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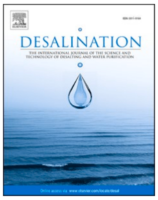

Economic evaluation of water and resource recovery plants: A novel perspective on levelized cost

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HIGHLIGHTS

- Introduces novel economic and dual allocation methods for resource recovery plants.
- Levelized costs vary across methods, highlighting the need for tailored assessments.
- Traditional non-allocation method overestimates costs, leading to overpriced products.
- Economic allocation reduces water LVC by 81 %, enhancing plant profitability.
- Dual allocation approach optimizes salt recovery, enhancing competitiveness in the market.

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ABSTRACT

Water treatment facilities are bound to incorporate resource recovery in the near future, necessitating novel economic assessments that capture the full economic potential of these systems. This study evaluates three cost calculation methods—Non-allocation, Economic allocation, and Dual allocation— to improve the accuracy of the Levelized Cost for multi-product desalination and brine treatment plants. The methods were tested across three technical scenarios: Sc1) maximum water recovery, Sc2) integrated desalination with brine treatment for resource recovery and Sc3) electricity-based desalination for chemical recovery. Results reveal that the traditional Non-allocation method tends to overestimate production costs by uniformly applying fixed costs across products, leading to inflated levelized costs. The Economic allocation approach reduces the levelized costs of water and other recovered products by up to 81 %, enhancing competitiveness with conventional production methods. The Dual allocation approach is most effective for recovered salts and chemicals, ensuring fair cost distribution and fostering competitiveness with linear systems. Sc2 is the most economically feasible under both novel approaches due to its balanced mix of high-value products and moderate operational costs. These findings suggest that cost calculation methods should align with plant objectives: Economic allocation for scenarios prioritizing water recovery and Dual allocation for maximizing the value of salts and chemicals. This study provides a foundation for tailored economic assessments and guides plant design and investment decisions.

1. Introduction

Seawater is a rich source of valuable and rare materials [1]. The integration of desalination and brine treatment technologies holds promise for water sustainability and the advancement of circular economy principles by recovering materials like NaCl and $Mg(OH)_2$ [2]. In recent years, there has been a notable shift toward integrating these technologies to achieve Zero Liquid Discharge (ZLD), ensuring both water sustainability and economic feasibility. As resource recovery gains prominence, traditional economic assessment tools, which focus solely on water production, are no longer sufficient. New tools are required to evaluate the economic feasibility of multi-product systems and to support investment decisions by fairly comparing recovered materials with their equivalent conventional products [2,3].

Historically, desalination plants have been evaluated based on water production costs using metrics such as unit cost [4–6], production cost [7], water cost [8–10] and levelized cost of water [11–14]. With a growing emphasis on circular desalination, the Levelized Cost of Water (LCW) has been modified. Lior and Kim [15] included the environmental and social costs of the plant in the calculation of LCW. In renewable

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energy-powered desalination plants, the costs and benefits of water and energy cogeneration are integrated into LCW [16–18].

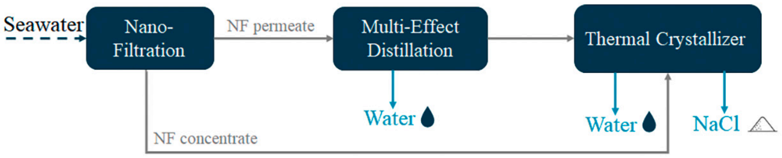
For the assessment of brine treatment plants, Micari et al. [19] introduced the levelized cost of the by-product, NaCl crystals, and the Levelized Brine Cost [20], considering concentrate brine as a by-product. These approaches modified the traditional Levelized Cost (LVC) calculation to account for revenues generated by by-products, thus providing a more comprehensive view of economic feasibility. Morgante et al. [21] further advanced this concept by evaluating the economic feasibility of multi-product systems through the Levelized Cost Index, which includes a specific cost index for each product.

Despite these advancements, there remains a significant gap in how costs are allocated across technologies in multi-product systems where water and other valuable products are recovered. Current methods typically load the total annual cost uniformly over each product, often failing to capture the complex interdependencies among technologies and operational synergies within multi-product systems, such as shared infrastructure and complementary processes, where one technology may serve as a pre-treatment for another. This simplification can reduce the accuracy of feasibility assessments by inflating costs for some products and undervaluing others, potentially leading to unprofitable plants and skewing investment decisions.

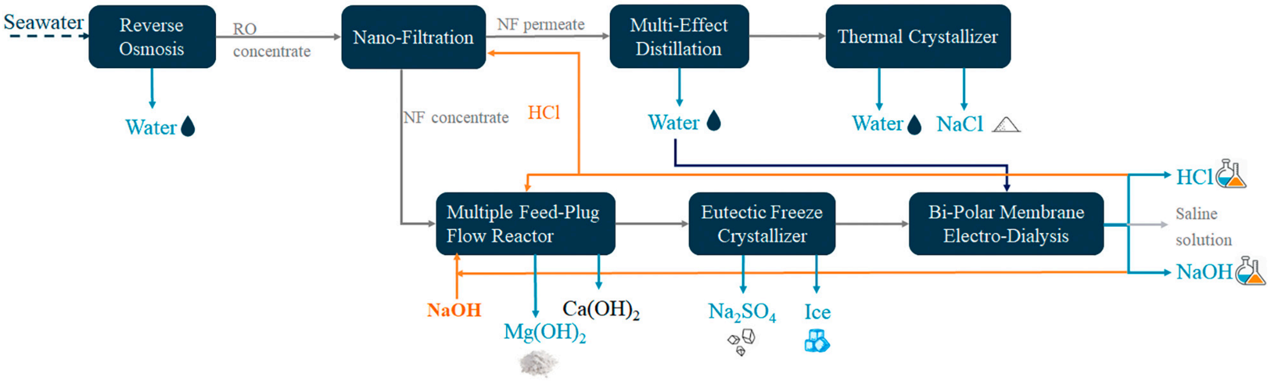
This study addresses this gap by introducing two novel cost allocation methods—the Economic allocation and Dual allocation approaches. Unlike existing methods, these approaches incorporate operational synergies and technological interconnections, ensuring fairer cost distribution and more accurate economic assessments. In particular, this study aims to investigate how different cost calculation methods influence the levelized cost of products in a multi-product desalination and brine treatment plant. The study compares traditional and the two novel cost allocation methods to clarify their impact on the economic feasibility of resource recovery.

To evaluate the effectiveness of these methods, we developed economic models for integrated desalination and brine treatment systems. Inspired by existing calculation methods in the literature [20,21], the theoretical background on joint costs [22], other domains such as life cycle assessment [23], and the need to evaluate the economic benefits of resource recovery plants, we introduced two novel calculation methods for levelized cost. Using varied technical scenarios that represent different operational conditions and objectives, we assessed the performance of each method in delivering representative economic outcomes.

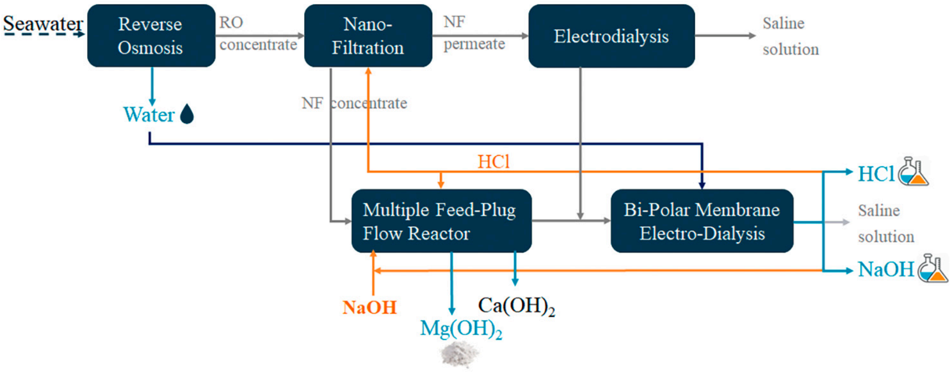
This study bridges methodological rigor with practical applications, advancing the understanding of fair cost allocation in multi-product



A) Scenario 1: Water Recovery



B) Scenario 2: Integrated RO plant with brine treatment



C) Scenario 3: Electricity-based desalination with chemical recovery

Fig. 1. Process diagram of the three scenarios illustrating the integrated desalination and brine treatment systems used in the present study [24].

systems. By optimizing resource recovery and economic feasibility, it supports the transition toward a circular economy. The insights gained can directly inform process design, investment decisions and policy frameworks, promoting sustainable resource recovery strategies in water-scarce regions and industries reliant on high-value materials.

2. Case study description

In this study, a case of integrated desalination and brine treatment plants aiming to recover valuable materials such as water, salts, and chemicals, as shown in Fig. 1 is used primarily to demonstrate the application of novel cost allocation methods. Although the study does not focus on a specific real-world site, it is informed by real-world cases and prior research, particularly the example of islands and coastal regions that rely on desalination as their primary freshwater source [25].

Building on prior research on treatment chains for resource recovery from brine effluent [2,12,21], this hypothetical but practical case simulates an integrated desalination-brine treatment system with a feed flow rate of 3000 m^3/d (capacity of a desalination plant on an island), reflecting real-world resource challenges [24]. The technical scenarios in this study test varying objectives and cost allocation methods, offering insights into the broader applicability of the calculation methods.

2.1. Definition of scenarios

In this work, technical scenarios are analysed to evaluate the calculation methods based on varying objectives for the studied plant configuration. Although all scenarios aim to increase water recovery and reduce brine discharge compared to typical seawater desalination, they differ in their specific objectives [24]. These technical scenarios aim to recover water, salts (NaCl, $Mg(OH)_2$, Na_2SO_4) and chemicals (HCl, NaOH) from seawater, as shown in Fig. 1.

- **Scenario 1 (Water recovery):** focuses on maximizing water recovery and minimizing brine discharge without the recovery of additional products, simulating a case where the primary objective is potable water production with minimal environmental impact.
- **Scenario 2 (Integrated RO plant with brine treatment):** integrates the Reverse Osmosis (RO) desalination plant with the brine treatment plant to optimize both water and salt recovery and minimize brine discharge.
- **Scenario 3 (Electricity-based desalination with chemical recovery):** integrated RO plant with brine treatment focusing on chemical recovery, such as HCl and NaOH, using only electricity-based desalination.

Each of these scenarios aligns with different real-world recovery objectives, from basic water recovery to comprehensive chemical extraction, thus offering a robust framework for assessing the economic implications of each configuration. Further details on the design, motivation and simulations of these scenarios can be found in Supplementary Information (see Section S1) and [24].

3. Material and method

Levelized cost is the price at which a product should be sold to cover all production costs and reaches break-even costs [12]. Until now, it is expressed as the ratio of all the capital and operating expenses and the revenues coming from the by-products of the plant over the economic life to the overall production of a product over the same period [12,16]. The purpose of this work is to investigate the influence of different cost calculation methods on the levelized cost of the products in a multi-product desalination and brine treatment plant. Input assumptions like capacity costs, maintenance, marginal operating costs, or average capacity factor vary by study and are critical to the calculation [26]. We applied the traditional approach alongside two novel methods under the same conditions to provide a baseline for comparison. This approach ensures that any observed differences in levelized cost are due to the methodologies themselves rather than external variables.

The different calculation methods are designed to evaluate the influence on the LVC when the by-products are not considered as by-products anymore but as valuable products of the plant (multi-functional system). Another parameter that is taken into account is the consideration of brine as a resource and not as a waste and how this would change the economic evaluation in the future. The different methodological approaches followed in this work are illustrated in Fig. 2. Below, a detailed explanation of three calculation methods is given.

3.1. Economic model: definition of input/outputs

For the calculation of the LVC, economic models were developed based on previous work [24]. The main purpose of these models is to provide the necessary data for LVC calculations. Interested readers can refer to the GitHub repository for the technical process and economic models [36] (see https://github.com/rodoulak/Desalination-and-Brine-Treatment-Simulation-.git). Table 1 shows the most relevant inputs and outputs of the economic model used in this study for the economic assessment of the technical scenarios. The mathematical description and the main assumptions can be found in the Supplementary Information (see Section S2. It is important to note that the main focus of this work is not the detailed calculation of major costs and revenues in desalination and brine treatment processes. Table 2 shows the annual production rate of each product across the three technical scenarios. Further technical details, including input data on products' flow rates and quality, as well as the energy, chemical, and water requirements, are available in Supplementary Information (see Section S3). To simplify the calculation of LVC, it is assumed that the production rates and operational costs are constant over the years.

3.2. Calculation method 1: non-allocation approach

The first calculation method is the commonly used approach based on the definition of the LVC without any allocation method. According to the knowledge of the authors of this article, the latest modification of the calculation method for the levelized cost of products in a multi-product plant, as described by Morgante et al. [21], is expressed in Eq. (1). In their study, Morgante et al. [21] considered the Annualized costs of the different units and the revenues of the multiple products in the calculation of the LVC. The following calculation is carried out for each product in the plant.

$$LVC_i = \frac{\sum_{units}(Annualized\ CAPEX + Annual\ OPEX) - \left(\sum_{units} REV - REV_i\right)}{M_i} \tag{1}$$

where LVC is the Levelized cost of the ith product in the plant (€/Ton or €/m^3), CAPEX is the capital cost of each unit/technology within the plant (€/year), OPEX is the operating cost of the unit (€/year), REV is the revenue from the ith product of the unit/technology (€/year) and M is the annual production rate of the interested ith product (Ton/h or m^3/h).

3.3. Calculation method 2: economic allocation approach

The Economic allocation method suggests the consideration of the by-products as the main products and the distribution of the cost based on their economic value. In the context of integrated desalination and brine treatment plants that prioritize resource recovery, the emphasis shifts from brine minimization to the recovery of valuable, high-quality products. In this case, each unit or technology essentially functions as a

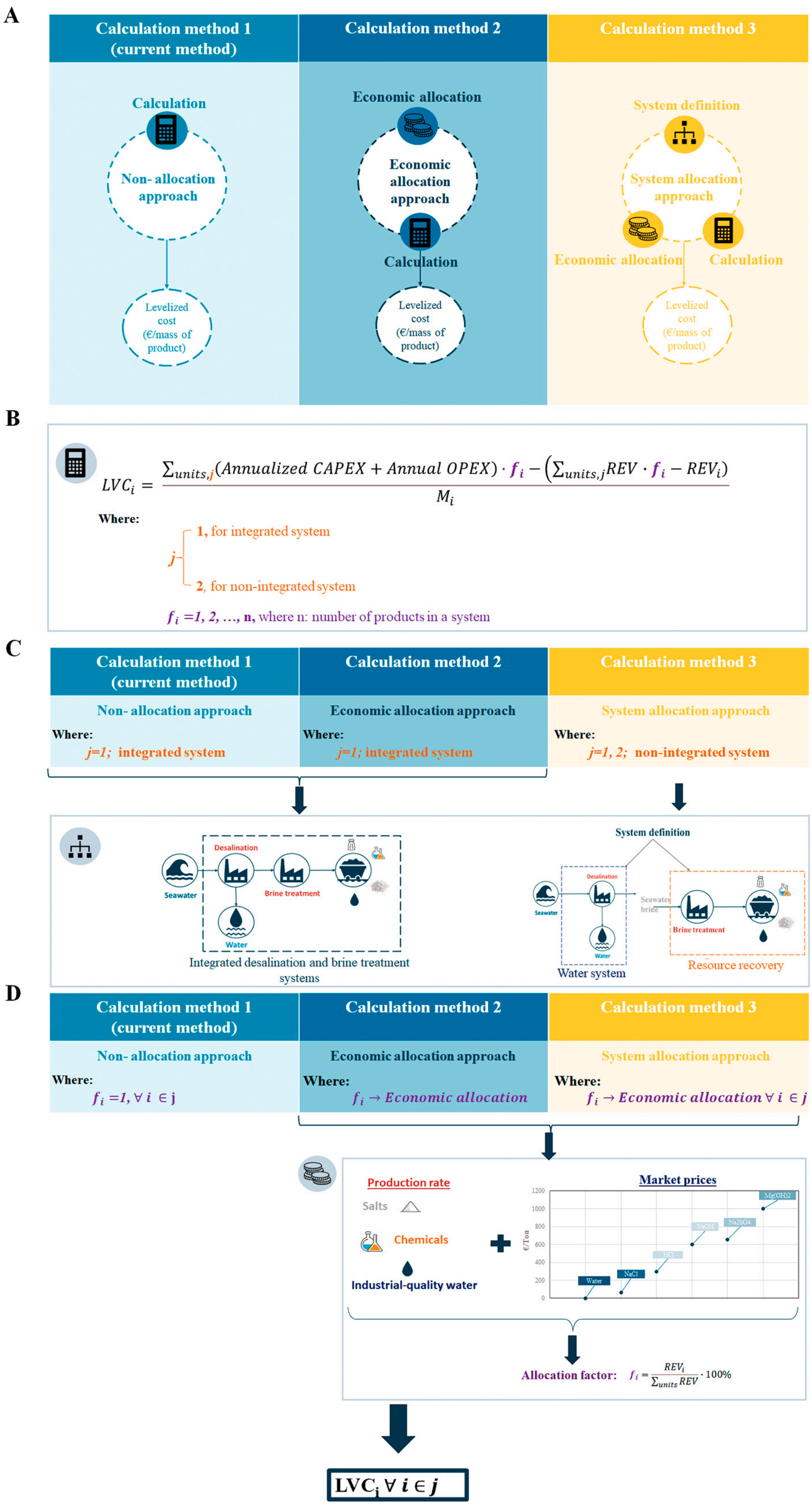


Fig. 2. Schematic diagram illustrating the methodology for calculating the levelized cost of products using three different calculation methods: Non-allocation, Economic allocation, and Dual allocation. (A) Overview of the three methodological approaches, including data and technical configurations inform the calculations; (B) Overview of the methodological approach adopted in this study for the calculation of the levelized cost of each product; (C) The methodological approach for system definition in Dual allocation approach: water system and resource recovery system; (D) Overview of the methodological approach adopted in this study for the calculation of the allocation factors, including production rates, market prices and the annual revenues of the products.

Table 1
Main inputs and outputs of the economic model for the economic assessment of the technical scenarios.

	Input	Output
Economic model	Equipment cost	Capital cost (CAPEX)
	Product mass flow rates	Operating cost (OPEX)
	Quality of products	Revenues
	Energy consumption	
	Chemical consumption	
	Cooling water requirements	

Table 2
Summary of the annual production rate of each product across the three technical scenarios.

Product	Scenario 1	Scenario 2	Scenario 3
Water (m^3/year)	8.82E+05	9.73E+05	3.70E+05
NaCl (Ton/year)	2.69E+04	2.32E+04	N/A
$Mg(OH)_2$ (Ton/year)	N/A	2.55E+03	2.55E+03
Na_2SO_4 (Ton/year)	N/A	2.91E+03	N/A
NaOH (Ton/year)	N/A	N/A	8.49E+03
HCl (Ton/year)	N/A	1.63E+03	1.15E+04

'pre-treatment' for the subsequent one. Consequently, capital and operating expenses, as well as revenues, need to be fairly distributed among all products in a multi-product plant (multi-functional system). This cost allocation is essential to avoid arbitrary distribution, which could misrepresent the economic value of individual products. To handle multi-functionality, Economic allocation is employed according to the life cycle assessment ISO standard [23,27] and life cycle costing [28], allocating a higher cost (or impact) to products generating the highest revenues. By considering the economic value of each product, this method ensures a rational and fair distribution of costs, aligning with the plant's overall objective—whether it prioritizes brine minimization or resource recovery.

Accordingly, the Economic allocation method used in this work considers the contribution of the products in the calculation, as is shown in Eq. (2). In particular, Economic allocation is considered for the distribution of the entire plant's annualized costs and revenues.

$$LVC_i = \frac{\sum_{units}(Annualized\ CAPEX + Annual\ OPEX) \bullet f_i - \left(\sum_{units} REV \bullet f_i - REV_i\right)}{M_i} \tag{2}$$

where f_i is the economic allocation factor of the ith product, representing the proportion of costs allocated to the ith product. The economic allocation factor is calculated based on the economic value of the products (see Supplementary Information, Table S.3) and, therefore, the revenues associated with that product (see results in Table 3).

The economic allocation factor of the ith product (f_i) is calculated:

$$f_i = \frac{REV_i}{\sum_{units} REV} \bullet 100\% \tag{3}$$

The revenues associated with selling a specific product is calculated as follows:

$$REV_i = M_i \bullet t_{operation} \bullet SP_i \tag{4}$$

where REV is the revenue from the ith product of the unit/technology (€/year), M is the annual production rate of the interested ith product (Ton/h or m^3/h), $t_{operation}$ is the total operation time in one year (in hr), and SP_i is the selling price of the ith product (in €/Ton or €/ m^3).

3.4. Calculation method 3: dual allocation approach

Inspired by the industrial symbiosis concept, defined as the collective approach to competitive advantage through the exchange of materials, energy, water, and by-products among traditionally separate entities [29], the Dual allocation method suggests the division of the treatment chain into distinct sub-systems: the water recovery sub-system and the resource recovery (or brine mining) sub-system. By applying this concept to the proposed desalination and brine treatment plant, the Dual allocation method lays the groundwork for potential separation in the future, emphasizing adaptability, resource efficiency, and the achievement of competitive advantages through symbiotic relationships between water and resource recovery systems. The resource recovery subsystem will operate as a stand-alone plant, using desalination brine as feedstock.

By distinctly accounting for water and resource recovery processes, the method ensures that each is evaluated on its economic merits independently, which allows for more context-specific cost distribution. This distinction is crucial for fair comparisons with conventional production systems and significantly influences decision-making, particularly regarding water pricing. Unlike the Economic allocation method, which can inflate water costs by factoring in brine treatment expenses, the Dual allocation method isolates these costs, preventing distortions. For example, the additional expenses of brine treatment or product recovery can affect the final price of water. As water is the primary objective of the proposed systems, distinguishing between water recovery and resource recovery ensures a transparent, unbiased comparison in economic assessments.

According to the above principles and building upon the Economic allocation method, the Dual allocation method first separates the annualized costs and revenues into distinct sub-systems. The division of the treatment chain into the water recovery and resource recovery subsystems is not predetermined; rather, it depends on the unique characteristics of each case study. For the calculation of the products in the water recovery sub-system, only the Annualized CAPEX and OPEX of the technologies in that sub-system are considered. Similarly, for the revenues of the additional products in that sub-system. Then, the economic allocation factor is applied, as in calculation method 2 (see Section 3.3).

$$LVC_i = \frac{\sum_{units,j}(Annualized\ CAPEX + Annual\ OPEX) \bullet f_i - \left(\sum_{units,j} REV \bullet f_i - REV_i\right)}{M_i} \tag{5}$$

where j is the number of the sub-system (water or resource recovery systems), and f_i is the economic allocation factor of the ith product. In

Table 3
Economic allocation factors for Scenarios 1, 2 and 3, based on revenues used in the second calculation method.

Product	Revenues (€/year)			Economic allocation (%)		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Water	8.82E+05	9.73E+05	3.70E+05	33.21 %	13.01 %	3.11 %
NaCl	1.77E+06	1.53E+06	N/A	66.79 %	20.51 %	N/A
$Mg(OH)_2$	N/A	2.55E+06	2.55E+06	N/A	34.16 %	21.52 %
Na_2SO_4	N/A	1.90E+06	N/A	N/A	25.38 %	N/A
NaOH	N/A	0.00E+00	5.30E+06	N/A	0.00 %	44.66 %
HCl	N/A	5.19E+05	3.64E+06	N/A	6.94 %	30.71 %

cases like the water recovery sub-system, where only water is produced, cost allocation becomes straightforward, as all costs are attributed solely to water production. This simplicity contrasts with more complex systems that require careful allocation of shared costs among multiple products (resource recovery system). The economic allocation factor is calculated based on the revenues associated with that product using Eq. (3) (see results in Table 4).

In this work, the economic value of the concentrate streams (brine) is assumed to be zero. This assumption is made because, at this stage, brine is considered waste with no current economic value. Brine is considered as by-product that can be used as a feedstock in a separate brine treatment plant for resource recovery. The potential economic costs of purchasing this feedstock should be considered in the operating costs of the plant. Additionally, in this particular approach, the water system does not include any treatment or handling of the brine. This ensures that the costs associated with handling and treating the brine are not included in the final cost of water, maintaining the independence between the water recovery and brine treatment systems. This approach aligns with the industrial symbiosis concept, where waste from one process becomes input for another, promoting resource efficiency and economic viability.

4. Results and discussion

4.1. *Levelized cost: results and implications*

The analysis of levelized costs across different scenarios reveals key insights into the impact of cost calculation methods. Fig. 3 provides a comprehensive overview of the levelized cost of key products across different technical scenarios using three different calculation methods. The results are compared with constant market prices for each product, which serve as reference values for assessing economic feasibility. These reference values differ for each product to reflect their specific market conditions. The results indicate significant variation in levelized costs within the same scenario depending on the calculation method applied. For example, the levelized cost of water varies significantly when desalination and resource recovery systems are separated (calculation method 3: Dual allocation approach), especially in Scenarios 1 and 2, when the water production process consists of multiple technologies. Note that in the Dual allocation approach, the price of water comes from the water system, while the prices of other products come from the resource recovery system. Water from the resource recovery system is not included in this comparison and analysis of the results.

The Economic allocation approach significantly reduces LVCs compared to the Non-allocation approach. For water, the reduction is particularly notable—57 % in Scenario 1, 41 % in Scenario 2, and 84 % in Scenario 3. Sodium chloride (NaCl) costs also see substantial decreases of 25 % and 28 % in Scenarios 1 and 2, respectively. These reductions have important implications for plant design and the implementation of circular economy principles. The Dual allocation approach further reduces NaCl costs by 60 % and 63 % in Scenarios 1 and 2, respectively, suggesting that separating resource recovery from desalination enhances market competitiveness. Overall, Fig. 3 reveals that the Non-allocation approach generally results in the highest levelized costs, while the Dual allocation approach, in most cases, achieves the lowest costs for recovered salts and chemicals. This cost distribution based on product value enhances competitiveness with conventional production systems.

Comparing the LVC of the key products using the three calculation methods with the reference market prices, Economic allocation results in competitive prices in Scenario 2 (12 %–18 % higher than reference), while the Dual allocation approach results in even more competitive prices for salts and chemicals (39–42 % lower than reference price). Scenario 1 shows no competitive results across any methods, while Scenario 3 sees the Economic allocation method as being more competitive for water production, with both novel methods performing similarly for other products compared to market prices. Although total annual costs are theoretically constant across all methods, the Non-allocation approach tends to overestimate them. This reduction in LVCs, particularly in high-value products like NaCl, enhances market competitiveness and could significantly influence investment decisions and the overall economic feasibility of integrated desalination and brine treatment plants.

To effectively interpret the results of levelized cost calculations (Fig. 3), decision-makers must examine the costs for different products in combination. This holistic approach provides a more nuanced understanding of how changes in the levelized cost of one product may influence other products within the same scenario. Detailed results for each scenario and product can be found in the Supplementary Information (see Sections S4 and S5).

Fig. 4 presents the total annual revenues for each scenario, using the levelized cost of the products calculated from the three different methods as the selling price. These revenues are compared with those from selling products at market prices (reference bar). The Non-allocation method yields significantly higher revenues in Scenarios 1 and 3 due to the higher levelized cost of products calculated by this method (see Fig. 3). However, lower revenues using the LVC as a selling price do not necessarily mean lower overall profitability. The LVC represents the breakeven price. If the selling price exceeds the LVC, it results in higher revenues. Thus, a lower LVC indicates greater competitiveness with conventional production methods and more potential for profit. Conversely, when the LVC is much higher than the market price, the potential for additional profit is limited. This also supports the hypothesis that separating the resource recovery system from the desalination plant enhances competitiveness in the market.

To understand why the Non-allocation approach generally results in the highest LVC and provide a detailed comparison of the total annual production costs calculated using the two different methods (Non-allocation and Economic allocation), Fig. 5 illustrates the breakdown of costs per product and for the entire plant in Scenario 2. Fig. 5A clearly demonstrates that the Non-allocation approach results in an overestimated total annual production cost of 3.45 M€/year because it applies fixed annual costs (CAPEX and OPEX) uniformly across all products, only adjusting revenues of the by-products. Under the Non-allocation method, the first term in the LVC calculation remains the

Table 4

Economic allocation factors for Scenarios 1, 2 and 3 based on revenues used in the third calculation method for resource recovery sub-systems.

Product	Revenues (€/year)			Economic allocation (%)		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Water system						
Water	5.53E+05	8.24E+05	3.70E+05	100 %	100 %	100 %
Resource recovery						
Water	3.29E+05	1.49E+05	N/A	15.63 %	2.24 %	N/A
NaCl	1.77E+06	1.53E+06	N/A	84.37 %	23.05 %	N/A
$Mg(OH)_2$	N/A	2.55E+06	2.55E+06	N/A	38.39 %	22.21 %
Na_2SO_4	N/A	1.15E+06	N/A	N/A	28.53 %	N/A
NaOH	N/A	0.00E+00	5.30E+06	N/A	0.00 %	46.10 %
HCl	N/A	1.09E+06	3.64E+06	N/A	7.80 %	31.69 %

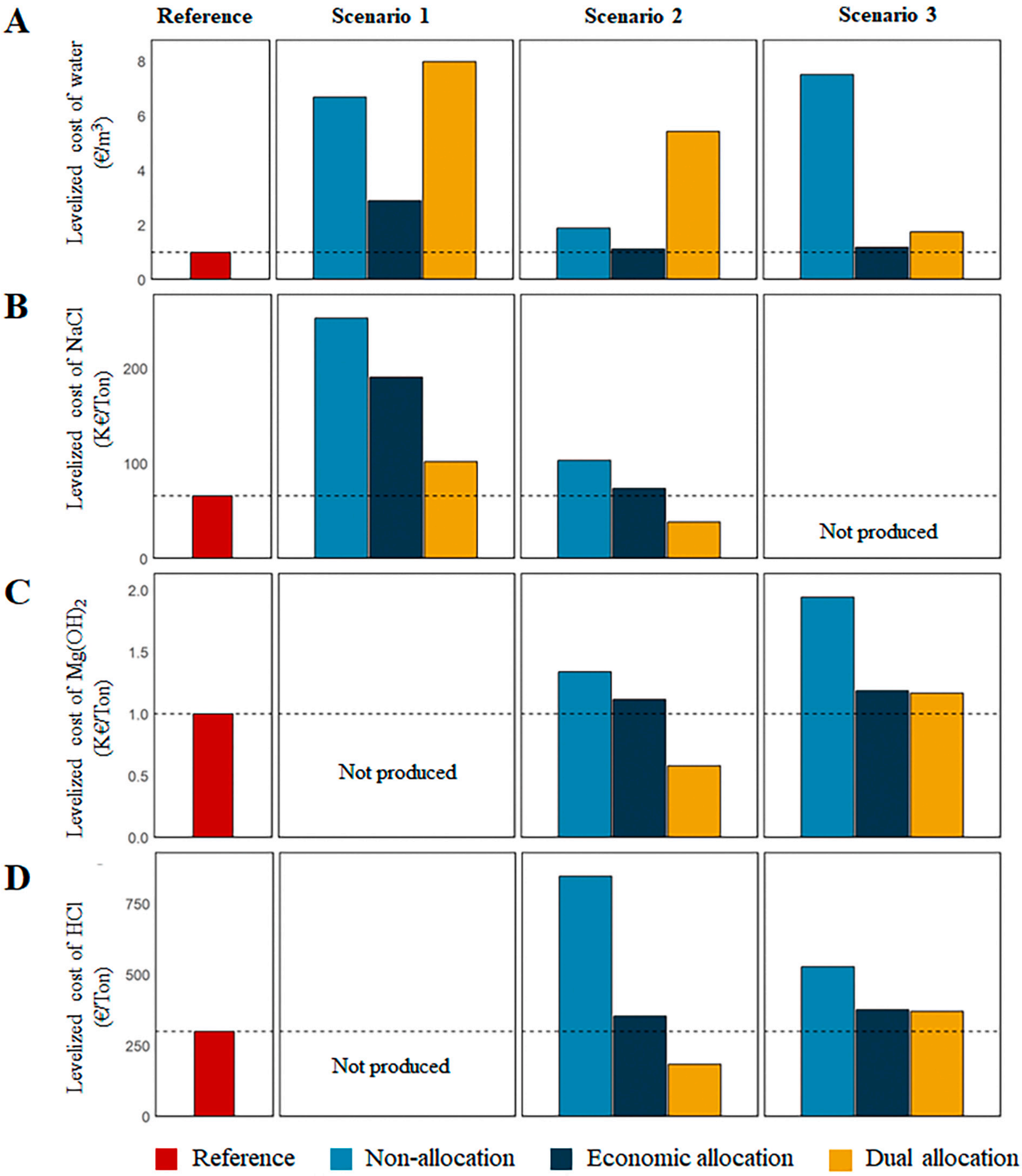


Fig. 3. Levelized cost of selected products (A) Water, (B) Sodium Chloride (NaCl) (C) Magnesium Hydroxide ($Mg(OH)_2$), and (D) Hydrochloric acid (HCl) using the three different calculation methods for each scenario. The Red bar denotes the specific cost of each product from the literature that is used as a reference for a comparison with the conventional systems. The Turquoise denotes the Levelized cost of each product using the Non-allocation approach. The dark teal denotes the Levelized cost of each product using the economic allocation approach. The yellow denotes the Levelized cost of each product using the Dual allocation approach.

same for all products, leading to a significant multiplication of total annual costs. This leads to an inflated overall production cost and, therefore, higher levelized costs for each product. In contrast, Fig. 5B illustrates how the Economic allocation approach distributes costs more proportionally based on the revenues coming from each product. This method avoids the overestimation seen in the Non-allocation approach by using allocation factors that ensure the cost assessment reflects the true economic contributions of each product. The allocation factor corrects the overestimation by aligning the total production costs with the revenues of the products; the numerator in the levelized cost equation reflects the actual production cost. Detailed results for the other two scenarios can be found in the Supplementary Information (see Section S5, Figs. S.3, S.4).

Fig. 6 further examines the impact of the calculation methods on the Levelized Cost of Water. Fig. 6A illustrates how the total annual costs of water, and thus the LVC, vary depending on the calculation method, with the corresponding specific €/m^3 values clearly labeled. The Economic allocation method achieves an 81 % reduction in the annual costs of water compared to the traditional Non-allocation method. This reduction results from reallocating costs to higher-value products and

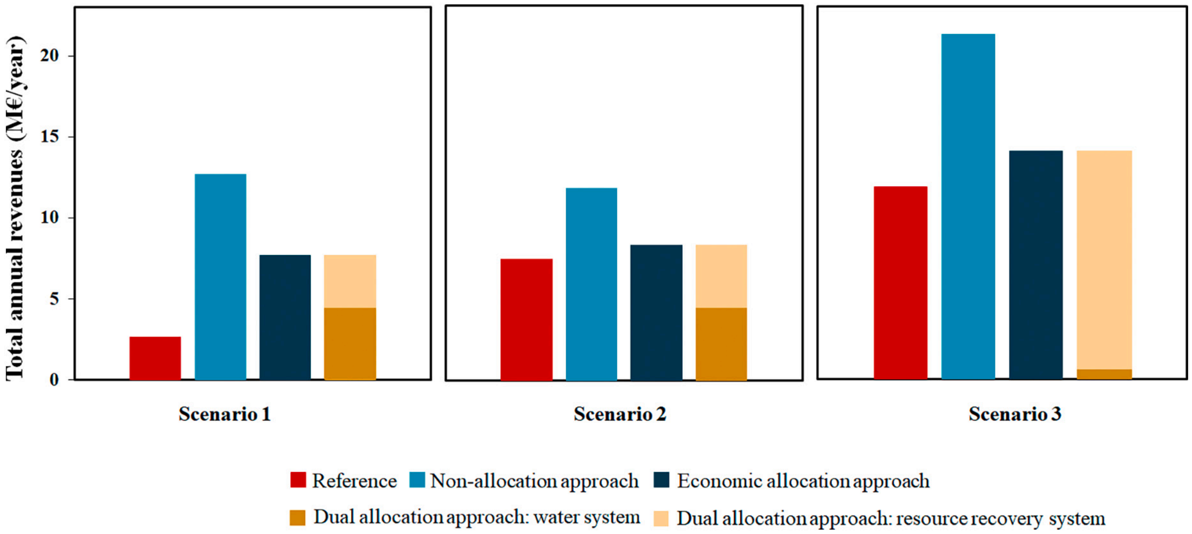


Fig. 4. Total annual revenues for each technical scenario from selling products using their levelized costs as a selling price. The red bar (reference) represents the revenues from selling products using the market price of each product.

avoiding overpricing. In this context, overpricing refers to an artificially higher value assigned to a product due to disproportionately loading costs onto it beyond its actual production cost. This overpricing effect is evident when comparing the significant difference between the annual costs in Fig. 6A and the revenues from selling water at the LVC in Fig. 6B. In contrast, the other two methods (Economic allocation and Dual allocation approaches) show better alignment between costs and revenues (see specific €/m^3 values), indicating that the LVC is accurately calculated to achieve break-even. This alignment suggests that any increase in the selling price beyond the LVC will directly enhance profitability, validating the effectiveness of Economic allocation in reflecting the true economic potential of water production. The detailed results for each product across the three calculation methods are provided in Supplementary Information (see Section S5, Tables S.11-S.13).

Fig. 7 shows how the annual production costs (sum of annualized CAPEX and OPEX) are distributed across the recovered products in Scenario 2 using the Non-allocation approach (Fig. 7A) and the Economic allocation approach (Fig. 7B). To make this comparison, the Non-allocation approach involves process-level distribution, considering the cost of each unit to produce a specific product. This approach differs from other calculations for Non-allocation in this work (see Figs. 3–6), as it aims to assess the impact of non-allocating the annual production cost based on revenues while maintaining the same annual production costs (without overestimation). Breaking down the annual production cost using the Non-allocation approach shows that 67 % of costs are loaded on water due to its large production rate. In contrast, the Economic allocation method distributes costs more equitably among products with higher market value, assigning only 13 % to water. This highlights a major drawback of the traditional Non-allocation method: it tends to overprice the main product, water, by uniformly applying fixed costs across all products. Detailed results for the other two scenarios can be found in the Supplementary Information (see Section S5, Figs. S.1, S.2).

4.2. Sensitivity analysis

A sensitivity analysis is performed to evaluate the effect of product market prices (see Section 4.2.1) and operating costs (see Section 4.2.2) on the calculation of the levelized cost of products using the three different calculation methods.

4.2.1. Effect of water market price

To analyse the effect of water price on the levelized cost of different products in the integrated desalination and brine treatment technical designs, the following water price scenarios were considered:

- **Baseline:** Standard scenario with no change in water market prices (reference value).
- **WMP + 25:** Water market price increased by 25 %.
- **WMP-25:** Water market price decreased by 25 %.

Note that in this context, *water market price* refers to the regulated baseline cost of water production. This analysis examines how changes in production costs affect the economic viability of resource recovery.

Fig. 8 provides an overview of the sensitivity of the levelized cost of key products across various scenarios and the three calculation methods in response to changes in water market price (+ or - 25 %). It also illustrates how these changes impact the levelized cost of water (Fig. 8B) and $Mg(OH)_2$ (Fig. 8C) in Scenarios 2 and 3.

The Non-allocation approach shows a consistent response to changes in water market price across all scenarios. Generally, the levelized cost of water increases or decreases proportionally to price fluctuations, reflecting the method's straightforward nature. Changes in the price of water have a uniform influence on the cost of products across different scenarios, with Scenario 2 having the most widespread impact.

The Economic allocation method is highly sensitive to changes in water market price, especially in scenarios with high external water usage and low water production, like Scenario 3. A 25 % price change leads to a 26 % fluctuation in the levelized cost of water in Scenario 3. Scenario 2 shows a 22 % increase in LVC with a 25 % WMP rise and a 23 % decrease with a 25 % reduction. This pattern is consistent across products, though the magnitude of change varies depending on the allocation factors and the proportion of water usage. The greater sensitivity in this method highlights how water prices directly impact cost distribution, particularly in more complex or water-intensive scenarios.

The Dual allocation approach provides a contrast between the water and the resource recovery systems. The water system remains stable across all scenarios, unaffected by water market price changes due to the absence of water consumption and by-products. In contrast, the resource recovery system is highly sensitive to water market price changes. In Scenario 2, a 25 % increase in WMP leads to a 27 % rise in the levelized cost of water, while a similar decrease causes a 26 % reduction. This method's stability in the water system, coupled with sensitivity in the resource recovery system, highlights the advantage of separating the integrated systems into the water system and resource recovery system, as it allows for more precise cost management and less volatility in the

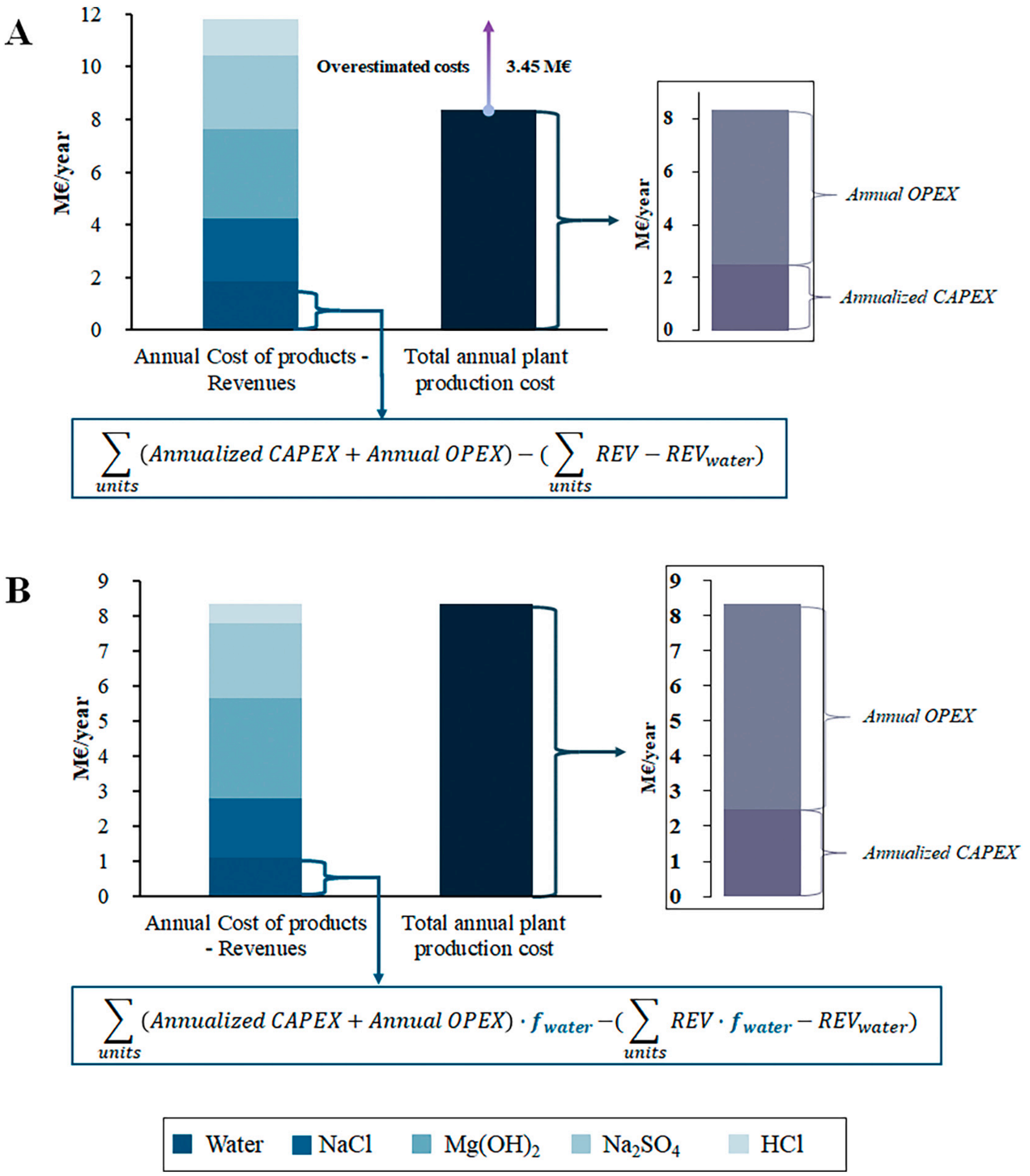


Fig. 5. Comparison of total annual production costs calculations per product and for the entire plant in Scenario 2 using two different calculation methods: (A) Non-allocation approach and (B) Economic allocation approach. The small bar charts on the right side of each subfigure illustrate the breakdown of the Annualized CAPEX and Annual OPEX contributing to the total annual plant production cost.

overall LVC.

In Scenarios 2 and 3, the LVC of water (see Fig. 8B) under the Non-allocation approach shows limited sensitivity to WMP changes, with increases of 4 % and 9 %, respectively, for a 25 % increase and corresponding decreases for a 25 % WMP reduction. This uniform response occurs because water price affects both the annual production costs and revenues, leading to a proportional change in LVC across these scenarios. Scenario 3 is slightly more sensitive due to its higher water consumption and, thus, higher operating costs. The Economic allocation approach is more sensitive in both scenarios, with LVC changes of ±22 % in Scenario 2 and ± 26 % in Scenario 3. The Dual allocation approach shows stability in the water system component of both scenarios, with no impact from WMP fluctuations due to the absence of direct water usage and by-products affecting revenues. However, in the resource recovery system, Scenario 2 shows a ± 27 % increase or decrease in LVC of water with a 25 % change in WMP, highlighting the critical role of water price in cost distribution.

For $Mg(OH)_2$ (see Fig. 8C), the Non-allocation approach shows low sensitivity to WMP changes, with LVC variations of ±5 % in Scenario 2 and ± 3 % in Scenario 3. This is because water price has a minimal effect on the overall production cost of $Mg(OH)_2$ in these scenarios. The Economic allocation method similarly shows low sensitivity, with only ±2 % LVC change due to higher allocation factors for $Mg(OH)_2$. The Dual allocation approach also demonstrates limited sensitivity for $Mg(OH)_2$, particularly in Scenario 2, where LVC change is aligned with changes in annual production costs. The small difference in allocation factors of water and $Mg(OH)_2$ compared to the baseline water price scenario ensures that water market price fluctuations have a minimal effect on $Mg(OH)_2$ LVC, maintaining a stable cost structure.

Overall, the water price sensitivity mainly affects more complex systems with significant water usage. Non-allocation approach, while straightforward, may oversimplify the impacts, whereas the Economic allocation method captures these effects in more detail but at the cost of greater variability. The Dual allocation approach provides more stability

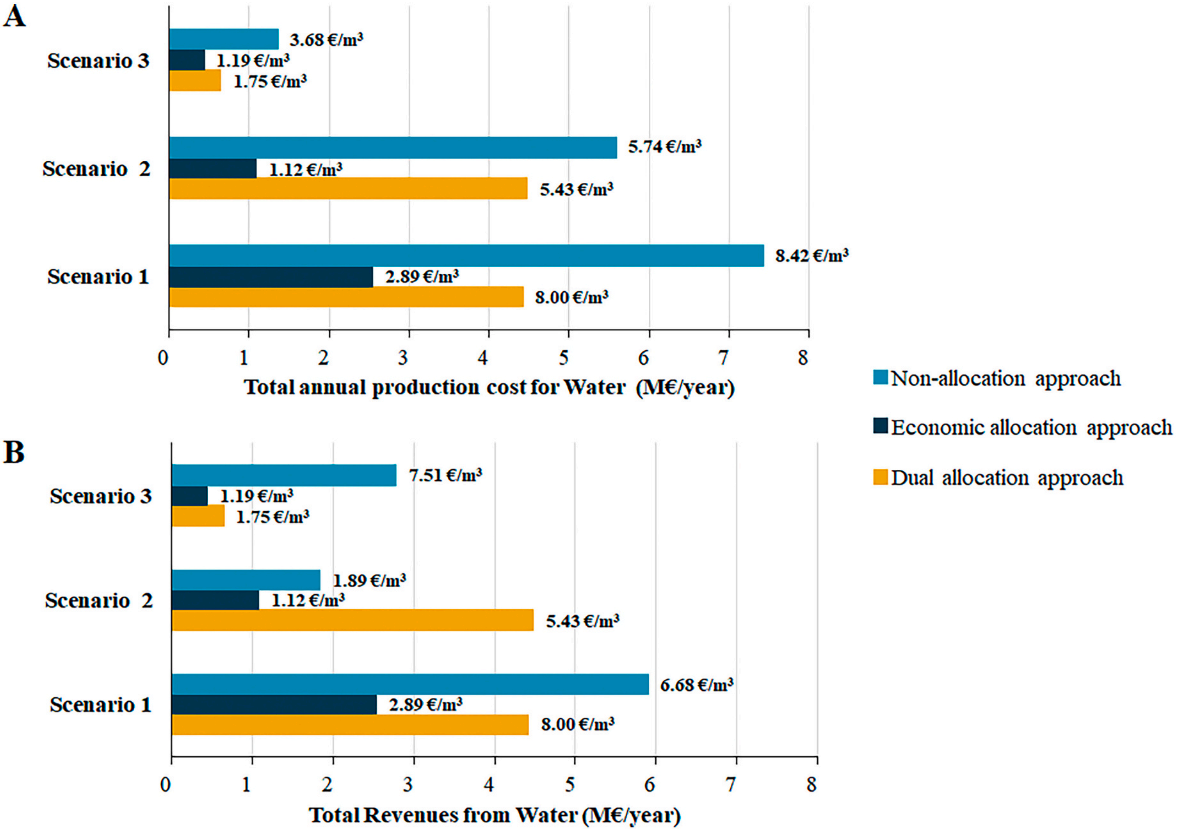


Fig. 6. (A) The total annual cost for water production using the three calculation methods, with specific €/m^3 values shown for each method. (B) Annual revenues from selling water at a levelized cost price using the three calculation methods with specific €/m^3 values shown for each method.

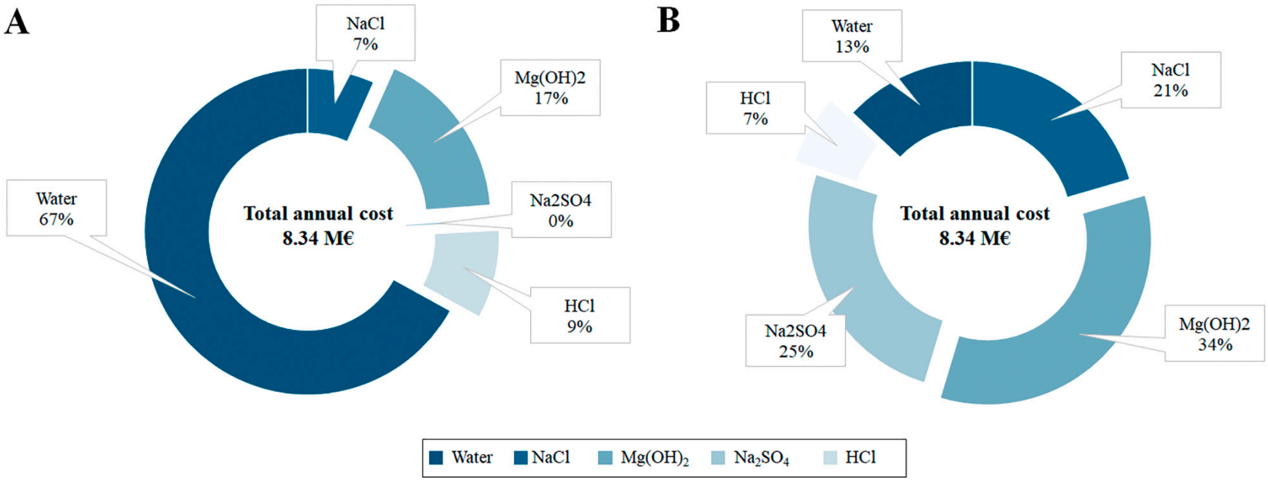


Fig. 7. Distribution of total annual production cost for scenario 2 using two different calculation methods: (A) Non-allocation approach, (B) Economic allocation approach.

in cost distribution by isolating the water system from resource recovery processes. Detailed results for all products are given in Supplementary Information (see Section S7).

4.2.2. Effect of electricity (operating) costs

To analyse the effect of electricity price on the levelized cost of different products in the integrated desalination and brine treatment technical designs, the following electricity price scenarios were considered:

- **Baseline**: Standard scenario with no change in electricity market prices (reference value).
- **EMP-25:** Electricity Market Price decreased by 25 %.
- **EMP + 25:** Electricity Market Price increased by 25 %.

Fig. 9 provides an overview of the sensitivity of the levelized cost of key products across various scenarios and the three calculation methods in response to changes in water market price (+ or − 25 %). It also illustrates how these changes impact the levelized cost of water (Fig. 9B) and $Mg(OH)_2$ (Fig. 9C) in Scenarios 2 and 3.

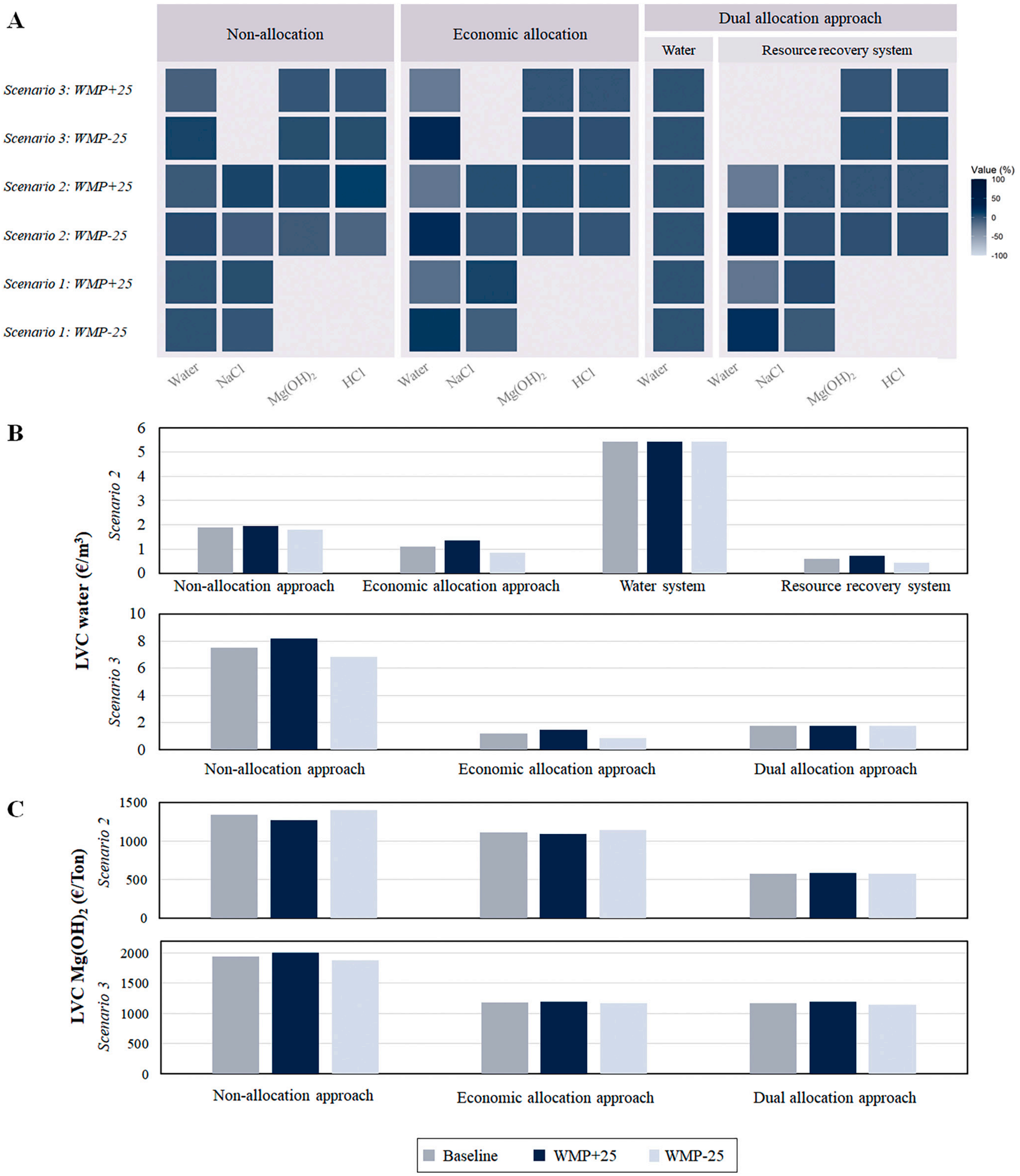


Fig. 8. Impact of water price variations on the Levelized Cost of key products across different scenarios and calculation methods: (A) The heatmap illustrates the percentage change in the Levelized Cost of water and other recovered products under two different water price scenarios (WMP + 25, WMP-25) and three calculation methods: Non-allocation, Economic Allocation, and Dual allocation approach. Darker and lighter shades indicate a higher percentage change (positive or negative), highlighting the sensitivity of specific products and methods to water price fluctuations. Each column represents a different product, and the rows correspond to the specific scenario and price variation. (B) Bar charts illustrate the change in the Levelized Cost of Water in Scenarios 2 and 3 under varying water prices. (C) Bar charts illustrate the change in the Levelized Cost of $Mg(OH)_2$ in Scenarios 2 and 3 under varying water prices.

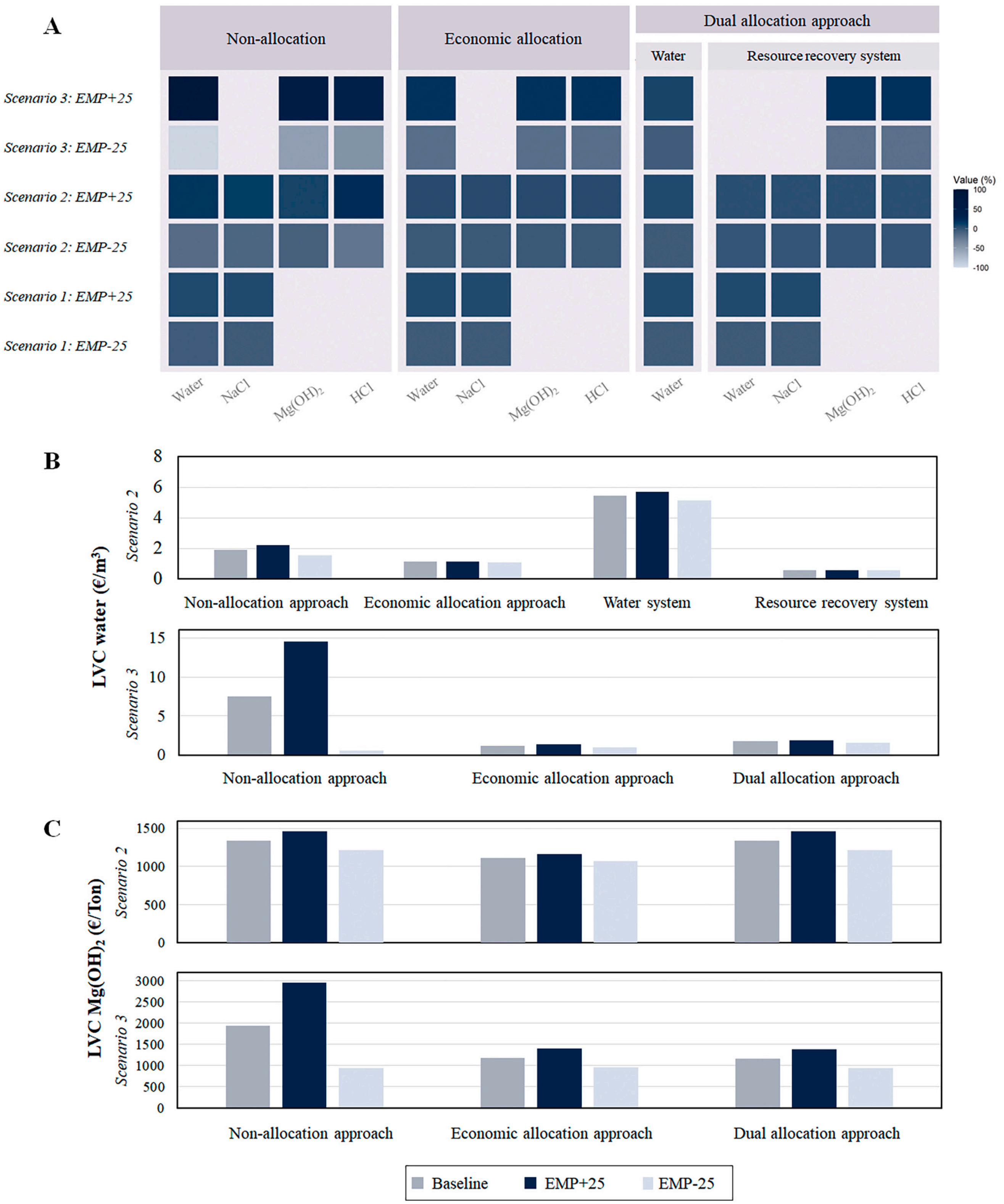


Fig. 9. Impact of electricity price variations on the Levelized Cost of key products across different scenarios and calculation methods: (A) Heatmap displaying the percentage change in the Levelized Cost of water and other recovered products under two electricity price scenarios (EMP + 25 and EMP-25) across three calculation methods: Non-allocation, Economic Allocation, and Dual allocation approach. Darker shades indicate greater sensitivity to electricity price fluctuations, with each column representing a different product and each row corresponding to a specific scenario and price variation. (B) Bar charts illustrate the change in the Levelized Cost of water in Scenarios 2 and 3 under varying electricity prices. (C) Bar charts illustrate the change in the Levelized Cost of $Mg(OH)_2$ in Scenarios 2 and 3 under the same conditions.

The Non-allocation method (current method) is the most sensitive to electricity price changes, particularly in Scenario 3. A 25 % change in electricity market price (EMP) increase results in a 17 % increase in LVC of water for Scenario 2, while Scenario 3 experiences a dramatic 93 % increase, reflecting its heavy reliance on electricity (see Fig. 9B). This high sensitivity reveals the instability of the Non-allocation method in energy-dependent scenarios like Scenario 3.

In contrast, the Economic allocation method shows more balanced responses to electricity price variations, mitigating the impact of electricity price changes by distributing costs based on the economic value and revenue of each product. Since the allocation factors and revenues remain constant across the sensitivity analysis, the variation in the levelized cost of products is directly aligned with changes in operating costs alone. Scenario 2's LVC of water rises by 4 % with a 25 % EMP increase, while Scenario 3's LVC of water increases by 18 %. This approach provides more stable and predictable cost estimates, particularly in energy-intensive scenarios like Scenario 3.

The Dual allocation approach shows the least sensitivity to EMP changes. In Scenarios 2 and 3, water system LVC changes are limited to ±5 % and ± 7 %, respectively, with a 25 % EMP variation, demonstrating resilience to price fluctuations. These changes directly relate to the annual operating cost fluctuations because the water system calculations remain unaffected by other variables, such as allocation factors or revenues from by-products. In the resource recovery system, the LVC of water shows moderate sensitivity to EMP changes, with a ± 2 % change in Scenario 2 reflecting a more stable response due to the balanced distribution of costs and revenues. Scenario 3, being more energy-intensive, exhibits a greater sensitivity with a ± 19 % change in LVC, indicating the significant impact of EMP fluctuations in scenarios with higher energy demands. Scenario 1 is the least affected by EMP variations, with modest fluctuations (5–6 %), indicating a stable cost structure.

For $Mg(OH)_2$ (Fig. 9C), Scenario 3 shows a 52 % LVC increase under the Non-allocation method with a 25 % EMP rise, while the Economic and Dual allocation methods limit this to ±18 % and ± 19 %, respectively. Scenario 2 shows moderate sensitivity, with LVC increasing by 9 % (with a 25 % rise in EMP) under the Non-allocation method, while the Economic allocation and Dual allocation approaches provide more stable responses (±4 % and ± 2 %, respectively). Scenario 2's inclusion of more products highlights the effectiveness of these novel methods in mitigating the impact of energy price variations.

Overall, the Economic and Dual allocation methods provide more reliable and stable cost estimates, particularly for high-revenue products like $Mg(OH)_2$, making them preferable for scenarios sensitive to electricity price fluctuations. Detailed results for all products are given in Supplementary Information (see Section S7).

4.3. Discussion and reflection on the different calculation methods

Desalination plants traditionally prioritize water production, especially in water-scarce regions where they are typically constructed [8]. However, as s seawater brines are increasingly seen as valuable resources rather than waste, the economic evaluation of resource recovery and the consideration of potential revenues from the sale of recovered resources become increasingly critical [30]. This study explores how different cost calculation methods influence the levelized cost of water and other recovered products, offering insights that could significantly impact political and investment decisions related to desalination and resource recovery.

The results underscore the importance of selecting an appropriate cost calculation method in the local social-economic context. This choice directly affects the economic viability of the plant and its competitiveness with conventional salt and chemical production systems. A key finding of this study is the overpricing issue linked to the traditional Non-allocation method. By uniformly applying fixed annual costs (annualized CAPEX and OPEX) across all products, this method overestimates costs. As a result, it inflates the levelized cost of water and other recovered products, making the system less competitive compared to linear systems brine disposal systems [31].

The Economic allocation and Dual allocation approaches introduced in this study address these issues by ensuring a fairer distribution of costs, reflecting the true economic value of each product rather than just the production rate [32]. The Economic allocation method reduces the levelized cost of water by up to 81 % compared to the traditional Non-allocation method. This reduction in water costs can profoundly influence investment decisions and operational strategies [14] and encourage the adoption of technologies that maximize the recovery of high-value by-products, ultimately improving overall plant profitability. The Dual allocation method isolates the water recovery and resource recovery processes, allowing for more accurate cost distribution by ensuring that water costs are not inflated by additional brine treatment steps.

Accurate cost allocation is essential for realistic economic assessments in resource recovery systems, where design choices are driven by local needs, values, and profitability. The critical decision in resource recovery systems is not just about building a desalination plant but determining the extent of resource recovery—whether to focus solely on salt or extend to HCl and $Mg(OH)_2$. This study shows that using fairer cost allocation methods, such as Economic allocation or Dual allocation, supports more informed decisions on economically viable resource recovery. While the traditional approach may work for basic desalination, assessing the full economic potential of seawater, brine valorisation requires choosing the right cost allocation method to justify more extensive recovery systems.

Although Economic allocation is sometimes considered too arbitrary, in multi-product systems, it is often considered the most practical because the market prices reflect the functionality of a material quality [33]. Similar to other resource recovery studies, cost allocation plays a crucial role in achieving fair assessments. As with allocating upstream burdens when waste is treated as a resource [34], or distributing fuel consumption between heat and electricity in cogeneration, careful allocation ensures accurate comparison and efficiency in multi-product systems [35].

Our analysis reveals that the economic feasibility of resource recovery systems can vary significantly depending on the cost calculation method applied. For instance, Scenario 2, which appeared economically unfeasible under the traditional Non-allocation method, becomes viable when the Economic allocation approach is employed. This approach significantly reduces the levelized cost of key products, including water, making the scenario competitive with conventional production methods. When comparing the three scenarios using the different calculation methods, it is clear that Scenario 2 emerges as the most economically feasible under both the Economic allocation and Dual allocation approaches, primarily due to its balanced mix of high-value products and moderate operational costs. Scenario 3, while still competitive, benefits more from the Dual allocation approach, which minimizes costs associated with resource recovery. Scenario 1, however, faces challenges across all methods due to the lower market value of its products.

While both novel methods offer improved cost distribution, they come with challenges. The complexity of the Economic allocation method lies in determining accurate market values for each product, particularly in fluctuating markets. This complexity was evident in the sensitivity analysis, which showed significant variations in the levelized cost of water and other products, with changes in water prices causing up to ±26 % fluctuations and electricity prices causing up to ±18 % fluctuations. These sensitivities highlight the difficulty of maintaining stable cost estimates in systems heavily influenced by market-driven factors. Similar challenges are faced in renewable energy projects, where market price fluctuations for market share can significantly impact economic viability [26].

Integrated systems, such as those involving water and brine treatment, present additional challenges. Defining system boundaries of water and brine treatment systems—as in the Dual allocation approach—can be complex and subjective, leading to potential inconsistencies in cost allocation. This challenge is not unique to resource recovery systems, but it is also observed in other multi-product systems, such as desalination combined with Concentrated Solar Power (CSP) [18]. In such cases, while the Levelized Costs of Water and Electricity are determined separately, the process is more straightforward due to clearer system boundaries and well-established methods. In such cases, thermoeconomic methods apply effectively, using exergy to allocate costs between energy and water. For brine treatment systems that do not produce energy as a co-product, thermoeconomic methods are less applicable, as their exergy-based approach does not align with systems where non-energy resources like salts and chemicals are the primary outputs.

Future research should explore the impact of financial incentives, such as tax breaks or subsidies, on the economic viability of resource recovery systems. Additionally, developing dynamic assessment models to account for fluctuating market conditions, such as variable water and energy prices, could provide more adaptive and accurate economic evaluations, reflecting the variability and risks faced by such projects. As the industry shifts toward viewing brine as a resource rather than waste, economic assessments must evolve to reflect this change, potentially leading to a reassessment of cost allocation strategies.

Although this study employs generalized scenarios to evaluate the proposed cost allocation methods, the methodologies are designed to be adaptable to real-world applications. By incorporating region-specific data—such as local market prices, energy costs, or policy-driven incentives—they can be tailored to address diverse operational and economic conditions. This flexibility ensures their practical relevance in varied contexts, including industrial desalination systems, water-scarce regions, or areas with high demand for specific recovered products.

The proposed calculation methods represent a step forward in addressing the complexities of resource recovery systems, although they may not apply universally. They serve as a pioneering attempt to emphasize the need for objective-oriented and context-specific cost allocation, considering the unique characteristics and economic values of the recovered products. As the first of its kind reported in resource recovery literature, this approach should be viewed as a starting point for future investigations, encouraging the development of more robust methodologies tailored to the complexities of resource recovery.

5. Conclusions

This study contributes to the ongoing discussion on assessing the economic performance of resource recovery plants by introducing two novel calculation methods—the Economic allocation and the Dual allocation approaches. Compared to the Non-allocation method (current practice in literature), the Economic allocation approach significantly reduces water levelized costs by up to 81 % and NaCl costs by up to 28 %, while the Dual allocation approach further reduces NaCl costs by over 60 %. Such reductions highlight the practical benefits of tailored cost methods in supporting circular economy goals and market viability.

The traditional Non-allocation method tends to overestimate production costs (up to 3.45 M€/year) due to uniform cost application, leading to inflated product prices, which emphasizes the need for refined allocation. By redistributing costs to higher-value products, the Economic allocation approach assigns only a minimal percentage to water costs, compared to the heavy loading seen with Non-allocation. This work underscores the ability of the methods to provide a more competitive economic outcome through fair cost distribution. The sensitivity analysis reveals the significant impact of fluctuating water and electricity prices on the levelized costs, emphasizing the necessity of adaptable, context-specific cost methods aligned with individual plant goals. These insights are critical for guiding investment and operational strategies in resource recovery plants, ensuring that decisions are economically sound and aligned with market realities.

While these innovative methods improve decision-making, it is essential to acknowledge potential debates, particularly with the Dual allocation approach. This method raises questions on cost allocation in multi-product systems, thereby serving as a starting point for future studies. Future research should refine these methodologies, address their limitations, and propose alternatives. The aim is not to establish a fixed calculation approach but to inspire critical thinking and develop robust methodologies for resource recovery in multi-product settings.

Acronyms

CAPEX	capital cost
LCW	levelized cost of water
LVC	levelized cost
OPEX	operating cost
RO	reverse osmosis
TCr	thermal crystallizer
ZLD	zero liquid discharge

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.desal.2024.118475.

Data availability

No data was used for the research described in the article.

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