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LCA methodological choices and environmental impacts performance of an integrated seawater desalination and brine treatment system

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ABSTRACT

As water research and industry shift towards resource recovery plants, comprehensive assessment methods are needed to capture environmental trade-offs. Existing life cycle assessments (LCA) on desalination often neglect key methodological challenges in multi-product zero-liquid-discharge (ZLD) systems, risking misleading conclusions. This study applies LCA to conventional desalination and with three resource recovery scenarios (integrated desalination and brine treatment) in Cyprus: Sc1) maximum water recovery using waste heat (WH), Sc2) integrated desalination plant with brine treatment using WH, Sc3) electricity-based desalination with chemicals recovery, to assess how key methodological decisions influence the results and decisions. Five impact categories were analysed: climate change, human toxicity, marine ecotoxicity, water depletion, and fossil depletion. Without product substitution, multi-product ZLD systems show higher absolute impacts than SWRO due to increased energy and chemical demands. However, when credits for recovered salts and chemicals are considered, Scenarios 2 and 3 achieve large net reductions compared to conventional production, highlighting the sustainability potential of resource recovery. Results proved highly sensitive to methodological choices: functional unit selection (increase up to 59 %), allocation methods (variation from 54 % to 90 %), while excluding WH altered impacts by up to 89 %, emphasizing the need for transparent reporting to support robust decision-making in desalination design. Sensitivity analysis showed that integrating renewable energy could cut climate change and fossil depletion impacts by up to 99 %, though with trade-offs in marine ecotoxicity and water depletion. Rather than proposing new methods, this work provides critical guidance on applying standardized LCA options to complex systems, offering directly relevant insights for practitioners and policy-makers in sustainable desalination design.

Acronyms

CSP	Concentrate Solar Power
ED	Electrodialysis
EDBM	Electrodialysis With Bipolar Membranes
EFC	Eutectic Freeze Crystallization
ESM	Early-stage methodologies
ESS	Energy Self-Sufficiency
FU	Functional Unit
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
MED	Multi-Effect Distillation
MF-PFR	Multiple Feed Plug Flow Reactor
NF	Nanofiltration
PV	Photovoltaic
RES	Renewable Energy Sources
RO	Reverse Osmosis
SWRO	Seawater Reverse Osmosis
TCr	Thermal Crystallizer
WH	Waste heat
ZLD	Zero Liquid Discharge

1. Introduction

Desalination is a crucial water treatment technology that addresses water scarcity in regions facing significant challenges due to its

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substantial energy needs and the disposal of brine, a saline waste stream. Zero liquid discharge (ZLD) and resource recovery practices from seawater brine are considered an opportunity for decreasing the environmental impact of desalination (Ihsanullah et al., 2022). Beyond water recovery, extracting valuable products from seawater can substitute traditional materials mining, reducing the environmental impact compared to conventional salt, metal and chemical production. Optimal recovery strategies for high-quality and multiple products are documented in the literature (Morgante et al., 2022a; Ihsanullah et al., 2022; Morgante et al., 2024). While ZLD offers the potential for near-complete brine minimization, recent system-level analyses show that this comes with very high energy penalties. For instance, O'Connell et al. (2024) evaluated 75 ZLD configurations and found that achieving >90 % water recovery typically requires energy-intensive crystallization steps, with corresponding increases in greenhouse gas emissions and costs. However, a comprehensive environmental assessment of multi-product ZLD systems, specifically tailored to address the complexities of resource recovery in desalination, remains underdeveloped (Ktori et al., 2024a).

Life Cycle Assessment (LCA) is a powerful tool for evaluating environmental impacts at different stages of technology development, from planning and conceptual design to operational phases (Corominas et al., 2020). Applying LCA early in technology development helps optimize processes, enhance understanding of design implications, and enable cost-effective redesign of products and processes (van der Hulst et al., 2020; Harris et al., 2021). However, accurately quantifying impacts in emerging technologies like ZLD is challenging due to limited data on material and energy flows (Harris et al., 2021; Elginoz et al., 2022b). Although assessing the environmental impacts of these emerging technologies at various stages of development poses uncertainties, it is essential for guiding investment, research, and development (van der Hulst et al., 2020; Elginoz et al., 2022a).

The novelty of this study lies not in proposing new LCA methodologies, but in critically demonstrating and guiding how existing ISO 14040 methodologies, compliant methodological choices shape outcomes when applied to emerging, complex systems such as integrated, multi-product ZLD systems, focusing on resource recovery. Specifically, this research examines how different methodological choices, such as the selection of functional unit, allocation methods, and the inclusion of energy source, affect environmental assessments and conclusions. By applying LCA systematically to integrated ZLD systems, this study provides practical guidance on the implications of methodological decisions for resource recovery strategies in desalination, highlighting environmental trade-offs and potential benefits. Based on the above, the following research questions are formulated:

- How do key methodological decisions such as functional unit, allocation and energy source influence the results and decisions within the context of an integrated desalination and brine treatment systems?
- What are the environmental benefits and disadvantages of integrated desalination and brine treatment systems compared with both conventional seawater desalination and salt production systems?

To address these questions, LCA analyses are conducted on a conventional RO desalination plant and three resource recovery-oriented ZLD systems at a demonstration scale in Cyprus.

2. Literature background

While LCA has been applied extensively to desalination technologies since the 1990s, primarily to examine and compare various desalination technologies (Raluy et al., 2006; Zhou et al., 2013; Shahabi et al., 2015; Aziz and Hanafiah, 2021), most studies focus on single-output systems or renewable energy integration (Raluy et al., 2005; Shahabi et al., 2014; Alhaj et al., 2022), with limited attention to multi-product resource recovery. Recent studies have addressed some aspects of brine management and resource recovery (Harris et al., 2021; Elginoz et al., 2022a; Tsalidis et al., 2022). However, LCA studies of emerging brine management technologies are limited (Elginoz et al., 2022a). For example, Salih et al. (2017) compared a ZLD system with brine disposal to deep wells, with and without by-product recovery. O'Connell et al. (2024) assessed ZLD configurations, demonstrating that energy source choice (e.g., renewable vs. grid mix) is critical for GHG emissions and overall sustainability. Grauberger et al. (2025) combined TEA–LCA to assess electrodialytic crystallization against other ZLD options while Senevirathna et al. (2025) applied LCA to evaluate specific brine valorization pathways, such as the recovery of MgO from desalination reject brine. These studies highlight the environmental benefits of transforming brine into valuable materials but generally focus on single-product recovery chains or energy efficiency improvements rather than integrated multi-output systems. Yet the integration of desalination and brine treatment remains an emerging area that combines established desalination technologies with newer resource recovery advancements (Cipolletta et al., 2021; Shah et al., 2022).

How effective are current assessment methods for evaluating the integration of technologies and systems in the early stages of development (Fernandez-Dacosta et al., 2019)? Historically, these studies have utilized an attributional modeling approach. However, modifications are needed for resource recovery systems in the field of desalination. Some initial steps have been taken by Zhou et al. (2011), who examined whether and to what extent the environmental impacts of Reverse Osmosis (RO) vary due to different Life Cycle Impact Assessment methods. Tsalidis et al. (2022) studied the effect of allocation type (mass and economic allocation) on the environmental impacts of brine treatment systems.

Existing LCAs on desalination largely overlook key methodological challenges specific to multi-product ZLD, such as an adequate selection of functionality and related functional units, managing multifunctionality, as well as other aspects like systems comparability, data availability, and uncertainty (Broeren et al., 2017; Elginoz et al., 2022b). Even recent works such as Grauberger et al. (2025), Senevirathna et al. (2025), and O'Connell et al. (2024) while advancing ZLD evaluation, do not explicitly resolve multifunctionality when multiple products (water, salts, chemicals) are co-produced. This may result in misleading impact assessments and conclusions. The implications of data availability are beyond the scope of this work, as it focuses on comparative environmental performance using consistent data sources and assumptions across all scenarios. This gap limits the ability of current LCA approaches to guide investment and development in integrated desalination and resource recovery systems.

3. Methods

This paper applies the LCA method, standardized through the ISO14040, and makes use of the software SimaPro and the Ecoinvent v.3.8 database to conduct the LCA. The methodological framework applied in this work is illustrated in Fig. 1. The main characteristics of the case study and the technical scenarios are described in Section 3.1. After the case studies description, this section presents the "Goal and Scope", Life Cycle Inventory", "Life Cycle Impact Assessment", and "Interpretation" steps (see Section 3.2).

3.1. Case study description

Cyprus is considered a relevant geographical case study as it heavily relies on seawater desalination for the majority of its drinking water supply. In 2018, 72.9 % of drinking water in Cyprus was desalinated water (Xevgenos et al., 2021). Currently, five large-scale (capacity >15,000 m^3/d) desalination plants are supplying drinking water to municipalities in Cyprus, while approximately 24 small-scale (output water <2500 m^3/d) desalination units are used by other sectors, such as power stations, industry and military purposes. The total installed

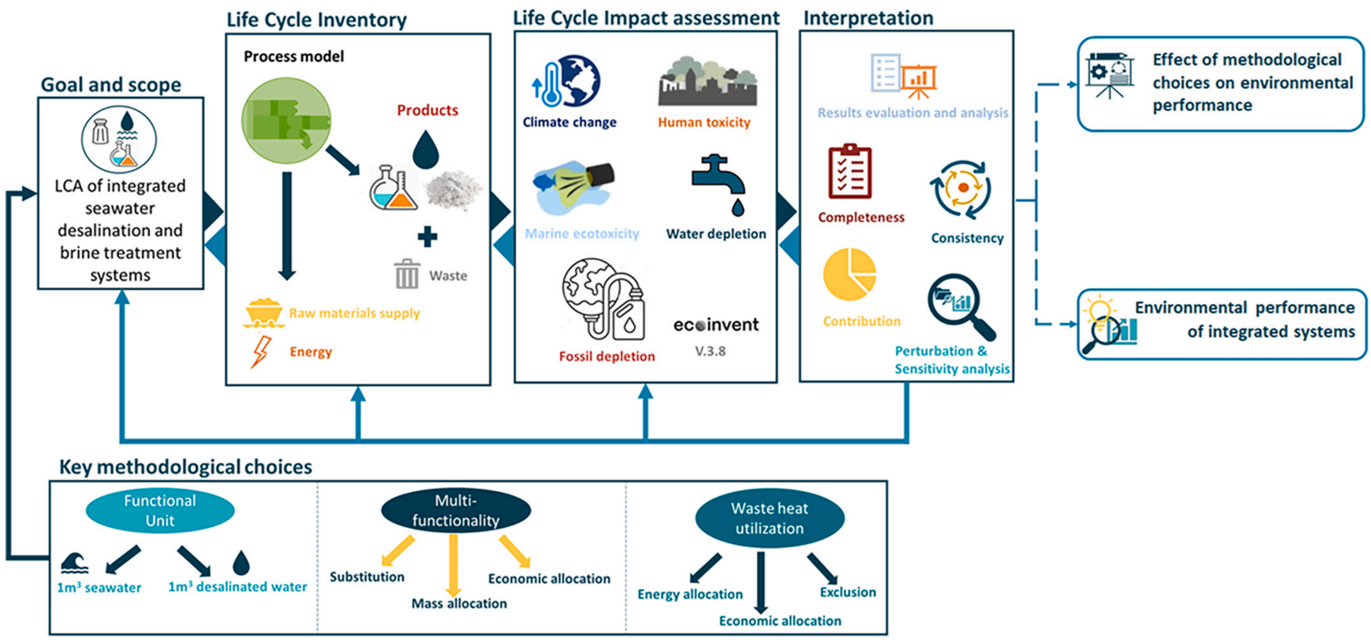


Fig. 1. Life Cycle Assessment (LCA) for integrated seawater desalination and brine treatment systems: an overview of methodological approach, related steps and key choices. Key methodological choices related to the functional unit, multifunctionality and the inclusion of waste heat utilization in the background system made in the goal and scope. Light blue line arrows denote feedback loops in the methodological steps and revisions in the methodological choices.

capacity of the large-scale desalination plants in Cyprus is 235,000 m^3/d, which results in approx. 103 million m^3/year of brine effluent as well (Xevgenos et al., 2021). The current brine management option is limited to disposing of the brine back into the marine environment.

In this work, innovative designs for integrated desalination with brine management and resource recovery are evaluated and compared with benchmark systems, including Seawater Reverse Osmosis (SWRO) for water production and conventional salt and chemical production. The methodological approach described in Fig. 1 has been applied for integrated desalination and brine treatment plants aiming to recover valuable materials such as water, salts, and chemicals. This is illustrated in Fig. 2, which refers to the case study description and system boundaries. A detailed illustration of the process diagram of the three scenarios and the system boundaries of integrated desalination and brine treatment systems is available in Appendix (see Section S1, Fig. S.1). Specifically, brine disposal is replaced with brine treatment techniques consisting of at least one technology in brine minimization and several technologies in brine treatment for resource recovery, such as NaCl, $Mg(OH)_2$, and chemicals (HCl, NaOH). Regarding energy sources, desalination plants can be integrated with power plants that depend on external fossil resources for power production. Part of the systems integration, in this paper, is the recovery of the available waste heat and utilizing it in the desalination plant.

In this study, technical scenarios are employed to evaluate the results and gain insight into the different levels of complexity for the studied plants. While all scenarios share the common goal of enhancing water

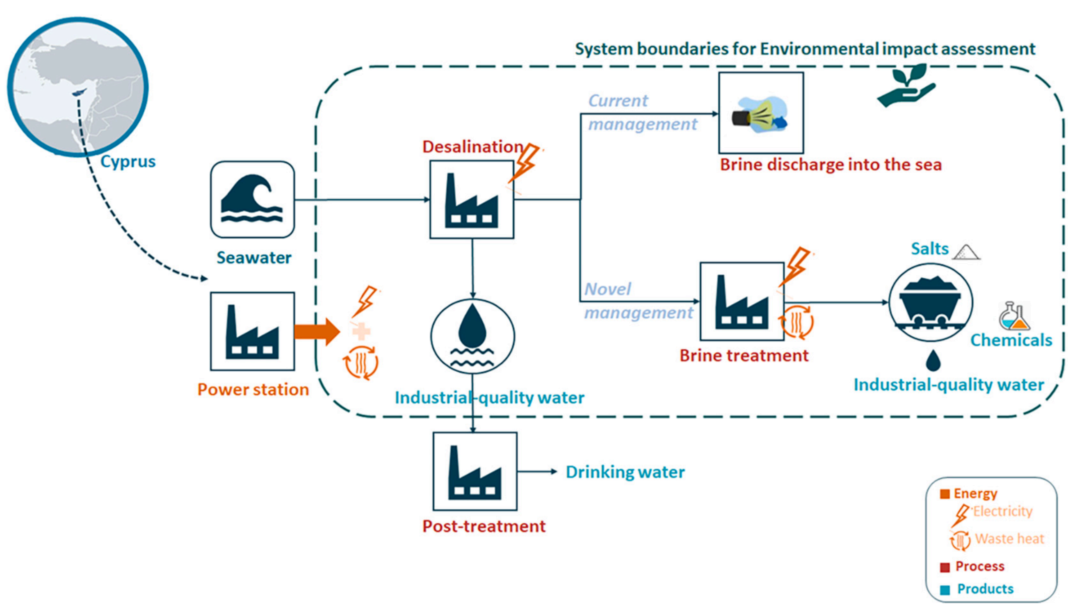


Fig. 2. Schematic description of the case study used in this work: integrated desalination and brine treatment plants aiming to recover resources in Cyprus. The green dashed line shows the System boundaries: Cradle-to-gate. Red colour denotes processes, orange colour denotes energy, and turquoise colour denotes output products.

recovery and minimizing brine discharges compared to conventional seawater desalination (see Fig. 2), they differ from each other on their specific objectives, namely: maximize water recovery (Scenario 1) utilizing waste heat for thermal requirements, integrate existing RO plant with brine management technologies utilizing waste heat for thermal requirements (Scenario 2) and integrate RO plant with electricity-based technologies for chemical recovery (Scenario 3). Table 1 provides an overview of the three technical scenarios (based on the four cases reported by (Ktori et al., 2024a), outlining their objectives, technologies involved, and products recovered. The technical scenarios are designed to recover industrial-quality water, salts (NaCl, $Mg(OH)_2$, Na_2SO_4), and chemicals (HCl, NaOH) from seawater. The feed flow rate remains consistent across all scenarios, set at 60,000 m^3/d (capacity of large desalination plants in Cyprus). The process flow diagrams of the technical scenarios are given in Appendix (see Section S1, Fig. S.1). For an in-depth explanation of the technical scenario design, including simulation details (like mass and energy balances, refer to (Ktori et al., 2024a; Ktori et al., 2024b). Each technical scenario outlined in Table 1 is systematically compared with the conventional methods of producing the same products. These conventional methods typically involve mining or industrial chemical processes for salts and chemicals, and SWRO for water. For detailed descriptions of these conventional processes, please refer to Section S4 of Appendix.

Note that the three technical scenarios produce industrial-quality water, which requires post-treatment for drinking water purposes (see Fig. 2). Additionally, the recovered water is recycled internally in the other processes. However, recycling may not be feasible if the required amount of water exceeds the production capacity, as in Scenario 3 (detailed mass flows for each scenario can be found in the Inventory tables in Appendix, Section S3).

3.2. Life cycle assessment (LCA)

3.2.1. Goal and scope definition

This LCA study aims to evaluate the environmental performance of three different designs. The focus is on desalination and brine treatment systems with the goal of resource recovery. Table 2 summarizes the main LCA components and choices for the goal and scope definition. As explained in the case study description (see Section 3.1), all technical scenarios aim to treat seawater to primarily produce water and treat brine at different stages, producing additional water with salts and chemicals.

To ensure a consistent and comparable FU base across the three scenarios, the functional unit (FU) chosen in this work is '*1m³ of seawater input at the plant*'. This choice diverges from the conventional practices, where either '*1m³ of desalinated water*' is considered as the FU in the

Table 1
Overview of technical scenarios.

Scenario	Objective	Technologies	Products
1	Maximize water recovery and minimize brine discharge	NF, MED, TCryst	Water, Mixed salts
2	Integrated RO plant with brine treatment for recovery of water and valuable products and minimizing brine discharge	RO, NF, MED, TCryst, MFPPR, EFC, EDBM	$Ca(OH)_2$, HCl, Ice, $Mg(OH)_2$, NaCl, NaOH, Na_2SO_4, Water
3	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.

Table 2
Overview of the main LCA components and choices for the evaluation.

LCA aspect	Case study
Goal and Scope	Evaluate the environmental performance of integrated desalination and brine treatment systems in Cyprus, considering the conditions in 2021–2022. Three different technical configurations (scenarios) with different objectives (see Table 1) are evaluated.
Functional unit*	1m³ of seawater feed
Allocation	Economic allocation at two points: i) for products' distribution, and *ii*) for energy sources when using waste heat.
System boundaries	Cradle-to-gate, for upstream processes, desalination and brine treatment
Data quality	Process Simulation data validated by primary data from pilot scale testing. Data quality is further validated with sensitivity analysis of key LCI parameters and pedigree matrix.
Impact categories	ReCiPe midpoint (H) method V1.13 / Europe Recipe H

* The alternative FU of '*1m³ of desalinated water*' is also considered for comparative purposes, and its related results are presented in the Appendix.

evaluation of desalination plants (Zhou et al., 2014; Aziz and Hanafiah, 2021; Alrashidi et al., 2024), or '*1m³ of brine input at the plant*' is considered as the FU in the assessment of brine treatment systems (Tsalidis et al., 2022). In the case of integrated desalination and brine treatment systems, which are multiproduct systems with different secondary objectives (see Table 1), water production depends on the specific secondary objective of each scenario. This means that in some scenarios, water may not be the primary product as other objectives take precedence. Hence, the comparison between the scenarios is not focused on the final products basket but on the rate of the environmental performance of integrated systems and their potential environmental benefits.

Furthermore, it is worth noting that, in addition to considering '*1m³ of seawater input at the plant*' as the primary FU, we also assess the system using '*1m³ of desalinated water*' as an alternative FU, with the results provided in Appendix (see Sections S5.1 and S5.2). This alternative FU highlights the importance of methodological decisions, which will be thoroughly analysed in Section 3.2.5 and Section 4.3 to assess its implications and potential effects on the comparison between scenarios.

The system boundaries—Cradle-to-gate—considered comprise only the production phase of the upstream processes for utilities (e.g., electricity and waste heat generation), chemicals production and the core processes of the designed scenarios for desalination and brine treatment systems (see Table 1). Although waste heat (WH) is often excluded in previous LCAs (Harris et al., 2021; Tsalidis et al., 2023), this study accounts for its environmental impacts. Waste heat is produced as a byproduct of various industrial processes, such as electricity production from natural gas compressor stations. Almost 50 % of the global energy consumed is wasted in the form of WH (Mahmoudi et al., 2018). However, this waste heat can be used for other purposes, such as desalination, as it operates at a lower temperature range below the boiling point of water. This makes the WH a valuable resource for driving thermal processes (Olabi et al., 2020).

Since waste heat is a co-product of electricity generation, an allocation approach was required to distribute environmental burdens between the two energy streams. For the baseline analysis, economic allocation was selected because it reflects the relative market value of electricity and waste heat, thereby aligning environmental burdens with economic drivers of their production. Alternative approaches, such as energy allocation or non-allocation (zero burden), were also assessed in the sensitivity analysis (see Sections 3.2.3 and 3.2.5).

Since the proposed integrated systems are multifunctional (i.e., several products are simultaneously generated, see Fig. S.1 in Appendix), and considering that the materials here co-produced are minerals (which otherwise would be obtained through multifunctional traditional linear large-scale extraction processes), the allocation method is applied here to address such multifunctionality. In particular, mass and economic allocation are both applied not only to distribute the overall environmental burdens of the integrated systems accordingly but also to analyse the effects of such methodological choice.

For the baseline results in Section 4.1, economic allocation is used. This choice is made because economic allocation is widely applied in the literature when comparing multifunctional systems, as it reflects the relative value of the products and aligns with how markets drive production decisions (Tsalidis et al., 2022). Substitution (system expansion) is also applied for comparative purposes, but it is not used as the baseline. Table 3 shows the market prices and the resulting mass and economic allocation factors for all products from Scenarios 2 and 3 (see Appendix, Section S2.1 for Scenario 1). Both sets of factors are calculated using the output flow rates reported in Table 4 as part of the life cycle inventory (LCI) in Section 3.2.2.

Finally, the results are presented in two steps to clearly separate different effects. In Section 4.1.1, the integrated ZLD systems are compared with each other and with a conventional SWRO desalination plant, representing the current practice in Cyprus. This first step isolates the additional operational burdens of the integrated systems relative to the baseline. In subsequent sections, the analysis is extended to include conventional production of salts and chemicals, and multifunctionality handling approaches (e.g., substitution and allocation).

3.2.2. Life cycle inventory

Technical process models, developed using the open-source software explained by (Ktori et al., 2024b), were employed to generate the inventory for data on mass and energy flows. The software, available at the GitHub repository (https://github.com/rodoulak/desalsim), facilitated the creation and implementation of these models. Table 4 presents the inventory data for scenarios 1–3. For data collection for background systems such as electricity supply, waste heat generation, and chemical production, the database Ecoinvent database v.3.8 (system process) is used. Additionally, the inventory for the process of producing *'high voltage electricity production by oil in Cyprus'* has been revised to include the co-production of waste heat from the system. The assumptions section (see Section 3.2.3) provides a detailed explanation of this addition and its allocation factor. Tables S.7, S.9, and S.11 in Appendix (see Section S3) present the inventory data per '*1m³ of seawater feed*' for scenarios 1–3, including the background processes and the intermediate streams. Inventory data per '*1m³ of desalinated water*' for scenarios 1–3 can be found in Appendix (see Section S3).

Table 3
Products market prices and mass and economic allocation factors for Scenarios 2 and 3.

Compound	Price (€/Ton)	Mass allocation factors [%]	Economic allocation factors [%]		
		Scenario 2	Scenario 3	Scenario 2	Scenario 3
Water	1	95.1	N/A	2.7	N/A
NaCl	66 (Morgante et al., 2022a)	3.3	N/A	6.1	N/A
$Mg(OH)_2$	1000 (Morgante et al., 2022a)	0.4	11.1	10.2	2.0
$Ca(OH)_2$	125(Morgante et al., 2022a)	0.1	2.6	0.3	0.1
Na_2SO_4	116 (Merck, 2024)	0.4	N/A	2.3	N/A
HCl	5780 (Merck, 2024)	0.7	49.6	78.4	51.0
NaOH	7200 (Merck, 2024)	0.0	36.7	0.0	46.9

Table 4
Inventory data per '*1m³ of seawater feed*' for scenarios 1–3.

Compound	Units	Scenario 1	Scenario 2	Scenario 3
Inputs				
Electricity	kWh/FU	4.302	7.853	10.433
Wasted heat	kWh/ FU	447.362	248.624	N/A
NaOH	kg/ FU	N/A	0.403	N/A
Water*	kg/ FU	N/A	N/A	352.189
Antiscalant	l/ FU	0.002	0.060	0.060
Outputs				
Water*	m^3/ FU	0.980	0.616	N/A
NaCl	kg/ FU	29.857	25.813	NA
$Mg(OH)_2$	kg/ FU	NA	2.838	2.838
$Ca(OH)_2$	kg/ FU	NA	0.661	0.661
Na_2SO_4	kg/ FU	NA	5.534	NA
HCl	kg/ FU	NA	3.782	12.715
NaOH	kg/ FU	NA	N/A	9.397

* Industrial-quality water. FU: '*1m³ of seawater feed*'.

Note that the three scenarios produce water of industrial-grade quality, which necessitates post-treatment in order to meet the standards required for drinking water. The water recovered from these processes is subsequently reused internally (see Fig. S.1 in Appendix). However, in the instance where the amount of water required exceeds the production capacity, such as in Scenario 3, recycling may not be a viable option.

To address data uncertainty, a pedigree matrix approach was applied following Weidema and Wesnaes (1996), with full details provided in Appendix (Section S7). The assessment highlights higher uncertainty for emerging technologies such as EDBM, MF-PFR, TCryst, and EFC, where pilot-scale data and expert input were used. Based on this evaluation, sensitivity analyses were conducted on three key LCI parameters: (i) ±20 % energy consumption of EDBM, (ii) ±20 % chemical consumption of MF-PFR, and (iii) ±20 % energy consumption of filtration units, where differences between pilot- and industrial-scale operation are expected. This combined approach ensures transparency in data quality and allows testing the robustness of conclusions against the most influential sources of uncertainty.

3.2.3. Assumptions

The following assumptions have been considered:

- Environmental impacts related to energy losses and the use of cooling water are not considered. This decision is based on both the minimal energy losses observed and the challenges posed by limited data availability and reliability in quantifying these impacts. Consequently, the analysis only includes the energy required for pumping these streams within the electricity requirements for the associated processes (Ktori et al., 2024a).
- Waste heat is integrated into the system by adjusting the Ecoinvent database. Economic allocation is employed to distribute the environmental impact between electricity and waste heat in energy production from oil in Cyprus, ensuring a comprehensive assessment of the system. Although the primary objective of the power plant is electricity production, it is important to note that waste heat utilization doesn't come with zero environmental impact. The allocation factors for electricity and waste heat are provided in Table 5. In order to calculate the economic allocation factor of waste heat, firstly, the economic value of the waste heat was calculated using the Eq. 1 from (Micari et al., 2019):

$$\text{Waste heat cost } (US\$/MWh_{th}) = 10.7 \ln P_{steam} + 24.2 \quad (1)$$

Table 5
Emission factor for waste heat based on economic allocation.

Type of energy	Economic value (per 1KWh)	Reference	Economic allocation	Emission factor ($kgCO_2eq$/kWh)	Reference
Electricity	0.192	(Eurostat, 2023)	85.11 %	0.664	(Xevgenos et al., 2021)
Waste heat	0.034	(own calculation, Appendix, Section S2.2)	14.89 %	0.116	(own calculation, Appendix, Section S2.2)

Then, the ratio between the economic value of electricity and waste heat in work by Micari et al. (2019) was determined for the year 2019. This value was then used as a fixed parameter to calculate the economic value of waste heat based on the economic value of electricity in 2023, according to Eurostat (2023). Once the economic value of both energy sources was determined for 2023, an economic allocation between the two energy sources was calculated. For detailed calculations, please refer to Appendix in Section S2.2.

- To integrate the waste heat into the inventory, the electricity dataset represents the production of high-voltage electricity at a grid-connected oil power plant. Emissions are generally calculated/estimated based on European quality fuel oil type S. This implies that the electricity is not sourced from the grid. Therefore, for the baseline analysis, 0 % renewable energy sources (RES) are assumed due to simulation constraints. This percentage will change only in the Sensitivity analysis (for more details, see Sections 3.2.5.4 and 4.4).
- Ice produced in Scenario 2 is considered water, and no post-treatment is taken into account.
- Treated brine outflow streams (e.g., RO-outflow, NF-retentate) are considered waste streams and therefore, their economic value is set as zero.
- The remaining saline solutions, such as discharge saline stream from EDBM in Scenarios 2 and 3 (see Fig. S.1 in Appendix), have lower salinity (as NaCl) -22 g/l and 20 g/l, respectively- than seawater (40 g/l). This means that they can be recirculated back into the systems.
- The environmental impacts due to infrastructure construction, maintenance and demolition are considered negligible (system boundaries).

3.2.4. Life cycle impact assessment

The ReCiPe method is utilized for the environmental life cycle impact assessment. While all midpoint indicators were calculated, five were selected for detailed discussion, as they represent the most relevant environmental pressures for integrated desalination and brine treatment systems in Cyprus (see Fig. 1). These categories were chosen because they directly reflect the energy intensity, chemical consumption, and resource dependencies characteristic of desalination and brine treatment systems:

- Climate change (kg CO_2 eq): Assess the carbon footprint of desalination and brine treatment processes, addressing their energy and materials intensity.
- Human toxicity (kg 1,4-dB eq): Assess the potential effects of chemicals consumption from the integrated systems,
- Marine ecotoxicity (kg 1,4-dB eq): Assess the potential toxicity in the marine environment,
- Water depletion (m^3): Assess the depletion of water resources to understand the sustainability implications of these process systems, and
- Fossil depletion (kg oil eq): Assess the depletion of fossil resources associated with desalination and brine treatment processes, promoting energy security and the transition towards renewable alternatives.

These categories have also been used in previous LCA studies for desalination or brine treatment processes (Alhaj et al., 2022; Elginoz et al., 2022a; Tsalidis et al., 2022). Results for all other ReCiPe midpoint categories are reported in Section 4 and Appendix.

3.2.5. Interpretation

The interpretation phase includes various analyses to understand the influence of key methodological choices and assumptions on the results. These choices are treated as Methodological Options (A, B, C, etc.), with corresponding actions used to analyse their impact. Scenario analyses are employed to explore the effects of different system design choices, such as energy mix and technology integration (e.g., waste heat recovery), rather than addressing variability in data inputs (see Fig. 1). Table 6 provides an overview of the methodological choices and assumptions identified in this study, along with the corresponding actions taken to evaluate their effects.

3.2.5.1. Methodological option A: effect of functional units. To analyse the impact of the FU on the results in resource recovery systems, LCA is conducted for two functional units: *1m³ seawater fed* and *1m³ desalinated water output* (see Section 3.2.1). Inventory data per '*1m³ of desalinated water output*' for scenarios 1–3 can be found in Appendix (see Section S3, Tables S.8, S.10, S.12). This methodological option examines how the choice of the functional unit affects the results and conclusions.

3.2.5.2. Methodological option B: effect of the multifunctionality approach. After selecting the functional unit, the approach to handling

Table 6
Summary of the methodological choices and assumptions identified in this study and corresponding actions.

Methodological choices and assumptions	Corresponding action or analysis to evaluate the effect of key methodological choices
Comparison with conventional production systems (Product basket)	Convert systems into comparable systems: Compare multi-product ZLD systems with the conventional production of all the products within a scenario. Conduct a 1:1 comparison of scenarios and a 1:1 comparison of products, after economic allocation. For conventional processes of the recovered products, see Appendix, Section S4, Table S.15.
Functional unit	Conduct an LCA using two functional units as scenario analysis and compare the results to determine their influence on the outcome and conclusion.
Handling of multifunctional systems and comparison with conventional systems	Expand the system boundaries and compare the results with a *product-basket* approach to determine the influence on the outcome.
- System expansion/Substitution	
- Allocation: Mass and Economic	Run the two different allocation models as scenarios and compare the results to determine their influence on the outcome and conclusion.
Inclusion of waste heat in the analysis	Conduct a scenario analysis using three different allocation approaches: economic, energy, and one that excludes waste heat.
Energy mix: energy policy for renewable energy transition	Conduct a sensitivity analysis using a baseline scenario and three different energy policy scenarios: e-55, eCSP-55, and eCSP-100.

multi-functionality in systems with multiple products follows. This paper compares three multifunctionality approaches applied to the three resource recovery desalination systems for the five selected impact categories at the midpoint level. This methodological option explores three approaches: economic allocation, mass allocation, and system expansion, comparing their effects on environmental impacts (see illustration in Appendix, Section S2, Fig. S.2.).

- Substitution is solving multifunctionality through the subtraction of avoided burdens related to the co-products that are not part of the FU (Heijungs et al., 2021). Note that the additional amount of recovered water compared to the conventional SWRO plant (with 40 % efficiency) is considered in the co-products of each scenario, and thus the credits from this avoided are included. Specifically, in this analysis, the inventory modeled for global (GLO) and the inventory for the regional markets for Europe (REW) were used for conventional production, and the credits from the avoided products (see Appendix, Section S4, Table S.15).
- Economic and mass allocation solves multifunctionality by dividing the inputs and outputs of the process or system between its products according to the allocation criterion (Heijungs et al., 2021). In this work, economic allocation is respective to the economic value of the products and the mass allocation to the volumetric flowrate of the products (see Table 3 and Appendix, Section S2.1).

3.2.5.3. Methodological option C: effect of allocation in alternative energy sources. Waste heat is often overlooked in previous works in the literature, considering it to have zero environmental impact for that energy stream. To analyse the effect of the inclusion and allocation factors concerning energy sources like waste heat, three different methodological options are considered: 1) Economic allocation (see Table 5), 2) Energy allocation (see Table 7 and Appendix, Table S.6), and 3) Non-allocation (non-inclusion, zero environmental impacts). Note that the economic allocation approach is used to input the energy source in the SimaPro database for other analyses in this work besides this scenario analysis.

3.2.5.4. Sensitivity analysis: effect of energy mix on the environmental impact. To analyse the effect of the energy mix on the environmental impacts of the three technical scenarios, a sensitivity analysis is conducted regarding energy policy, following the European Green Deal guidelines (Agnieszka, 2023). In 2021, the European climate law was approved, incorporating into EU regulations the goal of achieving climate neutrality by 2050 (i.e., eliminating net greenhouse gas emissions) as well as an interim objective of reducing net emissions by 55 % by 2030 compared to 1990 levels. Specifically, the 55 % reduction target set for 2030 has been used as a benchmark for the energy scenarios. These regulations, which set targets for emission reductions, form the basis for our analysis. To test the integrated desalination and brine treatment technical designs, the following energy scenarios were considered:

- **Baseline:** most updated available energy data for Cypurs in 2021, based on the electricity mix from oil power plant using fuel oil type S (0 % RES), using EU and global averages from the Ecoinvent database.
- **e-55:** 55 % of electrical energy comes from renewable energy sources, specifically from solar systems (Photovoltaic (PV)). According to IRENA (2015), PV is expected to be the dominant renewable technology, followed by wind. For simplicity, only one renewable source is chosen: solar (PV) over wind.
- **eCSP-55:** 55 % of electrical and thermal energy comes from renewable sources, specifically solar systems (Concentrated Solar Power (CSP) and PV). CSP is chosen to provide high heat, thus covering the thermal energy requirements and replacing waste heat. Additionally, CSP can be combined with existing fossil fuel sources, enhancing its versatility (Ahmed et al., 2022).
- **eCSP-100:** 100 % of electrical and thermal energy comes from renewable energy sources, specifically from solar systems (Concentrate Solar Power (CSP) and PV).

Table 7
Energy allocation factors for Cyprus based on (Xevgenos et al., 2021).

Type of energy	Energy value (ktoe)	Energy allocation
Oil for electricity production	1030	100 %
Electricity	355	34.47 %
Waste heat	675	65.53 %

For the sensitivity analysis, *1 m^3 of seawater* fed is used as a functional unit, while for multifunctionality, two approaches are considered: *system expansion* and *economic allocation*. Finally, the environmental burden from the waste heat is calculated based on *economic allocation*.

4. Results

The LCA-based environmental impact analysis is divided into four parts. In the first part, the performances of the three scenarios across the five environmental impact categories are analysed and compared with the conventional desalination system. In the second part, the hotspots are identified, and the energy and chemicals contributions to the impact categories are analysed and discussed. In the third part, the effects of methodological decisions, such as the functional unit and allocation, on the results are analysed (see Section 4.3). In the fourth part, the sensitivity analysis on different energy sources is performed using a specific set of methodological choices, including a functional unit of 1 m^3 of desalinated water, an economic allocation method, and a substitution approach for handling multi-functionality.

4.1. Life cycle assessment for scenarios and reference system

4.1.1. Results from LCA for 1m^3 seawater as functional unit

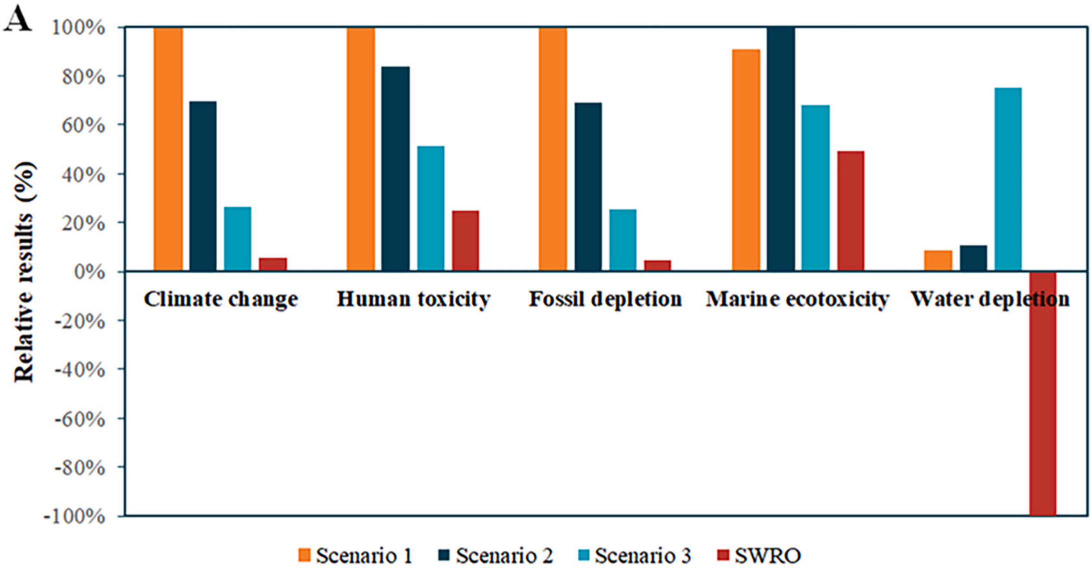
In this first step, the analysis focuses solely on comparing the three integrated ZLD scenarios with the conventional SWRO system, without yet accounting for the environmental credits associated with recovered products. The SWRO plant serves as the baseline for freshwater production in Cyprus. Fig. 3 presents the LCA relative impact scores (in figure) and absolute (in table) results for each resource recovery scenario and SWRO with 1m^3 of seawater fed as functional unit. Table 8 shows the total impact of all the impact categories.

All resource recovery scenarios result in higher environmental impacts in each of the four impact categories compared to the SWRO, as expected due to the integration of multiple technologies to minimize brine disposal and/or to recover valuable products. These integration strategies increase energy and chemicals consumption, leading to higher environmental impacts in comparison to the conventional desalination plant. It is worth noting that the difference between resource recovery scenarios and the SWRO for Marine ecotoxicity is much smaller than for the other four impact categories. For example, the difference between Scenario 3 and SWRO is only 0.03 kg 1,4-dB eq. (28 % relative impact score). This is because the brine disposal in the SWRO system directly impacts the marine ecosystems.

Additionally, the SWRO system results in a negative value for the water depletion impact category, indicating a net reduction in water depletion. This negative value results from the fresh water produced in the desalination process. This reduction was not considered for the other three scenarios because of simulation constraints. Thus, the water depletion category reflects the impact of water consumption in the three multi-product ZLD systems, but the net value is not calculated or shown in Fig. 3, affecting the interpretation of the results.

Scenario 1, while primarily focused on maximizing freshwater production and minimizing brine, still falls under the category of multi-

A



B

Impact category	Scenario 1	Scenario 2	Scenario 3	SWRO
Climate change (kg CO_2 eq)	39.96	27.89	10.52	2.24
Human toxicity (kg 1,4-DB eq)	3.18	2.66	1.64	0.79
Fossil depletion (kg oil eq)	12.02	8.34	3.09	0.57
Marine ecotoxicity (kg 1,4-DB eq)	0.10	0.11	0.08	0.05
Water depletion (m^3)	0.05	0.06	0.44	-0.58

Fig. 3. Life cycle impacts: (A) Relative impact score (%) for the three scenarios and the SWRO for 1 m^3 seawater fed as functional unit; (B) Absolute results for the three scenarios and the SWRO for 1 m^3 seawater fed as functional unit.

product ZLD systems because it produces a low-value salt mixture as a by-product. Scenarios 2 and 3, by contrast, explicitly target recovery of specific salts and chemicals alongside water.

These findings underscore the additional burdens associated with integrating a resource recovery system when evaluated without considering product substitution. A fair comparison, including the avoided impacts from recovered salts and chemicals, is presented in Section 4.1.2 to provide a more complete picture and avoid misleading conclusions.

When comparing only the resource recovery scenarios, Scenario 3 results in the best environmental performance across all impact categories except water depletion, while Scenario 1 results in the worst environmental performance. Thermal and electrical energy sources are the primary inputs in all technologies (see Table 4), indicating that all environmental impact categories are dominated by energy consumption. Only the MF-PFR (as seen in Scenario 2 and 3) and, to a lesser extent, membrane technologies use chemicals. Lastly, the significant external water usage in the EDBM unit for the chemicals production contributes to water depletion in Scenario 3 (see Table 4). This highlights a potential trade-off within Scenario 3, since water production remains the primary objective of desalination plants in Cyprus. Note that water production is not accounted for in assessing water depletion for these resource recovery scenarios. The environmental impact results using '1m^3 desalinated water' as functional unit are presented in Appendix (see Section S5, Table S.16, Fig. S.3).

4.1.2. Comparative environmental impact analysis of conventional and resource recovery systems

The environmental impact results of the recovered products in each technical scenario are compared by category with respect to their conventional production: industrial production for salts and chemicals, and SWRO desalination for freshwater. Fig. 4 represents a products basket approach (without any allocation), where the conventional and multi-product ZLD systems are compared based on the recovered products to evaluate the environmental advantages and disadvantages of recovering, besides water, multiple products from seawater. Table 9 shows the total impact across all impact categories for conventional production systems.

Recovering salts and chemicals in Scenarios 2 and 3 significantly reduces overall environmental impacts for all assessed impact categories compared to the traditional production systems. For example, the climate change impact is 70 % and 89 % lower in the resource recovery systems for Scenario 2 and 3, respectively, in comparison to the conventional production processes (see Fig. 4 A). Similarly, the reduction in environmental impacts for each product basket is between 70 and 95 % in the other impact categories for Scenario 2 and 44–96 % for Scenario 3 (see Fig. 4 B, C, D, E). Scenario 3 shows that utilizing only electricity-based technologies and recovering chemicals from seawater brines may result in significant environmental benefits compared to traditional production systems.

Thermal desalination and minimization of brine disposal with no additional recovery of products (scenario 1) result in a higher overall impact than conventional desalination systems. This is because of the higher energy requirements for water recovery. Although the ZLD system recovers more water than conventional desalination systems (with 40 % water recovery efficiency), the environmental impacts are higher for Climate change and Fossil depletion than those of the conventional system. It is worth noting that Scenario 1 performs better in human toxicity and marine ecotoxicity compared to the conventional system, because of the reduction of brine disposal. Appendix contains the relative impact scores for FU 1m^3 desalinated water (see Section S5.3).

A comparative analysis of water production using a conventional

Table 8
The total impact of all the impact categories for the three scenarios and the SWRO for 1 m^3 seawater fed as functional unit in ReCiPe midpoint (H) method V1.13/Europe Recipe H.

Impact category	Unit	Scenario 1	Scenario 2	Scenario 3	SWRO
Climate change	kg CO_2 eq	39.96	27.89	10.52	2.24
Ozone depletion	kg CFC-11 eq	0.00	0.00	0.00	0.00
Terrestrial acidification	kg SO_2 eq	0.30	0.21	0.08	0.01
Freshwater eutrophication	kg P eq	0.00	0.00	0.02	0.00
Marine eutrophication	kg N eq	0.01	0.00	0.01	0.00
Human toxicity	kg 1,4-dB eq	3.18	2.66	1.64	0.79
Photochemical oxidant formation	kg NMVOC	0.17	0.12	0.04	0.01
Particulate matter formation	kg PM10 eq	0.08	0.06	0.02	0.01
Terrestrial ecotoxicity	kg 1,4-dB eq	0.01	0.00	0.00	0.00
Freshwater ecotoxicity	kg 1,4-dB eq	0.06	0.09	0.07	0.06
Marine ecotoxicity	kg 1,4-dB eq	0.10	0.11	0.08	0.05
Ionising radiation	kBq U235 eq	2.21	1.58	1.03	0.17
Agricultural land occupation	m^2a	0.05	0.08	0.10	0.04
Urban land occupation	m^2a	0.06	0.10	0.08	0.01
Natural land transformation	m^2	0.01	0.01	0.00	0.00
Water depletion	m^3	0.05	0.06	0.44	−0.58
Metal depletion	kg Fe eq	0.24	0.27	0.19	0.04
Fossil depletion	kg oil eq	12.02	8.34	3.09	0.57

SWRO and a multi-product ZLD system (with economic allocation) highlights the environmental advantages and disadvantages of each approach. Conventional desalination (SWRO) in Scenario 1 has significantly lower environmental impacts across most of the five selected impact categories compared to the multi-product ZLD systems, with marine ecotoxicity being the exception. Specifically, the impact on climate change and fossil depletion is approximately five to six times higher for Scenario 1 because of high thermal energy requirements, with no high-value co-products to offset the burdens. This highlights the critical need for improving energy efficiency in thermal-based ZLD systems focused solely on water recovery.

In contrast, water production within a multi-product ZLD system like Scenario 2 has significantly lower environmental impacts across all impact categories (79 %–97 %) compared to conventional desalination. This demonstrates the potential environmental benefits of multi-product ZLD systems when additional co-products are recovered, making multi-product ZLD systems, like Scenario 2, a viable option for future designs (desalination systems). Details of this comparison can be found in Appendix (Table S.17 and Fig. S.7). A similar analysis for Magnesium can be found in Appendix (Section S5, Fig. S.8.).

4.2. Contribution analysis: identification of hotspots

Fig. 5 shows the contribution of each process unit to the impact categories, using Scenario 2 as an example to demonstrate the analysis and identify hotspots. Scenario 2 is selected here for simplicity, but similar analyses could be conducted for the other scenarios to provide a comprehensive understanding across all cases. The MED, MF-PFR, and EDBM units collectively contribute approximately 82 % to the four impact categories and 73 % to water depletion. These hotspots can be attributed to the substantial energy demands of the MED and EDBM units, coupled with chemical requirements (NaOH, HCl) for the MF-PFR. Identifying these hotspots reveals a map that guides the designers and decision-makers in making changes and improvements. For instance, environmental benefits are expected if all the chemical requirements can be produced internally (less dependent on external sources). Moreover, transitioning to more renewable energy sources, especially for the energy-intensive MED and EDBM units, holds promise for significant environmental benefits.

Building on the contribution analysis, the contribution of energy supply (thermal and electrical) and chemicals consumption to the five impact categories reveals that chemicals consumption accounts for 21 % of climate change impact, highlighting the need for a reduction in chemicals usage. Within each impact category, thermal energy use accounts for 49 %, indicating the need to decrease the thermal energy demand and also to shift towards more renewable energy sources for both electrical and thermal energy. Chemicals consumption contributes 43 % to water depletion, emphasizing the importance of addressing the supply of chemical requirements internally, minimizing the external costs and optimizing the EDBM unit to reduce water needs, which contributes to 18.3 % of water depletion in Scenario 2. This analysis not only identifies critical areas demanding attention but also illuminates pathways for a more ecologically friendly design. Results for the contribution of energy supply (thermal and electrical) and chemicals consumption are available in Appendix (see Section S5, Fig. S.5).

4.3. Effect of key methodological choices

Evaluating key methodological decisions is a crucial step in this LCA study to understand their influence on outcomes. This evaluation, divided into conceptual and numerical levels, provides valuable insights into the methodological adjustments necessary for assessing novel systems, particularly those focused on resource recovery. The numerical analysis, on the other hand, offers significant information for the design of process chains.

4.3.1. Methodological option A: effect of functional unit

The first and crucial methodological decision is the selection of a functional unit. Fig. 6 compares LCA results for two functional units: $1m^3$ seawater fed versus $1m^3$ desalinated water output, focusing on climate change (Fig. 6 A) and marine eco-toxicity (Fig. 6 B). This analysis uses economic allocation to address multifunctionality. Results for all the impact categories for both functional units are available in Table 8 and Appendix (see Section S6, Table S.18). Fig. 6 shows that the choice of functional units has a significant impact on Scenario 3. This is due to the lower quantitative difference between the volume of seawater fed and the volume of desalinated water recovered in scenarios 1 and 2 compared to Scenario 3. Scenario 1 aims to maximize water recovery, Scenario 2 aims at maximizing water and resource recovery, while Scenario 3 targets the recovery of valuable materials (like Mg) and chemicals. Consequently, choosing $1m^3$ desalinated water output as the functional unit results in lower water recovery and, therefore, higher energy and chemical intensity for Scenario 3, which in turn leads to higher impacts.

Similarly, higher environmental impacts by scenario 3 are observed across the other impact categories when $1m^3$ desalinated water output is used as functional unit instead of $1m^3$ seawater fed. This underscores the complexity of the decision-making process. The selection of a functional unit is a critical factor in LCA methodologies and should be based on the objective of the project. If the objective is to maximize water recovery, the functional unit should be set as $1m^3$ desalinated water output. In that case, the decision becomes more intricate, as Scenario 3 demonstrates a higher impact on marine eco-toxicity and water depletion than Scenarios 1 and 2. Additionally, the differences between Scenarios 2 and 3 are less significant when using $1m^3$ of desalinated water as a functional unit, making Scenario 2 more attractive compared to using $1m^3$ of seawater fed. In particular, for the climate change impact category, the

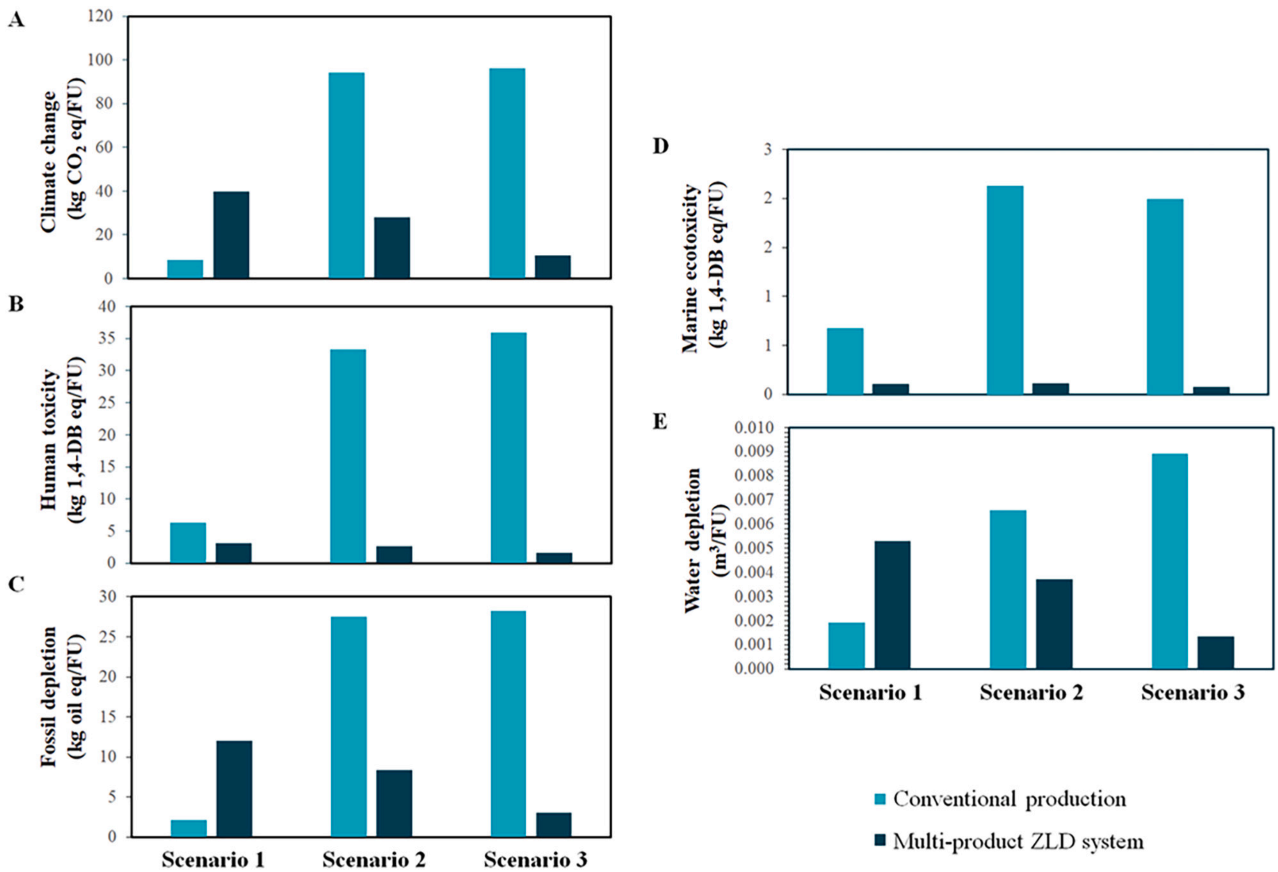


Fig. 4. Comparative analysis of the five environmental impact categories between the three resource recovery desalination scenarios with respect to the conventional production systems. Subfigures illustrate the comparison for (A) Climate change (kg CO_2 eq/FU), (B) Human toxicity (kg 1,4-dB eq/FU), (C) Fossil depletion (kg oil eq/FU), (D) Marine ecotoxicity (kg 1,4-dB eq/FU), (E) Water depletion (m^3/FU). FU: $1m^3$ seawater fed.

difference between Scenario 2 and Scenario 3 decreases significantly when comparing the two functional units: from 62 % with a functional unit of $1m^3$ of seawater fed to 12 % with a functional unit of $1m^3$ of desalinated water. Similarly, for fossil depletion, the difference between the two scenarios drops from 63 % to 14 %. For human toxicity, marine eco-toxicity, and water depletion, Scenario 2 results in lower impacts than Scenario 3 by 31 %, 39 %, and 94 %, respectively, when the functional unit of $1m^3$ desalinated water is used.

4.3.2. *Methodological option B: effect of multifunctionality approaches*

After selecting the functional unit, the question is how to handle multi-functionality in systems with multiple products. Two multi-functionality approaches (substitution and economic allocation) are compared when applied to three resource recovery desalination systems for the five selected impact categories at the midpoint level (see Fig. 7). Table 10 shows the total impact across all impact categories for the three scenarios using the substitution approach. Appendix contains the relative impact scores and absolute values for FU1m^3 desalinated water (see Section S6.3).

When the substitution approach is used, Scenarios 2 and 3 have significant credits from the avoided production of products elsewhere (see Fig. 7). In Scenario 2, the substitution approach resulted in a 54 % lower impact for climate change, 53 % in fossil depletion and over 86 % in the other impact categories compared to the economic allocation approach. Scenario 3 results in impacts that are approximately 90 % or more lower in the evaluated impact categories. Note that the water production itself, and thus its impact on the water depletion category, is not considered for the resource recovery scenarios because of simulation constraints (see Section 4.1.1). Scenario 1 focuses on water production and not on the recovery of multiple products, hence the deducted credits for product recovery are limited. Results for Scenario 1 suggest that focusing solely on water production may limit the environmental benefits of resource recovery systems, as shown in Section 4.1.2. Incorporating multiple product recovery, as in Scenarios 2 and 3, results in more sustainable economic outcomes.

When comparing multi-product ZLD systems with conventional systems, substitution can provide more useful information. Decision-makers can use the results, with the substitution approach applied, to inform their choice of desalination technologies based on their potential for resource recovery. One limitation of the analysis regarding substitution is the requirement of accurate data on the environmental impacts of substituted products, which may be difficult to obtain. Specifically, in this analysis, inventory modeled in global (GLO) and inventory for the regional markets for Europe (REW) were used for conventional production, and the credits from the avoided products (see Appendix, Section S4, Table S.15). Those choices can influence the results and lead to uncertainty.

Comparing the mass and economic allocation on a process level shows that the economic allocation results in lower environmental impacts across all the impact categories, ranging from a 33 % reduction for climate change to a 54 % reduction for water depletion. Economic allocation distributes the environmental impacts based on the economic value of the co-products, which often results in lower impacts for the main product when high-value co-products are present. This approach is useful for systems where economic revenue plays a significant role in design, such as resource recovery systems. When the overall system results are compared with the two allocation approaches, no difference is observed in the environmental impacts (see Appendix, Fig. S.9, Fig. S.10).

Table 9
The total impact of all the impact categories for the conventional production systems for 1 m^3 seawater fed as functional unit in ReCiPe midpoint (H) method V1.13/Europe Recipe H.

Impact category	Unit	Scenario 1	Scenario 2	Scenario 3
Climate change	kg CO_2 eq	8.40	94.31	96.39
Ozone depletion	kg CFC-11 eq	0.00	0.00	0.00
Terrestrial acidification	kg SO_2 eq	0.04	0.34	0.33
Freshwater eutrophication	kg P eq	0.00	0.04	0.04
Marine eutrophication	kg N eq	0.00	0.02	0.02
Human toxicity	kg 1,4-dB eq	6.33	33.32	35.99
Photochemical oxidant formation	kg NMVOC	0.03	0.44	0.44
Particulate matter formation	kg PM10 eq	0.02	0.45	0.45
Terrestrial ecotoxicity	kg 1,4-dB eq	0.00	0.01	0.01
Freshwater ecotoxicity	kg 1,4-dB eq	0.75	2.33	2.15
Marine ecotoxicity	kg 1,4-dB eq	0.68	2.13	1.99
Ionising radiation	kBq U235 eq	1.16	5.10	6.67
Agricultural land occupation	m^2a	0.58	2.52	2.52
Urban land occupation	m^2a	0.13	1.27	1.24
Natural land transformation	m^2	0.00	0.01	0.01
Water depletion	m^3	−1.43	−0.58	0.79
Metal depletion	kg Fe eq	1.72	4.49	3.93
Fossil depletion	kg oil eq	2.19	27.53	28.21

4.3.3. Methodological option C: effect of allocation in alternative energy sources

Fig. 8 presents the comparison of the LCA results for three different methodological options related to waste heat inclusion in the calculation: 1) Economic allocation, 2) Energy allocation, and 3) Non-allocation (zero environmental impacts). An effect analysis of the allocation methods (and related factors, or non-allocation with zero environmental impacts to waste heat recovery) is conducted, focusing on climate change (Fig. 8 A), fossil depletion (Fig. 8 B), and water depletion (Fig. 8 C). The impact categories are selected based on the relevance to the methodological decision. Additionally, Results for all impact categories using the three allocation approaches for 1m^3 seawater-fed FU are available in Table 11.

The three allocation methods have a significant impact on environmental impact performance and, consequently, the decision-making process. In the case of the energy allocation method, Scenario 1's environmental impacts increase by 75 % across all categories, Scenario 2 increases by 56–70 % across all categories, and Scenario 3 decreases by a wide range (2 %–114 %) compared to the economic allocation. This decrease in Scenario 3 is attributed to the absence of waste heat utilization. Despite not utilizing waste heat, Scenario 3 still allocates the environmental impacts of electricity consumption based on the energy value of both streams (electricity and waste heat). Notably, economic allocation assigns a 4.4 times higher environmental burden to electricity consumption than energy allocation. Consequently, even in the absence of waste heat utilization in Scenario 3, the choice of allocation methodology results in significant variations in assessed environmental impacts.

The analysis demonstrates that considering waste heat significantly influences the environmental performance of the scenarios and, consequently, the decisions based on the numerical results. The Non-allocation approach results in an 88–89 % lower value than the economic allocation approach across impact categories for Scenario 1 and 38–68 % for Scenario 2, highlighting the potential for misleading decisions when waste heat is excluded from the analysis.

Fig. 9 shows the contribution from electricity, thermal energy, and chemicals to the LCA results of the comparative analysis for waste heat inclusion by the three allocation approaches (economic, energy and no environmental burdens) across three impact categories (Climate change, Fossil depletion and Water depletion). Scenario 2, with *1m^3 seawater fed* as FU, serves as an example of the impact of the results. The contribution analysis facilitates discussions on design improvements to address the primary sources of impact and reduce the environmental impacts. The analysis reveals that the contribution of the three components varies significantly when using different allocation approaches.

This variation highlights the importance of the methodological decision. For instance, in the case of economic allocation, electricity emerges as the primary contributor across impact categories (51 %–71 %), directing attention towards energy optimization, reducing electricity consumption, and increasing the use of renewable energy sources. Conversely, when energy allocation is used, the results underscore the importance of measures like replacing waste heat, identifying alternative waste heat sources (e.g., solar energy) and utilizing renewable energy sources.

Finally, there is a notable variation in the contribution from

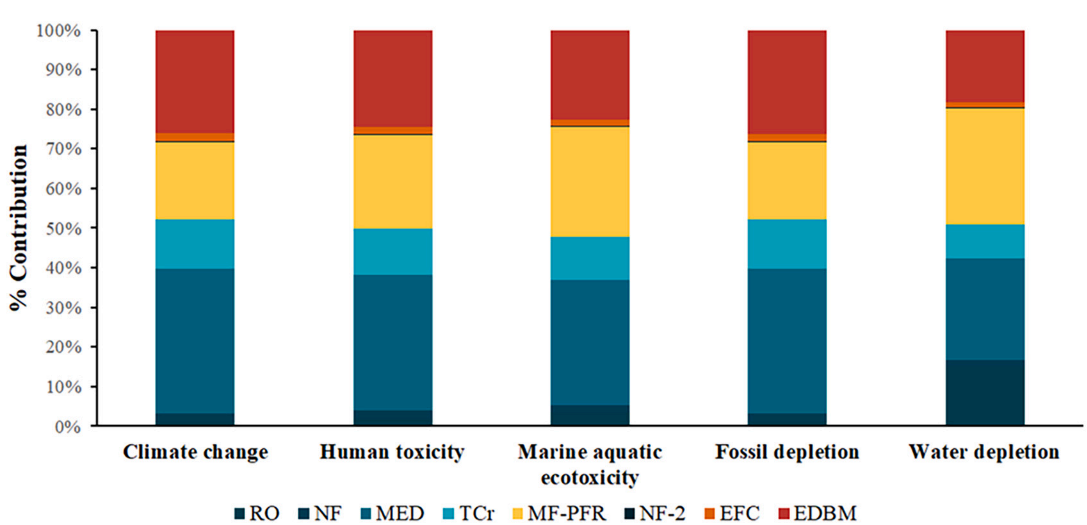


Fig. 5. Contribution analysis of the process stages, to the five environmental impact categories, for Scenario 2 with 1m^3 seawater fed as functional unit. ED: Electrodialysis; EDBM: Electrodialysis with bipolar membranes; EFC: Eutectic freeze crystallization; MED: Multi-effect distillation; MFPR: Plug-flow reactor; NF: Nanofiltration; RO: Reverse Osmosis, ThCryst: Thermal crystallizer.

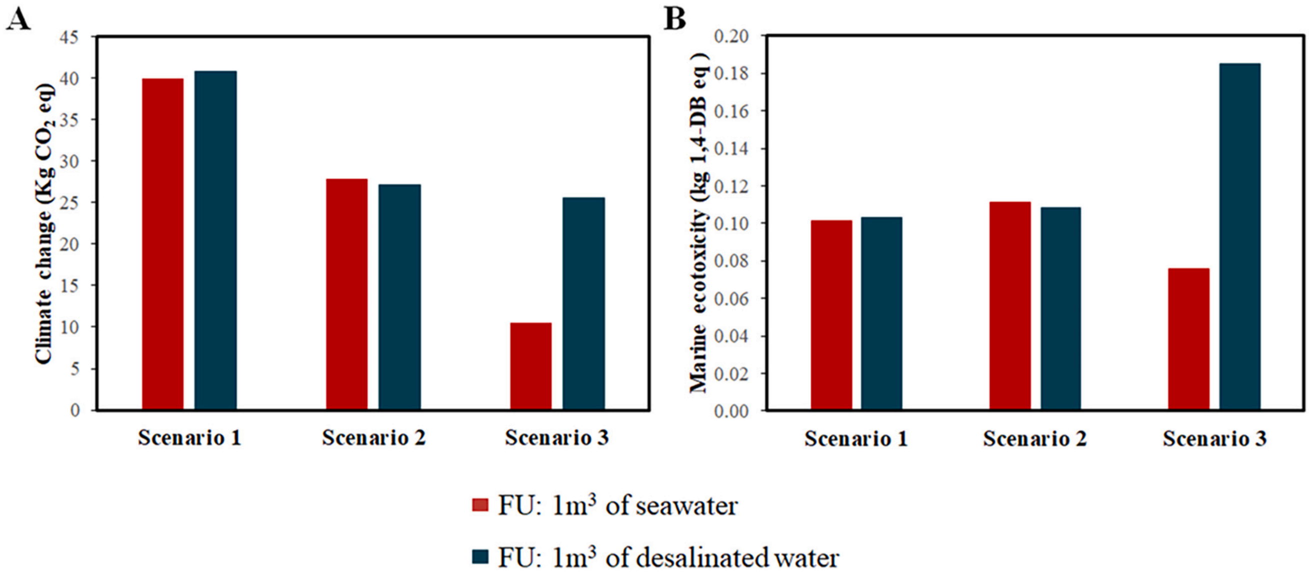


Fig. 6. Comparison of LCA results for $1m^3$ seawater fed vs. $1m^3$ desalinated water output as functional units for (A) climate change and (B) marine eco-toxicity impact categories.

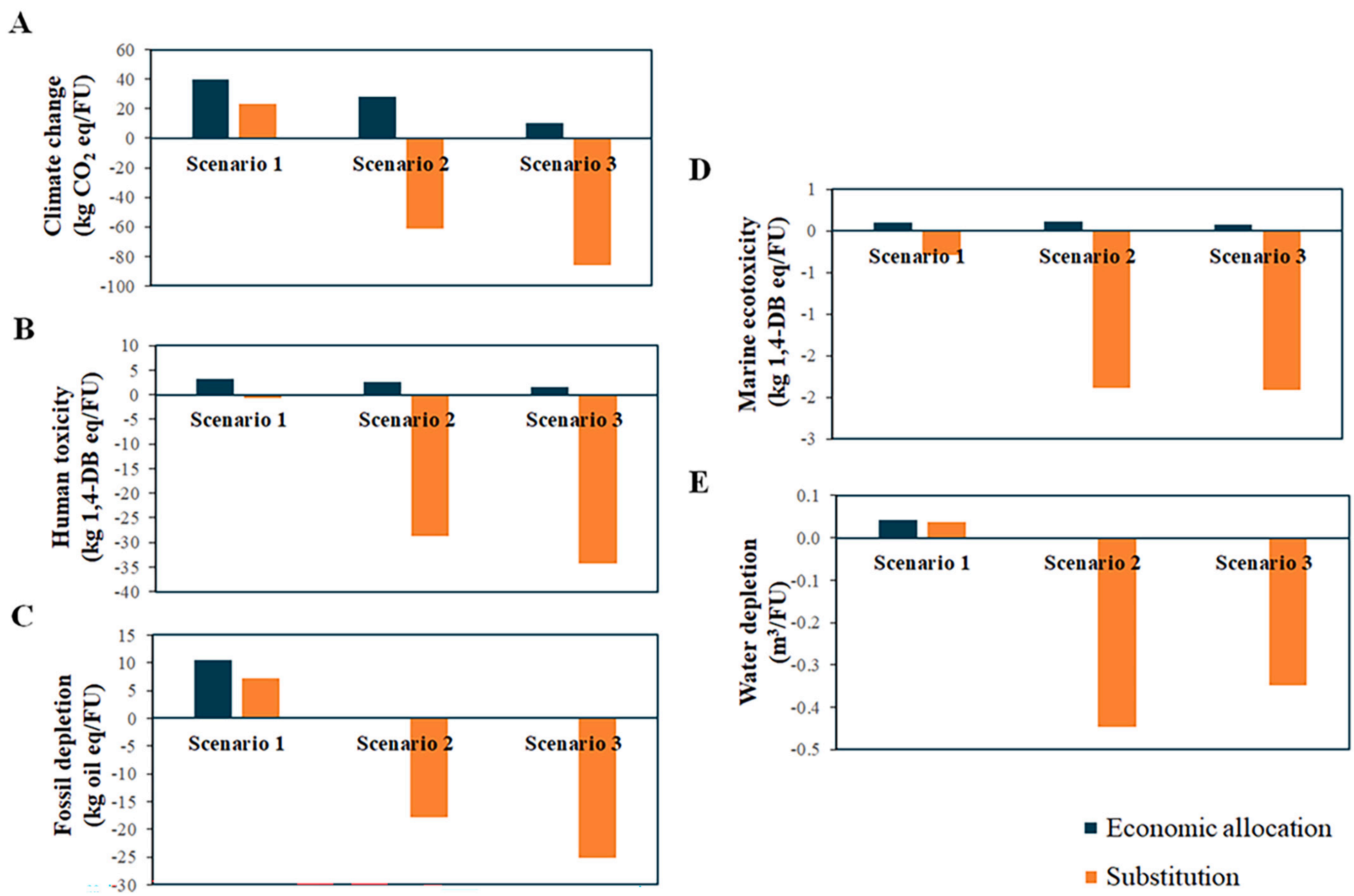


Fig. 7. Comparison of three resource recovery desalination systems using multifunctionality approaches (economic allocation, and substitution) for the five selected impact categories at the midpoint level. Subfigures illustrate the comparison for (A) Climate change (kg CO_2 eq/FU), (B) Human toxicity (kg 1,4-dB eq/FU), (C) Fossil depletion (kg oil eq/FU), (D) Marine ecotoxicity (kg 1,4-dB eq/FU), (E) Water depletion (m^3/FU). FU: $1m^3$ seawater fed.

chemicals consumption to the impact categories when different allocation approaches are applied: 21 %–44 % for economic allocation, 17 % for energy allocation, and 36 %–71 % for the non-allocation approach. This means that chemicals consumption can play an important role in design improvement. In the case of non-allocation, internal chemicals production and the utilization of renewable energy sources could

Table 10
The total impact of all the impact categories for the three scenarios using substitution approach for 1 m^3 seawater fed as functional unit in ReCiPe midpoint (H) method V1.13/Europe Recipe H.

Impact category	Unit	Scenario 1	Scenario 2	Scenario 3
Climate change	kg CO_2 eq	23.46	−61.32	−85.87
Ozone depletion	kg CFC-11 eq	0.00	0.00	0.00
Terrestrial acidification	kg SO_2 eq	0.18	−0.11	−0.26
Freshwater eutrophication	kg P eq	0.00	−0.04	−0.02
Marine eutrophication	kg N eq	0.00	−0.02	−0.01
Human toxicity	kg 1,4-dB eq	−0.80	−28.75	−34.35
Photochemical oxidant formation	kg NMVOC	0.10	−0.30	−0.39
Particulate matter formation	kg PM10 eq	0.05	−0.37	−0.43
Terrestrial ecotoxicity	kg 1,4-dB eq	0.00	0.00	−0.01
Freshwater ecotoxicity	kg 1,4-dB eq	−0.35	−2.09	−2.08
Marine ecotoxicity	kg 1,4-dB eq	−0.28	−1.88	−1.92
Ionising radiation	kBq U235 eq	1.10	−3.16	−5.64
Agricultural land occupation	m^2a	−0.29	−2.34	−2.42
Urban land occupation	m^2a	−0.03	−1.13	−1.17
Natural land transformation	m^2	0.01	0.00	−0.01
Water depletion	m^3	0.04	−0.45	−0.35
Metal depletion	kg Fe eq	−0.89	−4.08	−3.74
Fossil depletion	kg oil eq	7.16	−17.86	−25.13

substantially reduce the system's environmental impacts.

4.4. Sensitivity analysis: effect of the energy mix on environmental impact

A sensitivity analysis has been conducted regarding energy policy, following the guidelines of European Green Deal (Agnieszka, 2023) as explained in Section 3.2.5.4. As expected, transitioning to more renewable energy sources led to significant reductions in climate change impacts and fossil depletion impacts across all scenarios. For instance, in Scenario 1, transitioning to a case where 55 % of electrical and thermal energy comes from renewable energy sources (RES) resulted in a 54 % reduction in the impact of climate change. Similarly, in Scenario 2, this transition led to a reduction of approx. 53 % in the climate change impact, while in Scenario 3, the reduction was approx. 45 %. Furthermore, when considering a scenario where 100 % of electrical and thermal energy comes from RES, the reductions on the climate change impact were even more significant, with reductions of approx. 99 % for Scenario 1, 96 % for Scenario 2, and 82 % for Scenario 3.

The linear reduction observed specifically for Scenario 1 is due to the assumption that 0 % RES is used in the baseline energy mix (see Section 3.2.3). Scenario 1 is a very energy-intensive scenario, utilizing both electricity and waste heat, with minimal use of chemicals and other sources of environmental impact. Therefore, the impacts from energy consumption are dominant in this scenario, and they are reduced proportionally to the percentage of RES integrated into the energy mix.

Overall, Scenario 3 consistently exhibited the lowest reductions in the impact of climate change compared to Scenarios 1 and 2 under similar energy mix uses. This suggests that Scenario 3's environmental performance is less sensitive to changes in energy mixes or related policies compared to the other two scenarios as it utilises only electrical-based technologies, compared to Scenarios 1 and 2, where the thermal requirements are higher.

The impact of water depletion due to changes in the energy mix was

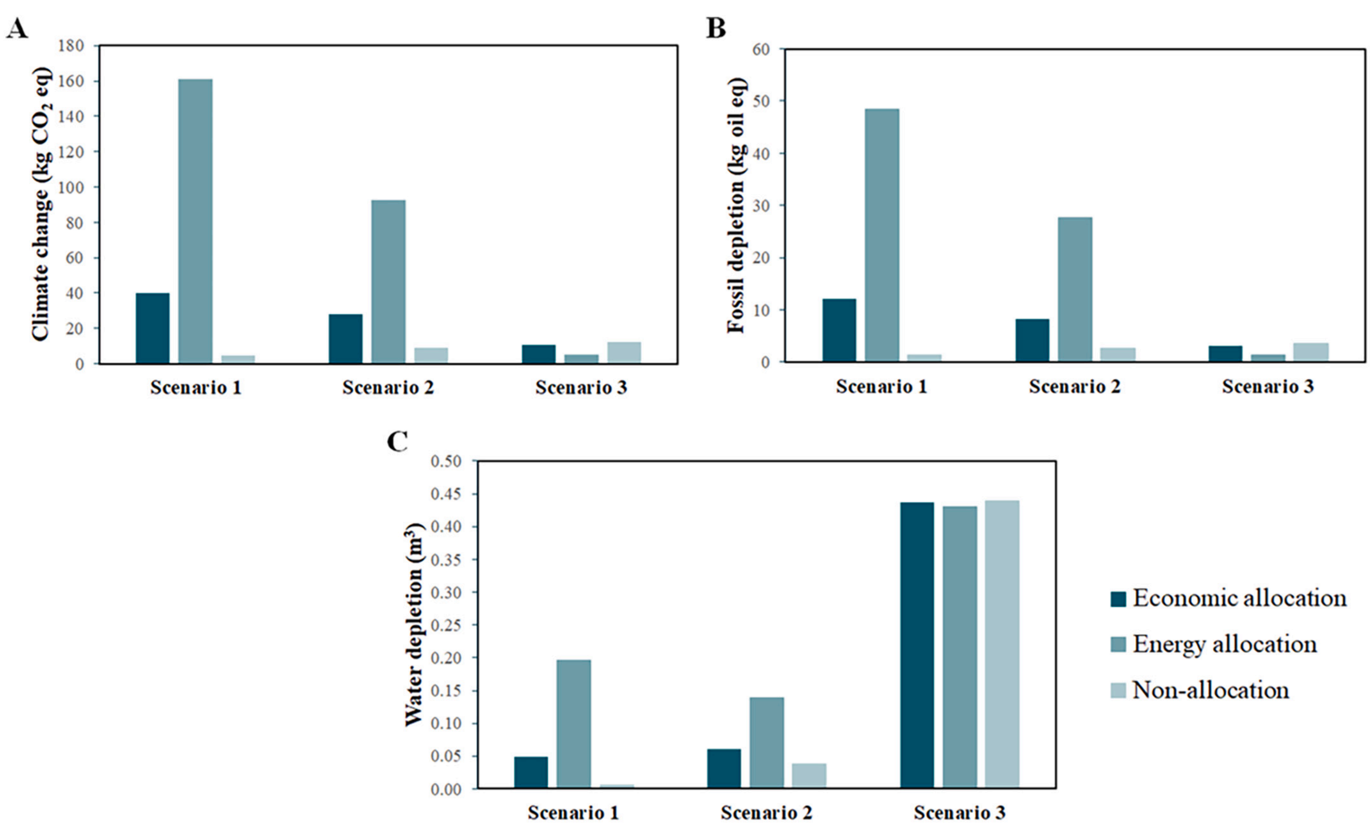


Fig. 8. Comparison of LCA results for waste heat inclusion by Economic allocation, Energy allocation and non-allocation (no environmental burdens), for three impact categories: (A) Climate change, (B) Fossil depletion and (C) Water depletion. FU: $1m^3$ seawater fed.

Table 11
The total impact of all the impact categories for the three scenarios for waste heat inclusion by Economic allocation, Energy allocation and non-allocation (no environmental burdens) for 1 m^3 seawater fed as functional unit in ReCiPe midpoint (H) method V1.13/Europe Recipe H.

		Energy allocation			Non-allocation		
Impact category	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Climate change	kg CO_2 eq	160.89	92.22	5.06	4.40	8.97	12.13
Ozone depletion	kg CFC-11 eq	0.00	0.00	0.00	0.00	0.00	0.00
Terrestrial acidification	kg SO_2 eq	1.20	0.69	0.04	0.03	0.07	0.09
Freshwater eutrophication	kg P eq	0.00	0.00	0.02	0.00	0.00	0.02
Marine eutrophication	kg N eq	0.02	0.01	0.01	0.00	0.00	0.01
Human toxicity	kg 1,4-dB eq	12.77	7.76	1.20	0.36	1.16	1.76
Photochemical oxidant formation	kg NMVOC	0.67	0.38	0.02	0.02	0.04	0.05
Particulate matter formation	kg PM10 eq	0.34	0.19	0.01	0.01	0.02	0.03
Terrestrial ecotoxicity	kg 1,4-dB eq	0.02	0.01	0.00	0.00	0.00	0.00
Freshwater ecotoxicity	kg 1,4-dB eq	0.24	0.19	0.06	0.01	0.06	0.07
Marine ecotoxicity	kg 1,4-dB eq	0.41	0.27	0.06	0.01	0.06	0.08
Ionising radiation	kBq U235 eq	8.90	5.14	0.73	0.24	0.54	1.12
Agricultural land occupation	m^2a	0.22	0.16	0.09	0.01	0.05	0.10
Urban land occupation	m^2a	0.24	0.20	0.07	0.01	0.07	0.08
Natural land transformation	m^2	0.05	0.03	0.00	0.00	0.00	0.00
Water depletion	m^3	0.20	0.14	0.43	0.01	0.04	0.44
Metal depletion	kg Fe eq	0.98	0.66	0.15	0.03	0.15	0.20
Fossil depletion	kg oil eq	48.42	27.70	1.44	1.32	2.64	3.57

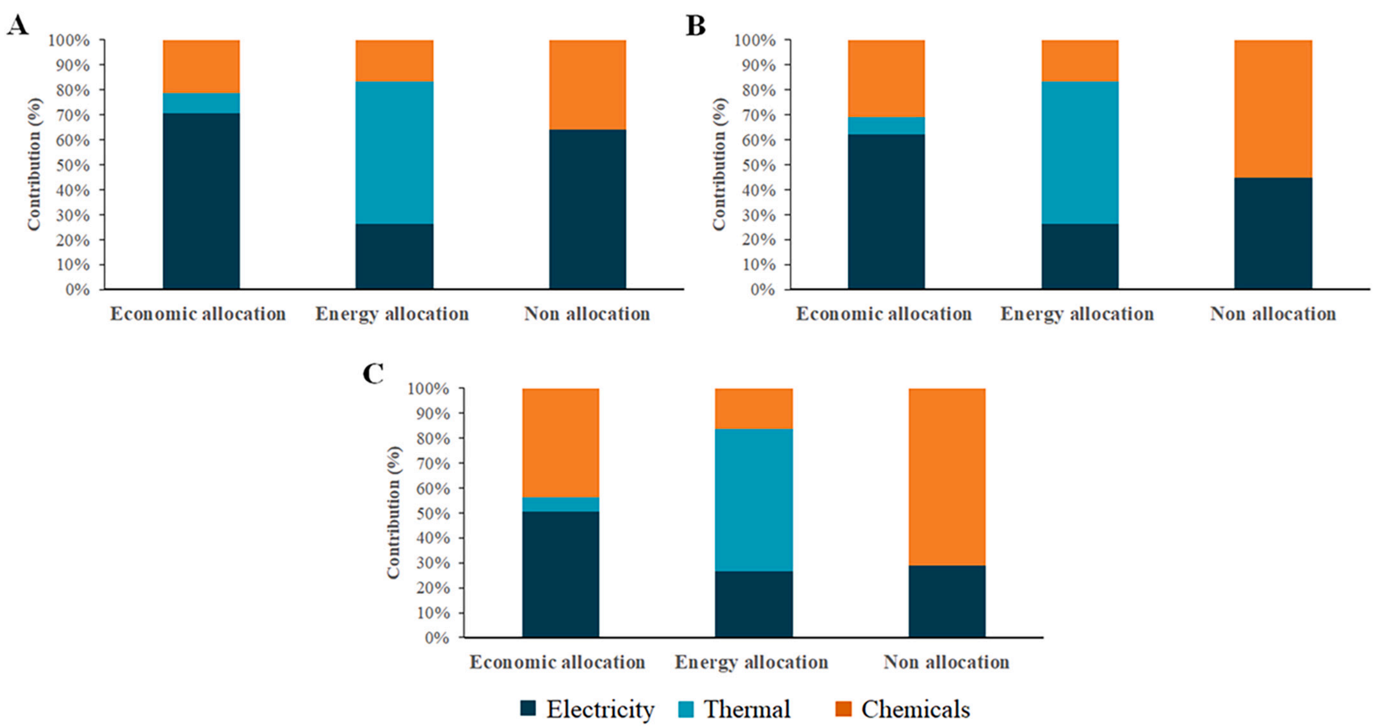


Fig. 9. Comparison of LCA's contributions (from chemicals and energy sources) for waste heat inclusion for Scenario 2 by considering: Economic allocation, Energy allocation and non-allocation (no environmental burdens); for three impact categories: (A) Climate change, (B) Fossil depletion and (C) Water depletion.

analysed by comparing water depletion impacts across different scenarios. For example, in Scenario 1, transitioning to the eCSP-55 case, where 55 % of electrical and thermal energy comes from RES, led to a decrease in water depletion impact of 47 %. Similarly, in Scenario 2, this transition resulted in a 18 % decrease in water depletion impact, while in Scenario 3, the increase is 1 % compared to the baseline. Furthermore, for the eCSP-100 case, the decrease in water depletion impacts is 85 % in Scenario 1 and 33 % in Scenario 2. The total impact of all the impact categories for the three scenarios for sensitivity analysis of energy mixes are available in Table 12.

After examining the sensitivity analysis results across various energy mix cases, Fig. 10 A zooms in on Scenario 2, revealing significant potential reductions in climate change, human toxicity, and fossil depletion impacts with the transition to renewable energy sources. Notably, a reduction of 95.5 % on climate change was observed for the eCSP-100 case, highlighting the effectiveness of renewable energy integration in mitigating climate change impacts. Similar to climate change, the impacts of human toxicity and fossil depletion decrease with the implementation of renewable energy sources. In particular, human toxicity decreased by only1% in e-55, 34 % in the eCSP-55 case and 62 % in the eCSP-100 case compared to the baseline, while fossil depletion follows the same trends as climate change. Transitioning to renewable energy sources led to increases in marine ecotoxicity in Scenario 2 (of 23 %–48 %), suggesting potential trade-offs between renewable energy use and environmental sustainability in Scenario 2.

Fig. 10 B zooms in on Scenario 3, which has different trends

Table 12
The total impact of all the impact categories for the three scenarios for sensitivity analysis of energy mixes for 1 m^3 seawater fed as functional unit in ReCiPe midpoint (H) method V1.13/Europe Recipe H.

		e-55			eCSP-55			eCSP-100		
Impact category	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Climate change	kg CO_2 eq	38.02	24.30	5.76	18.10	13.23	5.76	0.22	1.25	1.87
Ozone depletion	kg CFC-11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Terrestrial acidification	kg SO_2 eq	0.28	0.18	0.04	0.14	0.10	0.04	0.00	0.01	0.01
Freshwater eutrophication	kg P eq	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.00	0.02
Marine eutrophication	kg N eq	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01
Human toxicity	kg 1,4-dB eq	3.16	2.63	1.60	1.58	1.76	1.60	0.28	1.02	1.57
Photochemical oxidant formation	kg NMVOC	0.16	0.10	0.02	0.08	0.05	0.02	0.00	0.00	0.01
Particulate matter formation	kg PM10 eq	0.08	0.05	0.01	0.04	0.03	0.01	0.00	0.00	0.00
Terrestrial ecotoxicity	kg 1,4-dB eq	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Freshwater ecotoxicity	kg 1,4-dB eq	0.10	0.15	0.16	0.07	0.14	0.16	0.07	0.18	0.23
Marine ecotoxicity	kg 1,4-dB eq	0.13	0.17	0.15	0.08	0.14	0.15	0.06	0.16	0.21
Ionising radiation	kBq U235 eq	2.11	1.39	0.77	1.01	0.78	0.77	0.02	0.12	0.57
Agricultural land occupation	m^2a	0.06	0.08	0.10	0.03	0.07	0.10	0.01	0.06	0.11
Urban land occupation	m^2a	0.06	0.10	0.07	0.03	0.08	0.07	0.01	0.07	0.07
Natural land transformation	m^2	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Water depletion	m^3	0.05	0.06	0.44	0.03	0.05	0.44	0.01	0.04	0.44
Metal depletion	kg Fe eq	0.28	0.32	0.26	0.15	0.26	0.26	0.08	0.25	0.33
Fossil depletion	kg oil eq	11.44	7.25	1.65	5.44	3.92	1.65	0.06	0.31	0.47

compared to Scenarios 1 and 2. For the impact of energy mix on climate change and fossil depletion in Scenario 3, the impacts decreased by 45–82 % and 47–84 %, respectively, compared with Scenario 2, where the decreases in these two categories are 55–96 % and 55–96 %, respectively. The effect of energy mix on human toxicity for Scenario 3 is limited to 2 % for e-55 and eCSP-55 and 4 % for eCSP-100. Contrary to climate change, human toxicity and fossil depletion, transitioning to renewable energy sources led to increases in marine ecotoxicity by 95–173 % and water depletion impacts by 1 % for all energy mixes in Scenario 3. Note that for Scenario 3, there is no use of thermal energy, and therefore, there is no CSP, meaning that the effect is related to the use of PVs.

Overall, the results underscore the importance of considering the broader environmental implications of the energy mix used and the potential policy decisions. While renewable energy integration yields substantial reductions in the impacts of climate change and fossil depletion, it also introduces challenges such as heightened marine ecotoxicity and water depletion. To synthesize the main findings across scenarios and methodological dimensions, Table 13 summarizes the influence of functional unit choice, allocation approaches, waste heat treatment, and energy mix assumptions on the environmental performance of Scenarios 1–3. This integrative overview highlights the most significant insights.

4.5. *Sensitivity analysis: effect of key LCI parameters*

Sensitivity analysis of the EDBM unit's energy consumption (±20 %) shows that Scenarios 1 and 2 are largely unaffected (<2 % variation across categories), while Scenario 3 is moderately sensitive due to its reliance on electricity-based processes. For Scenario 3, the impacts of climate change and fossil depletion varied by −12 % to +10 %, and human toxicity by −6 % to +5 %. Marine ecotoxicity and water depletion were less sensitive (<4 % change). These results indicate that the robustness of Scenarios 1 and 2 is high, while Scenario 3 is more vulnerable to uncertainties in EDBM energy demand.

Adjusting energy consumption of filtration units for MFPFR, TCryst and EFC by ±20 % changed climate change impacts by less than 1 % across scenarios, with similarly small differences observed for the other impact categories.

Sensitivity analysis of chemical consumption in the MF-PFR process (±20 % NaOH and HCl use) shows negligible effects in Scenarios 1 and 3 (<0.1 % variation across all impact categories). In contrast, Scenario 2 is highly sensitive: a 20 % reduction in NaOH consumption decreases climate change and fossil depletion impacts by ~60 %, while a 20 % increase in HCl use raises marine ecotoxicity by ~20 % and water depletion by ~33 %. These findings indicate that Scenario 2's performance strongly depends on assumptions about chemical use, making it a critical uncertainty factor for emerging recovery systems. Full numerical results are provided in Appendix (Section S7).

5. Discussion

This study highlights the critical role of LCA in designing and evaluating multi-product ZLD systems for desalination and brine treatment. It is the first comprehensive LCA study to address methodological challenges specific to integrated desalination and resource recovery systems, including the impact of functional unit selection, allocation methods, and waste heat inclusion—factors that have not been fully explored in previous studies on desalination LCA.

5.1. *Functional unit selection*

This study uniquely compares two functional units (1 m^3 of desalinated water and 1 m^3 of seawater) to capture the diverse objectives of ZLD systems, which include both water and resource recovery. Selecting 1 m^3 of seawater as the functional unit proves more appropriate for maximizing resource recovery, while 1 m^3 of desalinated water aligns with minimizing brine discharge, similar to findings in wastewater treatment, where functional unit choice affects outcomes due to differences in influent and effluent volumes (Corominas et al., 2020). This highlights the need for flexible FU definitions in multi-objective systems.

5.2. *Allocation methods and co-product credits*

This study compares economic allocation and substitution, demonstrating that substitution provides a more comprehensive assessment by capturing the avoided impacts of conventional production for recovered products, economic allocation, remains useful for baseline results, since it aligns with market drivers and facilitates process-level comparisons. Together, the two approaches provide complementary perspectives: substitution highlights the broader sustainability benefits, while economic allocation supports design- and market-relevant evaluations.

5.3. *Waste heat inclusion*

This study examined the critical impact of waste heat inclusion on

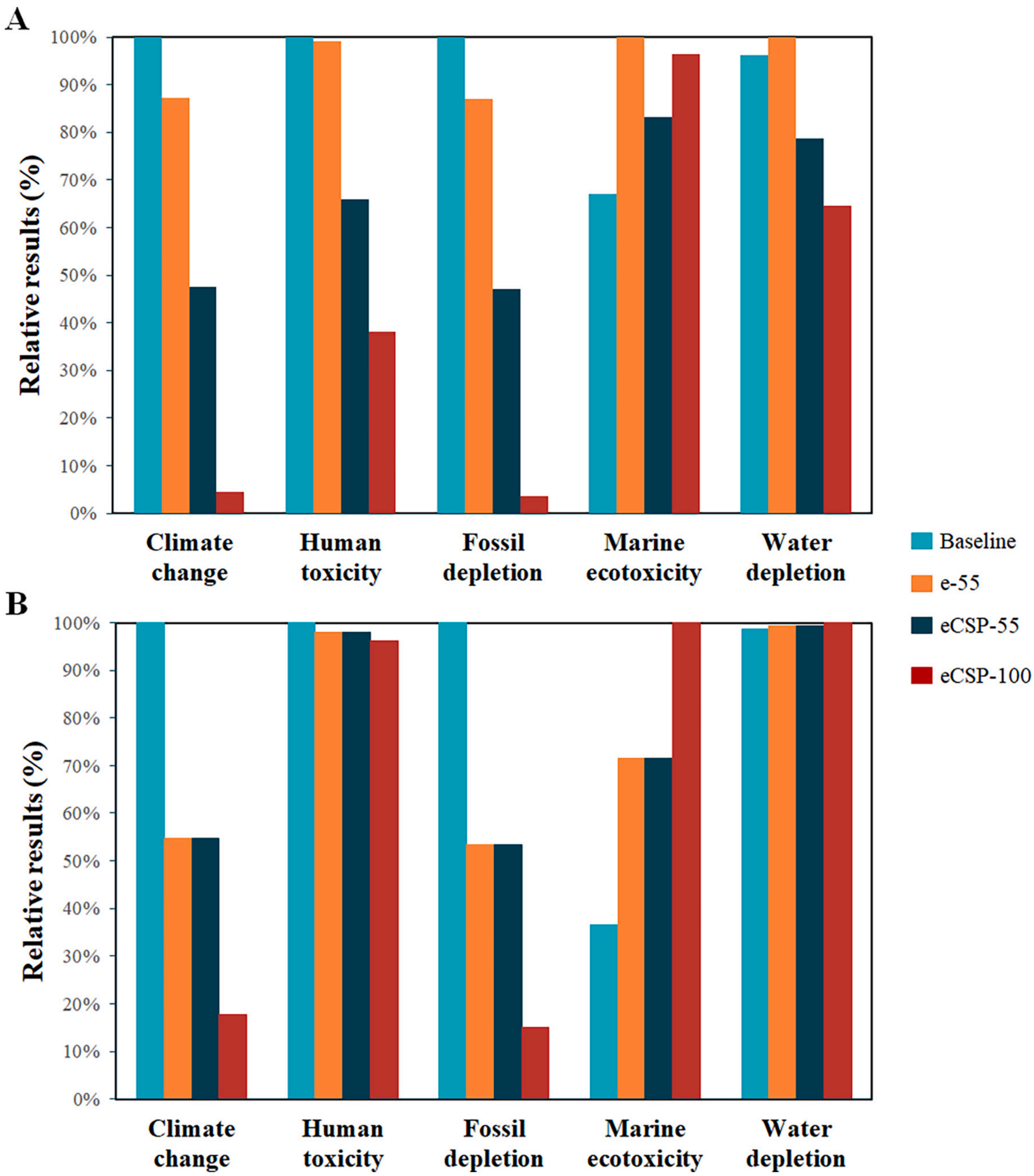


Fig. 10. Sensitivity analysis of energy mixes on the five environmental impact categories for (A) Scenario 2 and (B) Scenario 3.

LCA outcomes, challenging the common assumption of zero environmental burden for waste heat (Harris et al., 2021; Tsalidis et al., 2023) Excluding waste heat significantly underestimates impacts, potentially leading to misleading conclusions. Among the three methods, economic allocation is the most appropriate baseline choice because it reflects the relative market value of electricity and waste heat, aligning with the economic drivers of co-production and the motivation for integrating waste heat in industrial applications. Energy allocation, while useful for understanding physical energy balances, may underestimate the burden of electricity when it is the primary product, as in power generation systems.

5.4. Membrane replacement scenario

In addition to the core analysis, a scenario was evaluated to assess the potential environmental impacts of membrane replacement as consumables. The results indicated that the inclusion of membrane replacement did not significantly alter the environmental performance across the key impact categories. This suggests that, for this specific system configuration, membrane replacement has a relatively minor environmental impact compared to other factors, such as energy consumption and chemical use. Their disposal might affect the environmental impact of the system (Chen et al., 2023), but it is out of the system boundaries of this analysis. Detailed figures comparing the scenarios with and without membrane replacement are provided in Appendix (see Section S6.7).

5.5. Renewable energy integration and environmental trade-offs

This study provides a comprehensive analysis of the impact of renewable energy implementation on desalination and brine treatment. The results underscore the significant influence of the local energy mix

Table 13
Summary of the three technical scenarios (Sc1–Sc3) mapped against key methodological choices: functional unit (FU), allocation methods, treatment of waste heat, and sensitivity to energy mix.

Scenario	Functional Unit (FU)	Allocation Method	Waste Heat Treatment	Energy Mix Sensitivity	Key Results / Insights
Sc1: Maximize water recovery and minimize brine discharge	1 m^3 seawater / 1 m^3 water	Economic (baseline), Mass (alt), Substitution (alt)	Economic (baseline), Energy (alt), Zero burden (alt)	Baseline, e-55, eCSP-55, eCSP-100	High energy demand → higher impacts than SWRO. Performs better in Human toxicity and Marine ecotoxicity. Strongly sensitive to energy mix (up to 99 % reduction with 100 % RES).
Sc2: RO plant with brine treatment for recovery of water and valuable products and minimizing brine discharge	1 m^3 seawater / 1 m^3 water	Economic (baseline), Mass (alt), Substitution (alt)	Economic (baseline), Energy (alt), Zero burden (alt)	Baseline, e-55, eCSP-55, eCSP-100	Multiple co-products reduce impacts by 70–95 % vs. conventional production. Substitution gives large credits. Moderately sensitive to FU and waste heat allocation.
Sc3: Integrated RO plant with brine treatment focusing on chemical recovery, using only electricity-based desalination	1 m^3 seawater / 1 m^3 water	Economic (baseline), Mass (alt), Substitution (alt)	No WH	Baseline, e-55, eCSP-55, eCSP-100	Benefits from chemical recovery, but 59 % higher impacts if FU = 1 m^3 desalinated water. Excluding WH in comparisons changes results by up to 89 %. Less sensitive to energy mix, but trade-offs (↑ marine ecotoxicity, ↑ water depletion).

on assessment outcomes, with substantial reductions in climate change impact and fossil depletion impact (when transitioning to renewable energy sources. However, renewable energy integration can increase marine ecotoxicity and water depletion impacts. This pattern has been similarly observed in LCA studies for solar MED systems (Alhaj et al., 2022). By quantifying the impact of different energy scenarios on key environmental indicators, this analysis offers insights into the trade-offs and synergies between energy choices and environmental sustainability.

5.6. Environmental benefits

Beyond the methodological focus, this study provides actionable insights into the environmental impacts of integrated desalination and brine treatment systems. Compared to conventional seawater desalination (SWRO), multi-product ZLD systems have higher environmental impacts across all categories due to their complexity. However, resource recovery scenarios present significant environmental benefits associated with the recovery of salts and chemicals compared to conventional production processes of the recovered products, paving the way for more sustainable water treatment. This aligns with studies emphasizing the advantages of material recovery (Morgante et al., 2022b; Ktori et al., 2024a) but extends these findings by demonstrating that multi-product systems can match or exceed conventional water production's environmental performance.

5.7. Uncertainty analysis

This study incorporated both parameter sensitivity analysis and a pedigree-based data quality assessment. The main sources of uncertainty are linked to emerging technologies (e.g., MF-PFR, EDBM, TCryst, EFC), where pilot-scale data and assumptions from technology experts were used. The results indicate that variations in these parameters had a minor impact on overall environmental performance. Only Scenario 2 was highly sensitive to assumptions on chemical consumption in the MF-PFR unit because of the external usage of chemicals. These findings indicate that while the overall ranking of scenarios remains robust, Scenario 2's environmental performance is more vulnerable to uncertainty in chemical consumption. Future work should expand uncertainty quantification, ideally through full probabilistic methods such as Monte Carlo simulation, and explore technological improvements to reduce chemical demand.

5.8. Future directions

Future work should expand the system boundaries to include the full life cycle to provide a more comprehensive environmental evaluation.

6. Conclusion

This study underscores that the reliability of Life Cycle Assessment (LCA) results for integrated desalination and resource recovery systems depends strongly on methodological choices defined within existing ISO 14040 guidelines. By comparing conventional and multi-product Zero Liquid discharge systems, the work demonstrates how methodological decisions on functional unit, handling multifunctionality (e.g., economic allocation and substitution), and treatment of waste heat can fundamentally alter environmental outcomes.

The choice of a functional unit is crucial and aligns with the assessment objectives and the needs of decision-makers. This study demonstrates that the environmental impact can vary significantly depending on the chosen functional unit for desalination, especially when there are major differences in volumetric flows. This reveals a novel consideration for assessing resource recovery systems. Selecting an appropriate multifunctionality approach is essential, with economic allocation and substitution offering complementary perspectives. Substitution, in particular, provides a clearer picture of the environmental benefits of resource recovery systems. Similarly, excluding waste heat leads to underestimated impacts and misleading conclusions. Economic allocation provides the most realistic baseline for waste heat, ensuring that environmental burdens are distributed in line with economic value rather than assumed to be zero. These findings underscore the importance of carefully selected methodological choices to ensure reliable evaluations and informed system design.

The contribution of this work lies in providing a critical demonstration and guidance on how standardized methodological options should be applied to complex, emerging systems rather than proposing new LCA methods. This makes the findings directly relevant to practitioners and decision-makers designing sustainable desalination strategies.

CRediT authorship contribution statement

Rodoula Ktori: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **John A. Posada:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Mark C.M. van Loosdrecht:** Writing – review & editing, Supervision. **Dimitrios Xevgenos:** Writing – review & editing, Funding acquisition.

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.

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.2025.11.001.

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