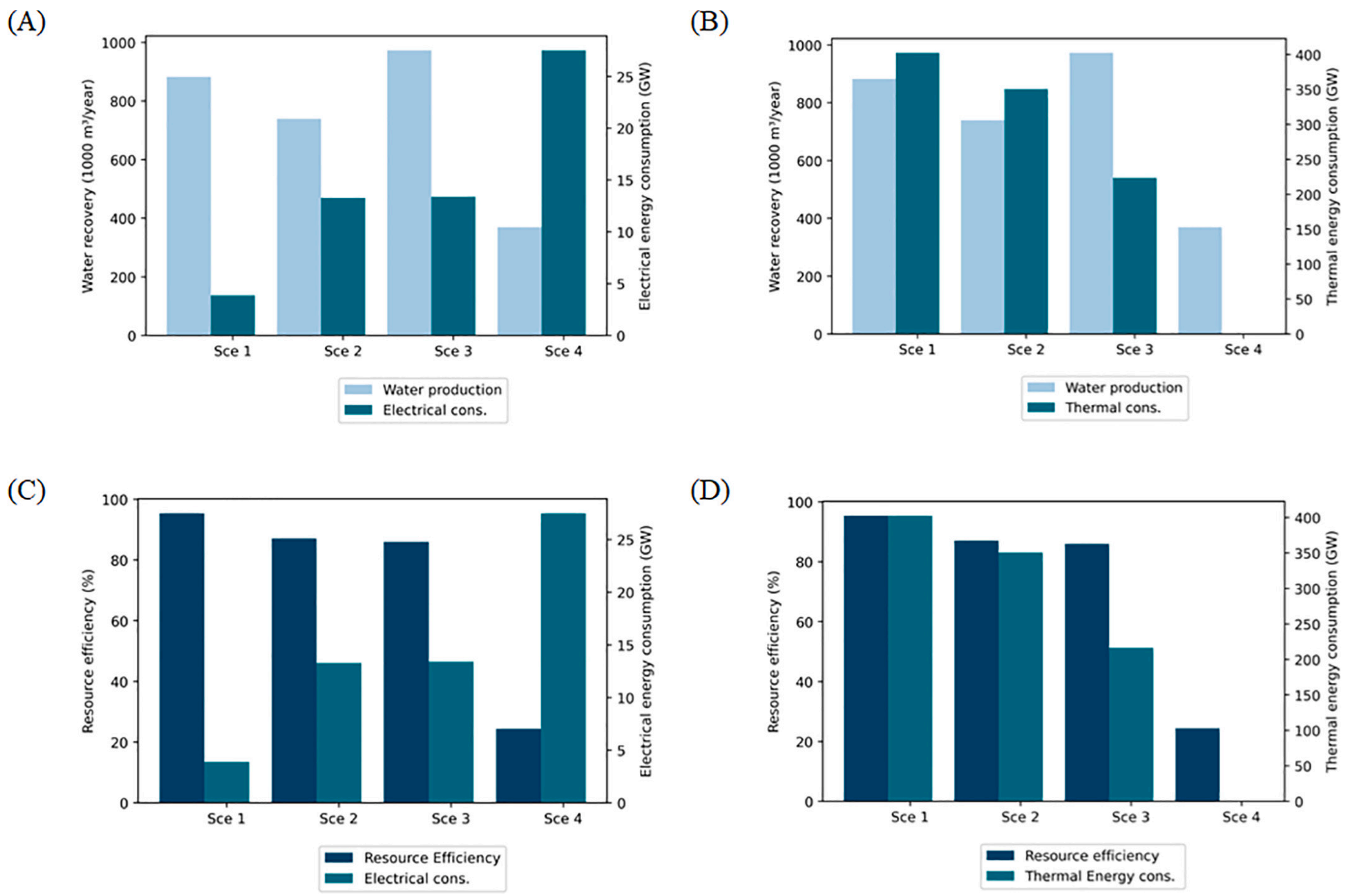


**Fig. 9.** Performance of integrated desalination and brine treatment systems in relation to electrical and thermal energy consumption and water production (A), B)), resource efficiency (C), D)).

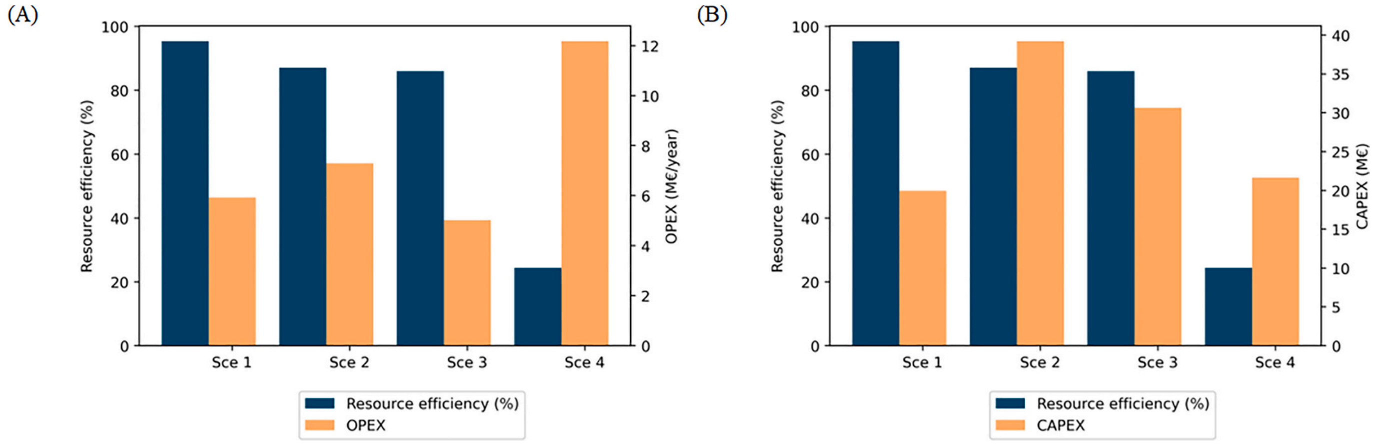


**Fig. 10.** Performance of integrated desalination and brine treatment systems in relation to resource efficiency (%) and (A) OPEX, (B) CAPEX.

efficiency, affordability, and environmental impact. By aligning each scenario with specific societal values our approach provides a more nuanced understanding of the scenarios' real-world implications. As shown in Fig. 12, Scenario 1 strongly aligns with values of water security, energy security, and efficiency due to its use of waste heat and lower electrical energy consumption. However, with water as the only valuable product and the generation of solid waste, its alignment with affordability is weaker, reflecting potential cost concerns.

Scenarios 2 and 3 excel in both water and high-quality salt production, demonstrating strong alignment with resource security and circular economy values. The increased energy requirements may pose challenges in terms of sustainability and energy security, potentially conflicting with stakeholder values associated with climate change mitigation and environmental protection. The potential economic viability and resource efficiency of these scenarios may support their alignment with affordability and efficiency, provided that energy challenges are adequately addressed.

While Scenario 4 aligns with resource security values, it also involves higher electricity consumption and increased $CO_2$ emissions, challenging climate change mitigation values. The lower production of

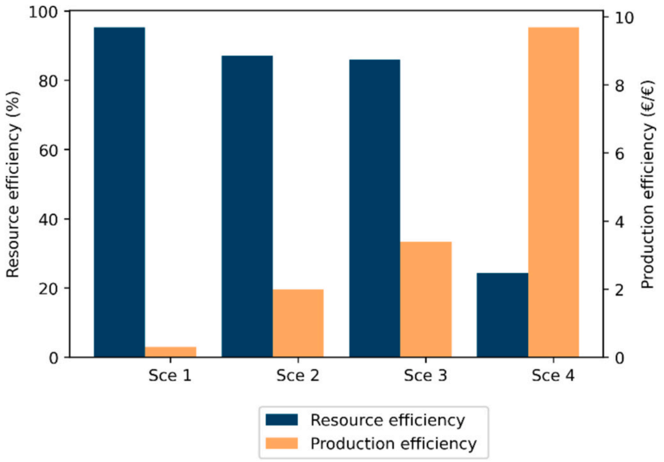


**Fig. 11.** Performance of integrated desalination and brine treatment systems in terms of resource efficiency and production efficiency.

water and salt results in a weaker alignment with water security. The economic viability and resource efficiency of Scenario 4's chemical production show a strong alignment with affordability value and a weak alignment with efficiency value.

### 3.4. Societal context and scenario suitability

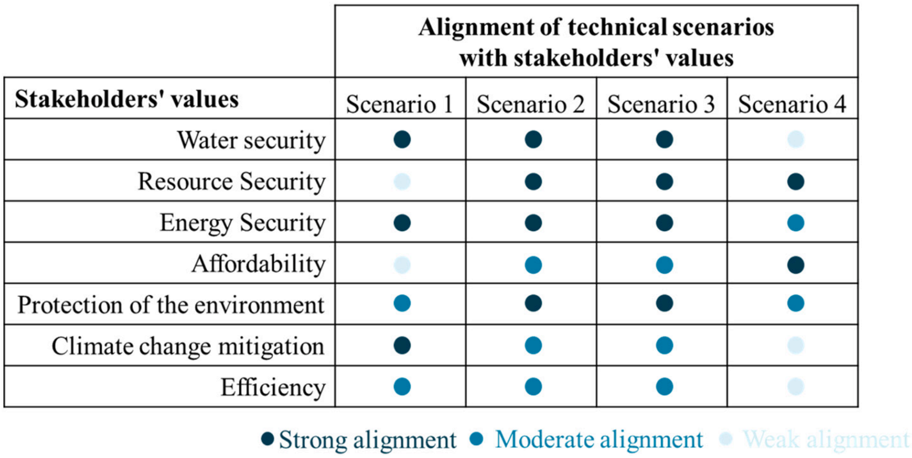
In addition to assessing each scenario's performance, it is crucial to evaluate its suitability within specific societal contexts. The benefits and drawbacks of each scenario may vary based on the unique characteristics and priorities of the society in which they are implemented. Based on these benefits and drawbacks, we discuss which scenario is suitable for a specific context.

For the sake of having low $CO_2$ and GHG emissions, it is desirable to implement electricity-based systems in areas where renewable energy sources are available or in areas where there are no restrictions for the deployment of renewable energy systems due to extensive land use. The use of waste heat results in lower (direct) GHG emissions. However, the risk of sustaining dependence on fossil fuels is higher with the utilization of waste heat to cover the thermal energy requirements of the systems. Ensuring flexibility in energy integration is crucial to avoid dependency on fossil fuels (long-term sustainability). To mitigate these risks, it is recommended to establish a flexible integration approach between thermal equipment and waste heat. This approach would involve obtaining thermal energy directly from renewable energy sources, such as solar hybrid systems or solar collectors, to supply the MED and thermal crystallizer units (Ahmed et al., 2022; He et al., 2023).

Based on the reported results and the above analysis, Scenario 1 is particularly suitable in regions where water scarcity is a critical issue and the primary goal is to maximize water production. Examples included small islands, the Mediterranean or the Aegean Sea, or arid coastal areas, where tourism is the main industry. For instance, in Lampedusa, a small island in the Mediterranean Sea, desalination often covers 100 % of the water demand due to limited freshwater sources Palmeros et al. (2023). Additionally, it is applicable in regions where the economic context is characterized by limited industrial activities or markets for by-products like salts/chemicals. In this context, water is the only valuable product due to the high demand. Those areas are often characterized by limited access to renewable energy sources due to land constraints; thus, the allocation of the energy sources is primarily for meeting the basic requirements of the local community, leaving limited capacity for producing additional products from recovered resources. Therefore, despite the higher profitability of Scenarios 2–4 from recovered resources, it can't compensate for the additional energy requirements in energy scarcity regions and the lack of local demand for the resources. Finally, utilizing waste heat from existing power plants helps lower the additional energy needs for extra water and the direct GHG emissions, making it environmentally viable in regions with limited land for renewable energy installations.

Scenario 4 focuses on chemical production using electricity-based technologies, making it suitable for coastal areas or larger islands with more electricity sources or no critical land limitations for applying solar or wind energy. However, the economic viability of Scenario 4 heavily relies on the presence of established markets or potential off-takers for the produced chemicals such as Mg, NaOH, and HCl. In regions where there is a strong market demand for these chemicals, this scenario not only offers a technically feasible solution but also supports local economies by integrating into existing supply chains. This consideration is crucial for the realistic implementation of resource recovery operations and underscores the importance of aligning technical solutions with market demands and societal needs.

In the case of regions with high industrial activities where there is a demand for high-quality salts and chemicals, Scenarios 2 and 3 are the most suitable since water and seven additional high-quality products are recovered from seawater desalination. The additional products would enhance/promote the circular economy and industrial symbiosis,



| | Alignment of technical scenarios with stakeholders' values | | | |
|---|---|---|---|---|
| **Stakeholders' values** | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
| Water security | ● | ● | ● | ○ |
| Resource Security | ○ | ● | ● | ● |
| Energy Security | ● | ● | ● | ◐ |
| Affordability | ○ | ◐ | ◐ | ● |
| Protection of the environment | ◐ | ● | ● | ◐ |
| Climate change mitigation | ● | ◐ | ◐ | ○ |
| Efficiency | ◐ | ◐ | ◐ | ○ |

● Strong alignment ◐ Moderate alignment ○ Weak alignment

**Fig. 12.** Qualitative performance assessment of scenarios for sustainable seawater desalination. This figure presents an overview of the four designed scenarios (Sc1: Water recovery, Sc2: Desalination for resource recovery, Sc3: Integrated RO and brine treatment plant, and Sc4: Electricity-based desalination and chemical recovery) relative to identified stakeholder values. A dark teal dot denotes strong alignment, a light teal dot denotes moderate alignment, and a turquoise dot denotes weak alignment.

bringing additional benefits to the local economy and community. The presence of industries that can utilize the recovered salts and chemicals helps justify the higher CAPEX and OPEX. The local production and consumption of those products could also prevent risks of future short supply chains. In the case of an existing RO plant, the investment cost is lower, and the implementation of the brine treatment chain would eliminate stakeholder's concerns about brine discharge and its potential environmental impact on marine life.

### 3.5. Discussion, limitations and future work

This study demonstrated the integration of stakeholders' values into the design and assessment of integrated seawater desalination and brine treatment systems, using a VSD approach. Unlike traditional evaluations in the desalination field that mainly prioritize economic gains or technical performance, this work integrates environmental, social, and ethical aspects that are often overlooked in the design assessment via VSD, providing a more holistic evaluation beyond evaluating indicators. The design of alternative technical scenarios can become very challenging and complicated, especially when technologies are integrated into a system. However, prioritizing the identified values, technical variables and constraints, and stakeholders' knowledge in the design of the scenarios promotes the development of solutions that are not only technically feasible but also socially acceptable and sustainable in the long run. This approach bridges the gap between technical feasibility and societal relevance by using stakeholders' values for scenario design and indicator selection and by validating the techno-economic models with stakeholders' knowledge, fostering more informed decision-making.

The methodology demonstrates the need to tailor desalination and brine treatment systems to the specific values, concerns, and expectations of different communities. It is informed by the example of Lampedusa and the values identified in previous work. The results reveal that in regions like Lampedusa, where water scarcity is acute and industrial activity is minimal, prioritizing water production directly addresses local needs, and resource recovery is not desirable. In more industrialized coastal areas, like larger islands or areas in the Mediterranean Sea, the focus on resource recovery and circular economy principles can support local industries and enhance economic resilience.

Analysing the tensions between scenarios through VSD fosters essential stakeholder dialogue, enabling the exploration of trade-offs and the identification of context-specific solutions. Discussing the performance results with relevant stakeholders allows the identification of general patterns and insights that can guide future designs based on regional differences, influenced by factors such as climate, economy, and cultural norms. For example, stakeholders in densely populated urban areas may prioritize efficient water production to meet high demand, while those in rural communities may prioritize environmental sustainability and local resource management. Scenarios tailored to address water scarcity in arid regions may prioritize water production and energy efficiency, while those in coastal areas may focus on environmental conservation and minimizing ecological impact.

The adaptability of these scenarios is a key finding, as it provides decision-makers with a range of options depending on their priorities, regional needs and constraints. The findings suggest that future desalination projects should prioritize early and continuous stakeholder engagement to ensure that technological solutions are not only technically and economically viable but also align with the societal values of the communities they serve. Policymakers should consider these insights when drafting regulations that support sustainable and socially responsible resource recovery.

Beyond the context of this study, our methodology holds valuable insights for technological developments in the field of integrated seawater desalination and brine treatment systems. By emphasizing the trade-offs and potential benefits of different scenarios, our approach provides a roadmap for researchers and engineers to refine and innovate technologies that address critical societal and environmental challenges.

#### 3.5.1. Limitations

While this study successfully integrates technical and social dimensions through the VSD approach, several limitations should be noted:

- Stakeholder Engagement: The stakeholder values used were derived from prior research rather than direct engagement through interviews or surveys. While these values are reliable within the context of previous research, the incorporation of broader engagement to capture diverse perspectives and validate the values in specific contexts would enhance the robustness of the analysis.
- Validation of Technical Scenario Design: The technical scenarios were designed based on stakeholder values, but further rounds of empirical validation with stakeholders are needed to assess the practical implications and feasibility of the proposed designs. Additional workshops and feedback sessions would help refine these scenarios.
- Energy Use Assumptions: The reliance on grid electricity with EU average emissions factors is a simplification. This approach does not account for the variability in energy mixes or the potential use of renewable energy sources, which could significantly alter the emissions outcomes. Therefore, the results should be interpreted with the understanding that alternative energy sources could yield different environmental impacts.

#### 3.5.2. Future work

Future work should apply this methodology to specific locations, incorporating broader stakeholder engagement through interviews or surveys to identify and validate values in a particular context. Empirical validation with stakeholders will provide valuable insight into scenario performance and real-world feasibility. Additionally, comparing scenarios with linear production systems that produce the same products using LCA methodology will assess the potential environmental benefits of resource recovery systems.

Exploring alternative energy sources will help evaluate the impact of the energy mix on identified tensions (water, resource security, and energy security) and provide insights into how renewable energy can mitigate $CO_2$ emissions. Expanding this framework to diverse geographic regions and cultural settings will ensure its relevance across societal contexts.

Finally, integrating system dynamics with the VSD approach could offer a more comprehensive understanding of the problem statement for resource recovery systems. While VSD effectively aligns technical configurations with societal values and stakeholder needs, system dynamics can increase understanding of the scope and complexity of the problem and trust in model results (Mirchi et al., 2012). This combination would support more informed and collaborative decision-making.

## 4. Conclusions

In recent years, the integration of desalination with brine treatment technologies has been increasingly studied, aiming to develop sustainable solutions for resource recovery from seawater. This study used four technical configurations to evaluate a Value-Sensitive Design (VSD) framework, demonstrating the importance of tailoring systems to specific societal and regional needs. Each scenario offers unique benefits and trade-offs, highlighting the need to balance water and resource recovery with energy consumption and environmental impacts.

Using the identified values from the example of Lampedusa island, the proposed technical scenarios reveal emerging trade-offs around seawater desalination and brine treatment, highlighting the importance of considering multiple perspectives in their design. Scenarios that prioritize water and salt recovery align with water and resource security values but require higher energy input, raising concerns about their economic and environmental sustainability. In contrast, scenarios utilizing existing waste heat or focusing on chemical production offer greater energy efficiency but may limit broader resource recovery or lead to higher $CO_2$ emissions. These findings underscore the importance of tailoring solutions to regional conditions and energy availability, ensuring that technological advancements are sustainable and contextually appropriate.

This study serves as an example for supporting decision-making and guiding the development of sustainable solutions for resource recovery from seawater. By using the VSD methodology, we gain insights that go beyond traditional techno-economic evaluations by incorporating societal values, ethical considerations, and stakeholder perspectives. This holistic approach is designed to support the development of solutions that are technically and economically viable, as well as socially acceptable, proactively addressing potential societal resistance and ethical dilemmas. As we move forward, embracing methodologies that incorporate societal aspects beyond social indicators will be crucial in ensuring that technological advancements contribute effectively to sustainable and equitable resource management.

## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT to improve the clarity and readability of this text. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

## CRediT authorship contribution statement

**Rodoula Ktori:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Mar Palmeros Parada:** Writing – review & editing, Methodology, Formal analysis. **Marcos Rodriguez-Pascual:** Writing – review & editing. **Mark C.M. van Loosdrecht:** Writing – review & editing, Supervision, Conceptualization. **Dimitrios Xevgenos:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.11.006.

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