CIE 5050-09 Additional Graduation Work, Research Project

Economic and cost-effectiveness analysis of integrated desalination and brine treatment systems

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Oct 7th, 2022

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Abstract

The brine generated from desalination is a threat to the environment, and its disposal has been a great challenge. A new concept Zero liquid discharge (ZLD) can minimize the environmental impact of brine. However, the high costs for construction and running of a ZLD plant limits its growth in desalination market. Therefore, a new strategy integrating brine mining with desalination is proposed to improve its economic performance due to the valuable minerals in brine. A cost-effectiveness analysis (CEA) is carried out to assess its economic performance and compare this strategy with other ZLD strategies. The results present that the cost-effectiveness of the studied strategy is lower than ZLD systems which only maximize water recovery. The cost-effectiveness ratio of the studied strategy is 0.056€/kg of freshwater, higher than ZLD maximizing water recovery (0.032€/kg of freshwater). However, its profitability is higher than other ZLD schemes. This study shows that the integrated desalination and brine mining strategy has a great economic potential. Its cost-benefit of is 1.12, far lower than that of ZLD only maximizing water recovery (26.08). In addition, it can be indicated that CEA is not comprehensive enough to assess the economic performance of a multi-product desalination system. It doesn’t include the revenues from by-products, which are an important part of the studied strategy. For further research, a more integrated approach of economic analysis is needed to make a decision on the different alternatives of desalination.

Keywords: Zero Liquid Discharge; Cost-effectiveness analysis; desalination; brine mining.

Nomenclature			
		n	Plant lifetime. year
		Ce	Energy cost. €/year
Acronyms		C_{el}	Electrical energy cost. €/year
		C_{th}	Thermal energy cost. €/year
BCr	Brine Crystallizer	E_{el}	Electrical energy consumption. kWh/hour
CBA	Cost-benefit Analysis	E_{th}	Thermal energy consumption. kWh/hour
CEA	Cost-effectiveness Analysis	$t_{operation}$	total operation time every year. Hour/year
EDBM	Bi-Polar Membrane Electro-Dialysis	P_{el}	Electricity price. €/kWh
EFC	Eutectic Freeze Crystallizer	P_{steam}	Steam price. €/kWh
LCC	Life Cycle Costing	R_t	Revenue of year t. €
MED	Multi-Effect Distillation	C_t	Operating cost of year t. €
MF-PFR	Multiple Feed-Plug Flow Reactor	I_0	Initial investment. €
NF	Nano-filtration	$M_{i,t}$	Amount of product i produced in the year t. kg
PoMs	Program of measures	REV	Annual revenue of each unit. €/year
RO	Reverse Osmosis	REV_i	Annual revenue of product i. €/year
ZLD	Zero Liquid Discharge	LPC_i	Levelized Product Cost of product i. €/kg
		CAPEX	Capital expenditure. €
Parameters		CER	Cost-effectiveness ratio. €/kg
f_a	Inflation rate. %	LCOW	Levelized Cost of Water. €/m^3
m	Scaling factor	LPC	Levelized Product Cost . €/kg
α	Amortization factor	NPV	Net Present Value. €
i	Discount rate. %	OPEX	Operating expenditure. €

1. Introduction

Desalination is an incremental technology for achieving water recovery. It recovers fresh water from seawater or brackish water by removing dissolved salts (Panagopoulos, 2020), and is widely used from 21st century to address the global water scarcity (Panagopoulos et al., 2019). Although desalination greatly improves the use of the water source on the earth, its main by-product brine might be a challenge to the environment. Brine is a hyper-saline solution in desalination (Pramanik et al., 2017). It contains salts from seawater, various chemicals and microbial contaminants from desalination treatment and transport, which would result in negative impact on environment. Different brine disposal methods have been developed to meet the requirement of desalination, these methods include surface water discharge, sewer discharge, deep-well injection, evaporation ponds and land application (Panagopoulos et al., 2019). However, these conventional brine disposal methods are considered unsustainable due to the environmental, physical, and cost constraints.

1.1 Zero Liquid Discharge

As the long-term environmental impact of brine disposal is getting global concern, regulations for brine disposal are getting stricter and it can be expected that several conventional brine disposal methods would be restricted in the future (Abualtayef et al., 2016; Jenkins et al., 2012; Tong & Elimelech, 2016). Researchers have studied extensively to find various approaches to minimize the environmental impact of brine during desalination, and zero liquid discharge (ZLD) is proposed. It aims at producing high-quality freshwater with the complete elimination of liquid waste from the plant so that environmental damage because of the brine disposal is minimized (Panagopoulos et al., 2019). ZLD is achieved by integration of thermal-based and membrane-based technologies. One of the main limitations for the implementation of an integrated desalination and brine treatment system is the economic costs (Morillo et al., 2014; Subramani & Jacangelo, 2014). The total cost for construction and running of a ZLD system is often higher than the cost of the actual desalination facility, which is a barrier for the growth of the ZLD market (Voutchkov & Kaiser, 2020). Considering the high cost, ZLD strategy is not always the first choice for desalination although it effectively removes the environmental impact of brine.

On the other hand, seawater could be considered as a potential resource for meeting the material needs of future energy system because of the large volumes of materials contained (Lundaev et al., 2022). Therefore, the possibility of extracting materials from desalination brine may create an extra economic opportunity and help to address resource depletion while addressing the environmental concerns (Lundaev et al., 2022). The economic problem of ZLD strategy might also be solved through integrated brine mining processes which allow the isolation of several commercial products from a process stream (Sharkh et al., 2022). The high value of salts in brine is getting more and more attention by the desalination industry (Lundaev et al., 2022). Furthermore, over the last ten years, extraction of minerals and metals from brine has become more cost-competitive resulted from the improvement in resource recovery technologies (Sharkh et al., 2022). As salts have relative high value, integration of technologies to maximize the recovery of valuable materials additionally to the purification of water with the minimum energy consumption might improve the economic performance of the treatment chain. Overall, brine mining has a great economic potential and increasing attempts are made to recover useful resource from brine. However, few studies have been attempted to integrate brine mining with desalination to relieve its financial strain up to now.

1.2 Economic assessment methods

The economic performance is a main criterion on whether to approve a desalination project. Therefore, it is necessary to assess the economic performance of the integrated brine mining and desalination strategy. In this section, a range of different methods to undertake economic assessment are compared. Commonly used methods are cost-benefit analysis (CBA), cost-effectiveness analysis (CEA), life cycle costing (LCC) (DTF 2016). CEA is a method for finding the least cost option for a certain physical outcome (Gachango et al., 2015). It is useful to assess the most cost-effective program of measures (PoMs) and evaluate whether the PoMs are disproportionately expensive (Balana et al., 2011). CBA is a higher-level analysis comparing to CEA (Postle et al., 2004). In CBA, both the costs and benefits are accounted in monetary terms, which intuitively inform the decision maker about economic efficiency of the project (whether the project is financially worthwhile) (Balana et al., 2011). However, it is also a big challenge to convert all the benefits to monetary terms, mistakes on which might result in wrong decisions. LCC is an economic assessment considering all significant and relevant cost flows throughout analysis expressed in monetary value (Ghafourian et al., 2021). It is mostly used in cost analysis of water projects; however, benefits and desired physical outcomes are not involved in LCC (Jeswani et al., 2010). In this study, the desalination outcome (water production) is a relative important part of the assessment.

In addition, it might be a challenge to convert benefits to money considering the complexity of the proposed system. In such a situation, CEA might be a better tool than CBA and LCC in this study.

This study focuses on exploring the economic feasibility of applying different brine mining strategies with desalination. The main objective of this study is to assess the economic performance of an integrated desalination and brine treatment system in the Sicilian Island of Italy. It is designed based on the principle of maximizing the recovery of valuable materials. Cost-effective improvements of such water mining should be achieved in desalination; therefore, a cost-effectiveness analysis (CEA) is carried out to compare the cost of different treatment configurations to find the most cost-effective treatment train.

2. Methodology

The decision making on desalination projects is complicated considering economy, environmental impact, and effectiveness, etc. Therefore, the development of tools which can help comparing many strategies and options particularly in economic terms are desired. Cost-effectiveness analysis (CEA) is one of these tools. It is a method to determine the least-cost option among multiple alternatives which target on reaching a desired physical outcome (Boerema et al., 2018; Gachango et al., 2015; Vuori & Ollikainen, 2022). It is an economic assessment method that focus on comparing the unit cost of a specific physical indicator of at least two choices that produce the same result (Ghafourian et al., 2021). Regarding the project studied by this research, it is necessary to compare its economic performance with other ZLD systems to clarify whether the constructed system is a low-cost and effective measure to recover fresh water and achieve zero brine discharge. The results of CEA are expected to demonstrate the financial feasibility of the proposed system and the most crucial variables influencing the cost-effectiveness.

CEA is conducted in many studies of water treatment, pollution abatement and seawater desalination which are similar to our study (Ahdab et al., 2021; Ancev et al., 2008; Balana et al., 2012; Boerema et al., 2018; Iho, 2004; Vuori & Ollikainen, 2022). The followed procedures are: *(1) problem definition; (2) effectiveness identification of measures; (3) scenarios building; (4) development of cost model; (5) cost-effectiveness analysis on scenarios; (6) sensitivity analysis* (Balana et al., 2011; Kranz et al., 2010).

2.1 Description of case study

The understudied system targets on achieving water and mineral recovery, and zero brine discharge simultaneously. It is an integrated desalination and brine treatment system combining membrane and thermal-based technologies. The schematic scheme is shown in Figure 1. Two subsystems are integrated in the ZLD system for water recovery and brine mining respectively. Nano-filtration (NF), Multi-Effect Distillation (MED), and Brine Crystallizer (BCr) are included in the water recovery system, while several brine mining technologies(Multiple Feed-Plug Flow Reactor, Eutectic Freeze Crystallizer, Bi-Polar Membrane Electro-Dialysis) are applied in the other subsystem to recover magnesium, calcium, sulphate, and other chemicals from seawater.

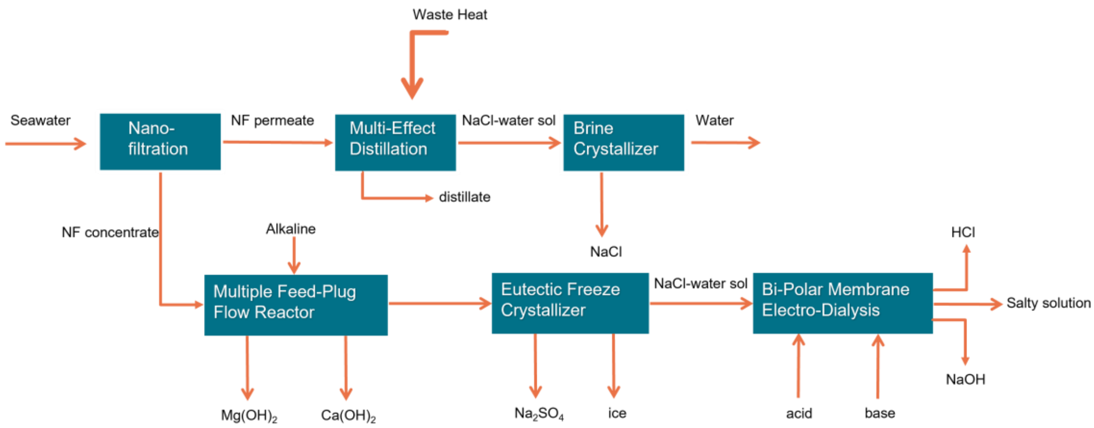


Figure 1. Schematic scheme of base scenario.

The mixed feed seawater is firstly pre-treated by NF and then separated into two streams: permeate and concentrate. It is a pressure-driven membrane process and is used to reject especially divalent ions (Micari et al., 2020). In the system, it is an important pretreatment step to concentrate the feed seawater and increase the efficiency of MED by rejecting divalent ions which might result in corrosion such as Mg^{2+}, Ca^{2+} and SO_4^{2-}.

The NF permeate is treated by MED and BCr to produce salt and pure water. The thermal-based technologies (MED and BCr) are often the core processes of desalination(Panagopoulos & Giannika, 2022). The feed is separated into condensed water vapor and concentrated brine in the MED (Panagopoulos et al., 2019). The concentrated brine then is circulated in the heater and crystallizer of the BCr to produce crystals continuously. Finally, distillate from MED and BCr are collected, and pure sodium chloride is produced after dried in the crystallizer.

The NF concentrate goes through Multiple Feed-Plug Flow Reactor (MF-PFR), Eutectic Freeze Crystallizer (EFC) and Bi-Polar Membrane Electro-Dialysis (EDBM) to recover various minerals. In the MF-PFR, two steps are included to produce $Mg(OH)_2$ and $Ca(OH)_2$ separately with different alkaline dosing. Each step is followed by a drum filter to produce Mg and Ca cake. Then the EFC simultaneously crystallizes pure sodium sulphate and ice from the brine solution under the eutectic point which is about 1.24℃.

Chemicals are recovered in the EDBM unit. Cations (Na^+) are moved toward the negatively charged cathode, while anions (Cl^-) are moved toward the positively charged anode(Panagopoulos et al., 2019). In this way, Na^+ and Cl^- are recombined with OH^-

and H^+ in the forms of hydrochloric acid and sodium hydroxide respectively, which can be also regarded as valuable co-products. As a result, the salinity of the final salty solution is significantly decreased and it can be circulated into the system to be re-treated, no liquid is discharged by the system.

The amount of energy and chemicals consumed by each unit are needed for economic analysis, and these data are reported in Table 1 and Table 2 respectively.

Table 1. Energy consumption of each technology in the base scenario.

Technology	Type of energy	Energy consumption	Units
NF	Electricity	23	kWh/hr
MED	Steam	531	kWh/hr
	Electricity	12	kWh/hr
BCr	Electricity	10	kWh/hr
MF-PFR	Electricity	9	kWh/hr
EFC	Electricity	9	kWh/hr
EDBM	Electricity	4	kWh/hr

Table 2. Material consumption of each technology in the base scenario.

Technology	Materials	Consumption	Units
NF	Antiscalant	5	ml/h
	HCl	0.27	ml/h
MED	cooling water	42088.15	kg/hr
BCr	cooling water	3000.71	kg/hr
MF-PFR (step 1)	NaOH	240.40	l/h
MF-PFR (step 2)	NaOH	110.20	l/h
EDBM	$FeCl_2$	0.32	kg/d
	$FeCl_3$	0.41	kg/d
	HCl	0.11	kg/d
	water	453.34	l/h

2.2 Effectiveness identification of measures

To give an initial evaluation of the effectiveness of the selected measures in the system, the performance, pros & cons, and energy requirement of each process unit are presented in Table 3.

Table 3 Summary of desalination technologies in base scenario.

Process step	Feed	Energy consumption	Target	Performance	Pro	Cons	Reference
NF	Seawater	2.09-3.92 kWh m^{-3} produced water	concentration of seawater	87.7% rejection of divalent ions	1. Removal of Scaling risk 2. Improve MED efficiency	1. High fouling risk and less durability 2. High operating costs	(Chowdhury et al., 2021; Liu et al., 2013; Nthunya et al., 2022; Panagopoulos et al., 2019; Sharkh et al., 2022)
MED	Brine(seawater or brackish water)	12.5–24(el) 200–250 (th) kWh m^{-3} produced water	To achieve ZLD; Water recovery	93% water recovery	1. Ability to treat highly saline feed waters 2. Low thermal energy consumption 3. High-quality water produced 4. Use low quality energy sources	1. High energy consumption 2. High capital cost 3. Possible corrosion	(Cipolletta et al., 2021)
BCr	Brine	52-70 kWh m^{-3} produced water	To achieve ZLD; Crystals recovery	97–99% water recovery; 98% purity sodium chloride	1. Ability to treat highly saline feed waters 2. Recovered crystals	High capital and operating costs	(Cipolletta et al., 2021; Panagopoulos et al., 2019)
MF-PFR	Brine	-	Mg^{2+}, Ca^{2+} recovery	High quality of Mg^{2+} (>95%)	Selectively extraction of salts	High operation costs	

				and Ca^{2+} salts			
EFC	Brine	43.8–68.5 kWh m^{-3} produced water	To achieve ZLD; Crystal recovery	Up to 98% of water recovery, 99.9% of salt recovery	1. Ability to treat high concentrated streams 2. A 100% yield can be achieved	1. High capital costs 2. No multicomponent brine 3. Ice scale layer formation	(Cipolletta et al., 2021; Lewis et al., 2010; Reddy et al., 2010)
EDBM	Brine	20-40 kWh m^{-3} produced water; 0.12–0.45 kWh kg^{-1} NaCl	Concentration of brine; Water recovery; To achieve ZLD	60%-70% chemicals recovery(NaOH & HCl)	1. Selective separation 2. A substantially high recovery 3. No pressure applied	1. Fouling/scaling issues 2. High costs	(Cipolletta et al., 2021)

The material and energy flows are fundamental for cost estimations (Micari et al., 2020), which correspond to inputs and outputs in the technical models. The inputs and outputs of the technical units we applied in our study are shown in the appendix.

2.3 Scenarios design

To assess the cost-effectiveness of the studied system, two other scenarios are defined for comparison:

Scenario 1 : A ZLD system which recovers fresh water, magnesium hydroxide, calcium hydroxide and mixed salt.

Scenario 2 : A ZLD system which only recovers water, while other minerals in a mixed form.

The schemes of the two systems are shown in Figure 2 and Figure 3 respectively.

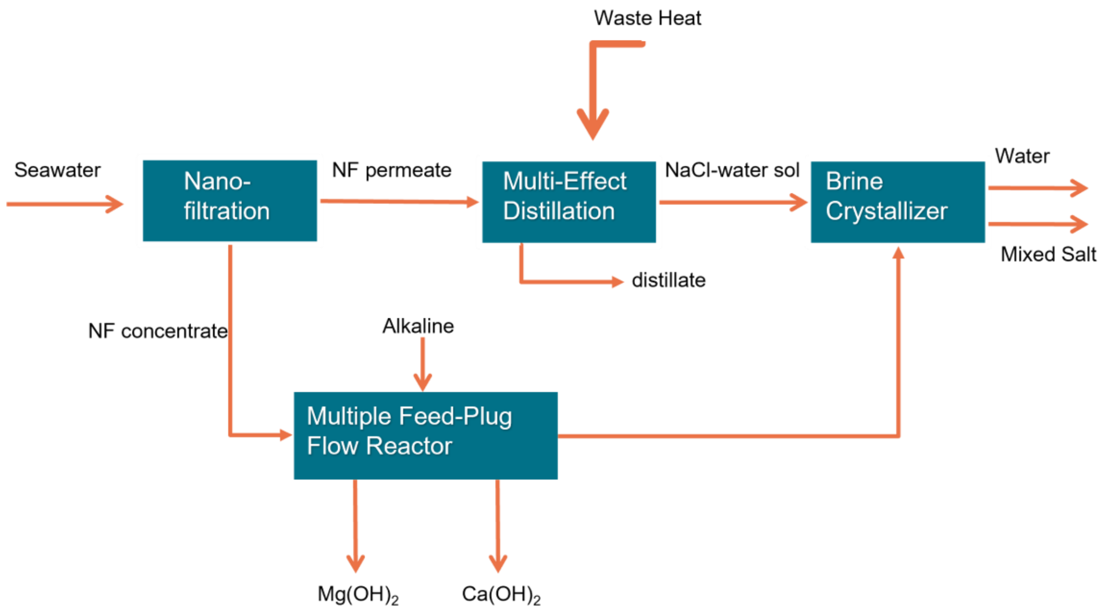


Figure 2. Scheme of Scenario 1.

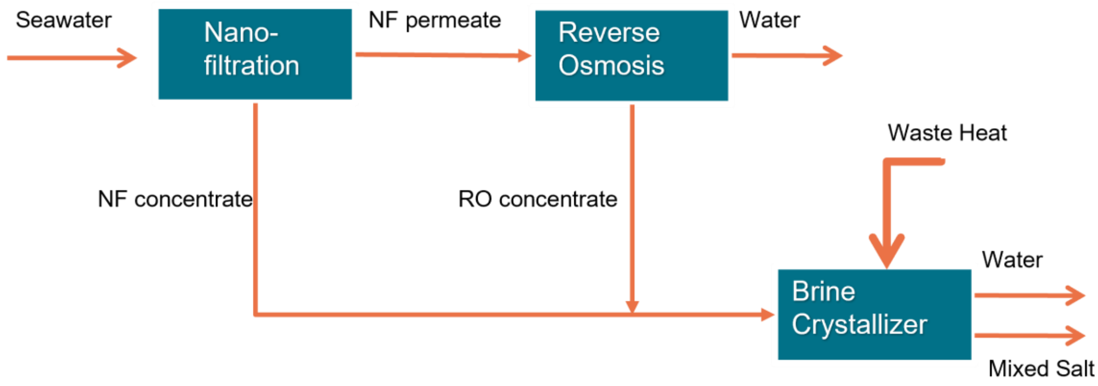


Figure 3. Scheme of Scenario 2.

Concerning Scenario 1, a compromise strategy of brine mining is adopted to balance the complexity of the system and the recovery of materials. It is designed to recover part of the minerals to obtain benefits but avoid the use of expensive technologies. In this way, it is expected to achieve brine mining through a simple and cheap system.

After pre-treated in the NF, the permeate goes through MED and BCr to recover water. On the other hand, the NF concentrate flows into MF-PFR to recover magnesium and calcium. The effluent of MF-PFR flows into BCr to produce freshwater and mixed salt.

Concerning Scenario 2, the primary objective is to maximize water recovery. It gives up brine mining but aims at minimizing the energy and cost requirement while achieving the function of a ZLD system. Instead of increasing the benefit of the system, it is designed to reduce the cost to the greatest extent to increase the economic feasibility. Therefore, in Scenario 2 , only a NF-RO-BCr chain is designed to recover water and various minerals are not separated but produced in the form of mixed salt. The mixed salt produced in both scenarios can be used as de-icing agent in roads, highways, etc. (Panagopoulos, 2021a).

Overall, the technologies used in the scenarios and the main outputs are given in table 4 and table 5 below respectively. Table 4 shows the technologies and number of stages constructed, and Table 5 shows the main products in the three scenarios.

Table 4. Technical units in the three scenarios.

SCENARIO	NF	RO	MED	BCR	MF-PFR	EFC	EDBM
BASE SCENARIO	Yes	No	Yes	Yes	Yes	Yes	Yes
SCENARIO 1	Yes	No	Yes	Yes	Yes	No	No
SCENARIO	Yes	Yes	No	Yes	No	No	No

2	

Table 5. Main outputs of the three scenarios.

SCENARIO	FRESHWATER OUTPUTS	SALT OUTPUTS	CHEMICAL OUTPUTS
BASE SCENARIO	MED distillate, BCr distillate, ice from EFC	NaCl, $Mg(OH)_2$, $Ca(OH)_2$, Na_2SO_4,	HCl, NaOH
SCENARIO 1	MED distillate, BCr distillate	$Mg(OH)_2$, $Ca(OH)_2$, mixed salt	-
SCENARIO 2	RO permeate, BCr distillate	mixed salt	-

2.4 Cost model

The major costs of a desalination plant are composed of capital expenditure (CAPEX) and operating expenditure (OPEX).

2.4.1 Capital costs

The CAPEX consists of fixed-capital investment and working capital, and the former one includes hardware costs, costs of buildings, process, and auxiliary, land, working capital and other indirect costs (Peters et al., 2003). Hardware costs are the sum of costs on purchased equipment and installation which can be directly obtained from the industrial companies operating the system (Papapetrou et al., 2017), while other CAPEX is estimated based on the obtained data and empirical assumption.

To apply economic analysis on a full-scale desalination plant, the pilot plants in the scenarios are scaled-up to a capacity of 30000 m^3/d. The CAPEX of the full-scale plant is estimated using a Capacity Factored Estimate (Kesieme et al., 2013) as Eq. (1). The costs of purchased equipment in the full-scale plant are derived from the cost of the same equipment in the pilot plant with known capacity.

$$\frac{Cost\ of\ purchased\ equipment(Plant\ A)}{Cost\ of\ purchased\ equipment(Plant\ B)} = \left(\frac{capacity\ of\ plant\ A}{capacity\ of\ plant\ B}\right)^m \quad (1)$$

This calculation method is known as six-tenths factor rule (m=0.6), which can be applied for a rough evaluation of the influence of equipment size on its cost (Peters et al., 2003). For desalination plants the exponent m is usually closer to 0.8 (Wittholz et al., 2008; Zhang et al., 2021), which is used in this work.

For easier application of capital costs in economic analysis, annualized life cycle cost method is used in some cases (Abraham & Luthra, 2011; Bilton et al., 2011; Choi et al., 2015; Kesieme et al., 2013), where the capital costs are annualized by using amortization factor (α). Annualized CAPEX reflects service-related capital costs for the construction of new desalination plants (Kesieme et al., 2013). Eq. (2) shows the calculation of annualized CAPEX, it is calculated by multiplying initial CAPEX with amortization factor (α):

$$Annualized\ CAPEX = CAPEX * \alpha \tag{2}$$

The amortization factor (α) is defined by:

$$amortization\ factor\ \alpha = \frac{i(1+i)^n}{(1+i)^n-1} \tag{3}$$

where i is discount rate, n is plant lifetime (year).

2.4.2 Operating costs

The OPEX refers to expenditure directly generated by manufacturing operation or connected to the equipment of a technical unit. It covers utilities, maintenance, operating supplies, operating labor, direct supervisory and clerical labor, laboratory charges, patents and royalties, fixed charges, and plant overhead costs (Peters et al., 2003). The utilities in this system are mainly energy, chemicals, and water costs. In addition, carbon emission cost is considered as cost of environmental impact (Papapetrou et al., 2017) and in this study only carbon emission costs from the energy use during operation are classified into OPEX as externality.

2.4.2.1 Energy, chemicals, and water

Energy cost (C_e) is a main contributor to ZLD desalination system's operating costs, as it is an integration of membrane and thermal-based technologies which have high electrical and thermal energy requirements. In the base scenario, only MED unit consumes waste heat as thermal energy resource. The calculation of electrical (C_{el}) and thermal (C_{th}) energy costs for every year follows Eq. (4) – Eq. (6):

$$C_{el} = E_{el} \times t_{operation} \times P_{el} \tag{4}$$

$$C_{th} = E_{th} \times t_{operation} \times P_{steam} \tag{5}$$

$$C_e = C_{el} + C_{th} \quad (6)$$

Where E_{el} and E_{th} are energy consumption per operating hour (in kWh/hr), $t_{operation}$ is the total operation time in one year (in hr), and the P_{el} and P_{steam} are the price of electricity and steam respectively (in €/kWh).

The calculation of chemicals and water costs are similar to the energy cost, multiplying the amount of consumption every year with their price.

2.4.2.2 Carbon emission cost

Carbon emission costs from electrical and thermal consumption are calculated as Eq. (7):

$$Carbon\ cost\left[\frac{€}{yr}\right] = Energy\ consumption\left[\frac{kWh}{hr}\right] \times$$

$$CO_2\ emission\ factor\left[kgCO_2 - \frac{e}{kWh}\right] \times Carbon\ tax\left[\frac{€}{ton}CO_2 - e\right] \times \frac{1}{1000}\left[\frac{ton}{kg}\right] \quad (7)$$

2.4.2.3 Other operating costs

Other operation costs are estimated based on the obtained data and empirical assumption which will be introduced in the following sections.

2.4.3 Economic data

Costs of purchased equipment of the base scenario are obtained from the factories operating the pilot. As discussed in section 2.4.1 and 2.4.2, some assumptions were made to calculate the CAPEX and OPEX of the base scenario, which are reported in Table 5.

Table 5. Assumptions on CAPEX & OPEX (Papapetrou et al., 2017; Peters et al., 2003).

CAPEX	Assumption
Installation	25% of purchased equipment cost
Buildings, process, and auxiliary	20% of purchased equipment cost
Land	6% of purchased equipment cost
Indirect costs	30% of direct cost
Working capital	20% of total investment

	cost
Annual OPEX	
Maintenance	7% of the fixed-capital investment
Operating Supplies	15% of maintenance
Operating Labor	15% of annual OPEX
Direct supervisory and clerical labor	15% of operating labor
Laboratory charges	15% of operating labor
Patents and royalties	3% of annual OPEX
Fixed charges	15% of annual OPEX
Plant overhead costs	10% of annual OPEX

In the cost model we developed, the amortization factor is calculated by using discount rate and plant lifetime. In addition, price of the materials and products, carbon tax and carbon emission factor, operating time are needed for annual OPEX calculation. These parameters are reported in the appendix.

2.5 Cost-effectiveness analysis

For CEA and further economic analysis, indicators are developed and applied on the scenarios. The indicators are reported in the following sections.

2.5.1 Cost-effectiveness ratio (CER)

CER is the total cost over the amount of physical objective generated by the system (Gachango et al., 2015). The physical objective of CEA is defined as the amount of desalinated water produced by the whole system, so the CER is defined as Eq. (8):

$$CER = \frac{annual\ total\ costs[€]}{mass\ of\ produced\ water[kg]} \tag{8}$$

For further economic analysis, some other indicators are developed and applied on the scenarios.

2.5.2 Net Present Value (NPV)

NPV is a most applied time-discounted method of evaluating capital investment expenditures (Levy & Sarnat, 1994). The calculation of NPV follows Eq. (9):

$$NPV = \sum_{t=1}^{n} \frac{R_t - C_t}{(1+i)^t} - I_0 \tag{9}$$

NPV is derived by discounting the net receipts every year which is revenue of year t (R_t) minus operating cost of year t (C_t) using discount rate (i), summing them over the plant lifetime (n) and deducting the initial investment (I_0).

Taking inflation into account, R_t and C_t can be calculated in the following equations.

$$C_t = C_1 \times (1 + f_a)^t \tag{10}$$

$$R_t = R_1 \times (1 + f_a)^t \tag{11}$$

Here, C_1 and R_1 are operating cost and revenue at the first year respectively. f_a is the annual inflation rate.

A positive value of NPV means that recovery of minerals from seawater is profitable for the project, and the concentrate in the system can be considered as a valuable resource instead of worthless waste. A negative value of NPV means that the concentrate has no value and there is no benefit to recover minerals in the system.

2.5.3 Cost-benefit

Cost-benefit is defined as the total cost over the total revenue generated by the system, the equation to calculate it is shown in Eq. (12). A single language of monetary values is used and by calculating the total cost and capturing the external financial gains, it is feasible to assess the ability of the system to earn profit and the internal correlations between cost and benefits (Ghafourian et al., 2021).

$$Cost - benefit = \frac{Total\ cost[€]}{Total\ revenue[€]} \tag{12}$$

2.5.4 Levelized Product Cost (LPC)

Concerning that multiple products are produced by the studied system, it is necessary to assess the benefit it generates from the recovery of each material. Therefore, LPC is introduced and applied on each co-product, which is an assessment of the price at which the product must be sold in the market to compensate the total cost generated during its production (Papapetrou et al., 2017). The Eq. (13) is given to calculate the LPC:

$$LPC = \frac{I_0 + \sum_{t=1}^{n} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{i,t}}{(1+i)^t}} \tag{13}$$

Where I_0 is the initial capital cost, n is the plant lifetime, C_t is the operating cost in the year t, $M_{i,t}$ is the amount of product i produced in the year t.

In many cases, an assumption is made to simplify the calculation of levelized cost, which is that the amount of products and the operation cost are the same every year (Ali et al., 2021; Hossam-Eldin et al., 2012; Micari et al., 2019, 2020). It is reasonable as the system is assumed to operate at a stable sate during its lifetime and too detailed calculation should be avoided when doing estimation. In addition, joint cost should be separated for each product in a multiple product system when calculating levelized cost. It is the cost of a production process that produces several products simultaneously (Deevski, 2016; Overland & Sandoff, 2014). Substitution method is applied to achieve this. In this way, the LPC should be calculated as Eq. (14):

$$LPC_i = \frac{\sum_{units}(Annulized\ CAPEX + Annual\ OPEX) - (\sum_{units} REV - REV_i)}{M_{i,t}} \quad (14)$$

Where LPC_i is the Levelized Product Cost of product i, annualized CAPEX are depreciated capital costs of each unit in the treatment chain, annual OPEX are operating costs of each unit, REV is the annual revenue of each unit, REV_i is the annual revenue of product i, $M_{i,t}$ is the annual production mass of product i. It should be noted that the base scenario is separated into two subsystems (NF-MED-BCr and MF-PFR-EFC-EDBM). LPC is calculated individually for each subsystem, and units after production of product i are excluded in the calculation of LPC_i.

In addition, if the NPV is positive, the NF concentrate should be considered as a resource of brine mining. Costs of NF should be partly allocated to the brine mining subsystem (MF-PFR-EFC-EDBM). Economic allocation is applied on the cost of NF based on the value of NF permeate and NF concentrate. If the NPV is negative, the NF concentrate should be considered as a waste stream, and zero value is assigned to this stream.

2.6 Sensitivity analysis

Sensitivity analysis on treatment capacity, plant lifetime and electricity price are conducted to assess their effect on the cost-effectiveness and levelized cost of water of the studied strategy. The variations of these factors are reported in Table 6.

Table 6. Variations of sensitivity factors.

Treatment capacity(m^3/d)	30000	40000	50000	60000	
Plant lifetime(yr)	20	25	30	35	
Electricity	0.202	0.228	0.253	0.278	0.304

price	

* A treatment capacity of 30000 m^3/d, plant lifetime of 20 year, and electricity price of 0.253 €/kWh are applied in base scenario.

** Concerning the electricity price, a 10% increase/decrease per change referring to the base scenario is applied.

3. Results and discussion

The cost model is applied on the three scenarios to calculate the capital and operating costs, and this is followed by a cost-effectiveness analysis to evaluate their economic performance. Then sensitivity analyses are performed to illustrate how the studied ZLD system performs with different plant capacities and energy price. Finally, a discussion on the adopted methods is done to assess the validity of the economic evaluation model developed in this work.

3.1 Cost-effectiveness and cost-benefit

Cost-effectiveness ratio is the most important indicator for CEA. It indicates the costs for water production in desalination systems. Table 7 presents the CER of the three scenarios.

Table 7. Cost-effectiveness ratio of different scenarios.

	CER (€/kg freshwater)
Base scenario	0.074
Scenario 1	0.088
Scenario 2	0.032

Scenario 2 has the lowest CER among the three scenarios, only 0.032€/kg freshwater. It means that the cost to produce 1kg freshwater is the lowest. Scenario 1 generates the highest CER (0.088€/kg), 118% higher than that of the base scenario (0.074€/kg). As expected, Scenario 2 is the most cost-effective strategy to produce freshwater. Scenario 2 only targets on maximizing water recovery and achieving zero brine discharge. Comparing with other scenarios, fewest thermal-based technologies are used in Scenario 2, which significantly reduces its investment costs and energy consumptions, while the water recovery is almost the same. The capital cost of Scenario 2 is only 67% of Scenario 1, 79% of base scenario. In addition, the specific energy consumption of Scenario 2 is 0.015kWh/kg freshwater, lower than base scenario (0.038 kWh/kg freshwater) and Scenario 1 (0.076 kWh/kg freshwater).

Although base scenario has a worse performance on the cost-effectiveness of water production, it performs better on the overall finance, which is indicated by the cost-benefit shown in Table 8. A cost-benefit of only 1.12 is achieved by base scenario, which is far lower than the Scenario 1 and Scenario 2 (21.97 and 26.08 respectively). The recovery of minerals and chemicals bring large benefits to the system. The revenue obtained by base scenario is 43 times more than Scenario 2. It makes the base scenario a more competitive strategy and might compensate for the disadvantages in terms of cost-effectiveness.

Table 8. Cost-benefit of different scenarios

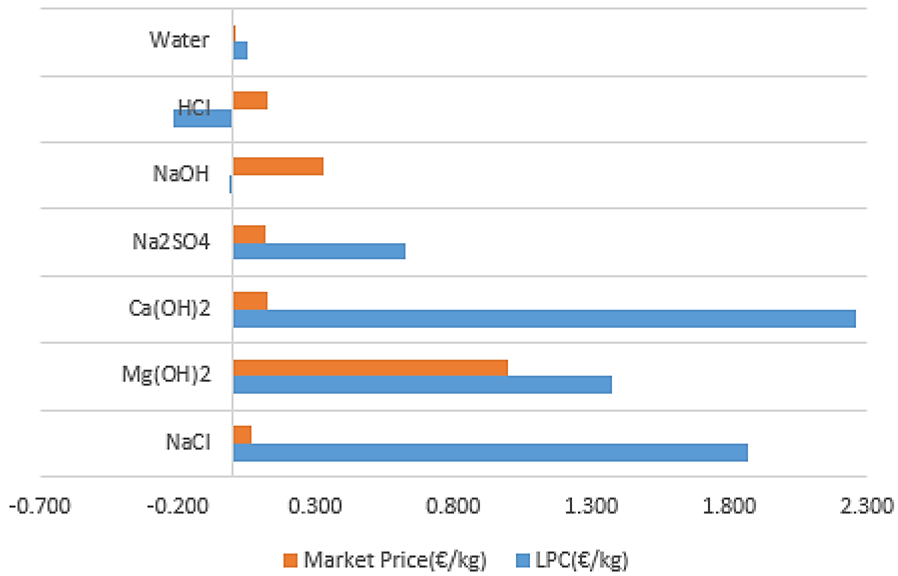
	Cost-benefit
Base scenario	1.12
Scenario 1	21.97
Scenario 2	26.08

It is worth noting that the compromise strategy of Scenario 1 results in a less cost-effective system than base scenario. The total costs and energy consumption of Scenario 1 are both higher than base scenario. The reason might be that in Scenario 1 the large volume of concentrate from MF-PFR flows into the BCr, significantly increasing its throughput. Therefore, the energy requirement and costs of Scenario 1 are higher. Meanwhile, due to the less material recovery, Scenario 1 has no obvious advantage over Scenario 2 in terms of cost-benefit (21.97 and 26.08 respectively).

3.2 Levelized Product cost

For all the three scenarios, the NPV are negative. Therefore, the concentrate in the system is supposed to be considered as a waste stream, instead of a resource for brine mining. For the calculation of LPC, the value of NF concentrate is zero and the cost of NF is allocated to the water recovery subsystem.

Concerning the base scenario, the LPC of each product are presented in Figure 4. Figure 4 illustrates that the LPC of all the minerals and water are higher than their market price, which means the production costs are higher than the profits on sale. It is worth noting that the LPC of sodium hydroxide and hydrogen chloride are negative (-0.01€/kg and -0.21 respectively). This indicates that the recovery of chemicals generates benefits for the system, the EDBM can be a very appealing technology in brine treatment.



Note: The products in base scenario are water, HCl, NaOH, Na_2SO_4, $Mg(OH)_2$, $Ca(OH)_2$ and NaCl. The LPC(€/kg) are 0.06, -0.21, -0.01, 0.63, 1.37, 2.26, 1.86 respectively. Only water produced by the water recovery subsystem is included in the LPC of water.

Figure 4. Levelized Product costs and market price of products in the base scenario.

Among the LPC of all the products, the levelized cost of water (LCOW) is worth noted. By calculating LCOW it is easier to compare the relative feasibility of different technologies and plant layouts (Papapetrou et al., 2017). Both costs and revenues of the system are considered in the water production. Figure 5 shows the LCOW of the three scenarios. the highest LCOW is carried out by Scenario 1 (0.084€/kg), which is followed by base scenario (0.056€/kg) and Scenario 2 (0.032€/kg). Even though no revenue from brine mining is obtained in Scenario 2, its LCOW keeps the lowest in the three scenarios. Brine mining doesn't perform better than ZLD strategy only recovering water (Scenario 2) in terms of LCOW. The reason might be that only products in the subsystem of water recovery are included in the calculation of LCOW, the revenue of co-products cannot effectively compensate for the high costs. Provided that the costs and revenues from the whole system are included in the calculation of LCOW as what (Morgante et al., 2022) did, then the result of base scenario would be 0.008€/kg, only a quarter of Scenario 2's.

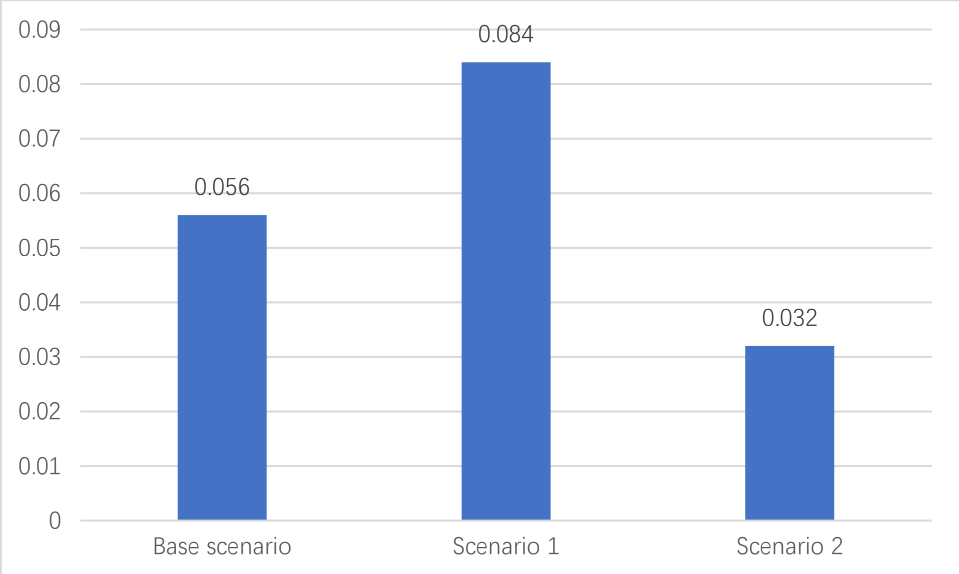
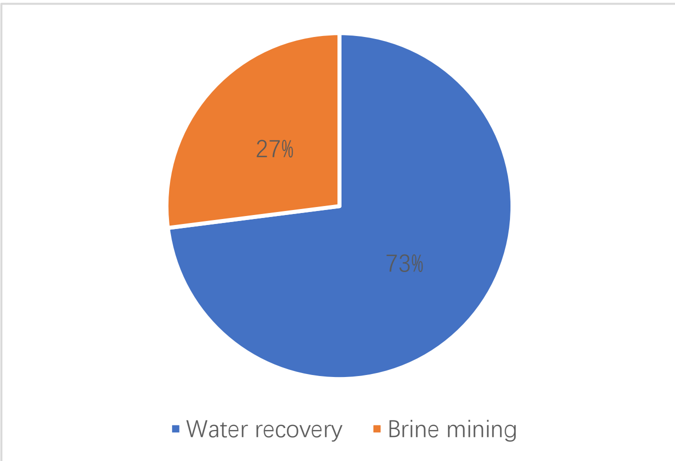
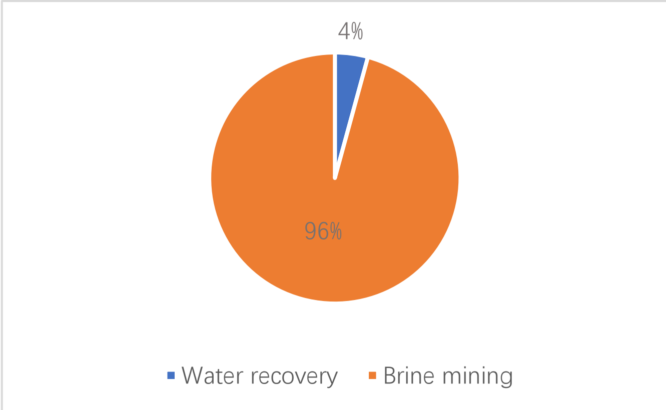


Figure 5. Levelized Cost of Water(€/kg) in different scenarios.

Overall, comparing with Scenario 2, base scenario performs better in terms of cost-benefit, but worse on cost-effectiveness and levelized cost of water. The results illustrate that brine mining and water recovery are unbalanced in terms of income and expenditure in base scenario. Figure 6 shows the share of the two subsystems of base scenario in the overall revenue and expenditure. While brine mining contributes to 96% of the total revenue, its cost is only 27% in the system. Therefore, when doing comparison between different desalination strategies, the specifics of system costs and benefits need to be reasonably taken into account.



(a)



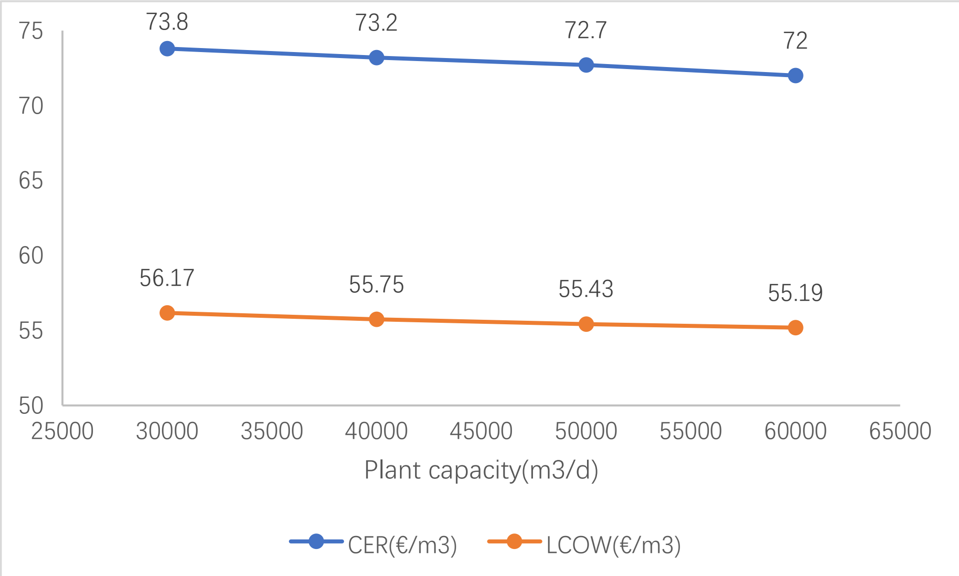
(b)

Figure 6. The percentage participation of water recovery and brine mining subsystems in the total expenditure (a) and revenue (b) in base scenario.

3.3 Sensitivity analysis

3.3.1 Treatment capacity and plant lifetime sensitivity

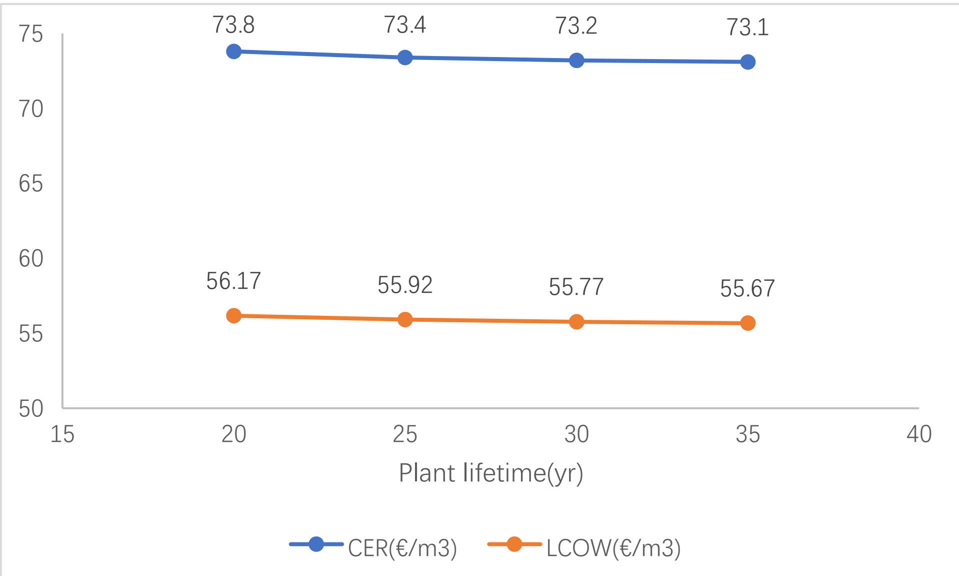
A sensitivity analysis on treatment capacity of base scenario is carried out by varying the feed flow rate of seawater. The capacity has been varied in the range of 30000m^3/d to 60000m^3/d to see the effect of plant size on CER and LCOW. The results are reported in figure 7. A linear decreasing trend is presented by CER and LCOW because of the scaling-up. Lowest CER (72€/m^3) and LCOW (55.19€/m^3) are achieved by a 60000 m^3/d full-scale plant, while the highest CER (73.8€/m^3) and LCOW (56.17€/m^3) are indicated by the 30000 m^3/d plant. It is illustrated that large plant size can effectively reduce the water production cost of the integrated brine mining ZLD strategy.



Note: Plant capacity of 30000, 40000, 50000, and 60000m^3/d are studied on the variations of CER and LCOW of a desalination plant with 20 years lifetime.

Figure 7. Cost-effectiveness ratio and Levelized cost of water against plant capacity.

To have a better insight of the effect of project size on CER and LCOW, a sensitivity analysis on plant lifetime is also carried out. The results are presented in figure 8. Similar negative correlations between plant lifetime and CER & LCOW are indicated. CER and LCOW reduce with a longer plant lifetime. It should be noted that plant capacity has a bigger impact on CER and LCOW than plant lifetime. The variation in capacity results in a larger decrease of CER and LCOW than plant lifetime. It can be concluded that a larger desalination plant with a longer lifetime would result in better economic performance of the integrated brine mining ZLD strategy.



Note: Plant lifetime of 20, 25, 30, and 35m^3/d are studied on the variations of CER and LCOW of a 30000 m^3/d desalination plant.

Figure 8. Cost-effectiveness ratio and Levelized cost of water against plant lifetime.

3.3.2 Electricity price sensitivity

The energy cost is high in ZLD systems due to the application of various thermal-based technologies. Since the electricity price varies a lot in different districts, the application of the studied strategy might be limited by electricity price in some regions. Therefore, a sensitivity analysis is carried out on the electricity price to assess the effect on CER. The results are presented in Figure 9. As shown in Figure 9, desalination cost-effectiveness is very low (CER up to 79.3€/m^3) when electricity price is very high (electricity price up to 0.304€/kWh), while in districts where the electricity prices are low(0.202€/kWh), CER reduces to 68.3€/m^3. It is reasonable that electricity price has a great impact on the cost-effectiveness of desalination, as the energy cost takes a large percentage in the total costs of the base scenario (16.3%).

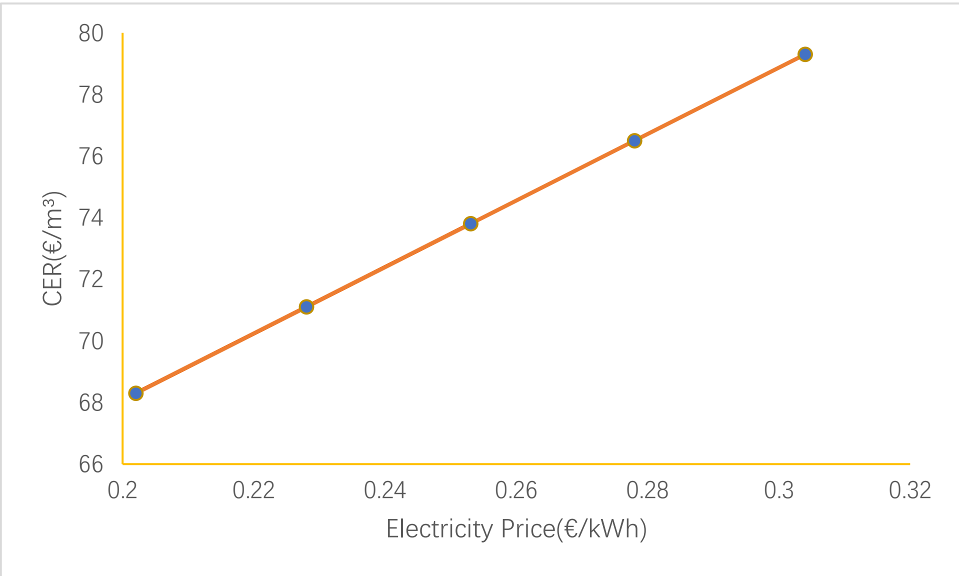


Figure 9. Cost-effectiveness ratio against electricity price.

3.4 Discussion on methodology

In this study, the CER, LCOW, cost-benefit of different scenarios indicate completely opposite priorities on desalination strategies. NPV and cost-benefit can provide accurate insights on financial performance of the systems, but the effectiveness of desalination strategies is not indicated, while CER is the exact opposite.

CEA is adopted as the main method to analyze the economic performance of the integrated desalination and brine treatment system. It was expected to find the least-costly option among multiple alternatives. CEA well assessed how cost-effective a desalination system is to produce freshwater. However, only the total cost and the water production are considered in CEA, while the economic impact of by-products is excluded. Therefore, only the high costs resulted from brine mining are presented by CEA, but no benefit is included. This is not a comprehensive economic assessment for the studied strategy as CEA amplifies disadvantages but excludes advantages of the strategy. It is one of the main limitations of CEA that it cannot assess if the preferred option is of net benefit to the society, but only which option is capable of delivering the outcome most cost effectively (DTF 2016). The Levelized Cost seems to be a better indicator than CER, as it includes both costs and revenues of the whole system, and the desired outcome (water production) into calculation. It has a more comprehensive evaluation of system economics. However, as discussed in section 3.2, it is important to decide which parts of the system should be included into the calculation of LPC. Overall, a more integrated approach balancing the economic impacts of different inputs and outputs of a complicated system is desired to assess the economic performance of the studied strategy. It is suggested to apply the Levelized Cost which calculate for the whole system, rather than splitting it into several subsystems which is done in this study.

4. Conclusion

Since the environmental impact of the conventional brine disposal methods is getting global concern, Zero Liquid Discharge (ZLD) becomes an attractive strategy to minimize such influence. The economic potential of brine mining makes it possible to address the finance stress of ZLD by integrating brine mining and desalination in a ZLD system. The base scenario of this study is designed based on this strategy. It contains two subsystems: NF-MED-BCr for water recovery and MF-PFR-EFC-EDBM for brine mining. Cost-effectiveness Analysis (CEA) is applied to assess the economic performance of such ZLD strategy, and two other scenarios are proposed for comparison. Different combination of technologies (NF, MED, BCr, MF-PFR; NF, RO, BCr) are included in the two scenarios.

The results show that the CER ranges from 0.032 €/kg freshwater to 0.088 € /kg freshwater with the highest CER in Mg^{2+} & Ca^{2+} mining scenario (Scenario 1) and the lowest in water recovery scenario (Scenario 2). LCOW indicates similar performance in the three scenarios, with the highest LCOW in Scenario 1 (0.084€/kg freshwater) and the lowest in Scenario 2 (0.032€/kg freshwater). The base scenario is the most profitable system, it has the lowest cost-benefit (1.12) in the three scenarios. Sensitivity analysis illustrates that the studied system performs better in larger desalination plants with longer lifetime, and electricity price can greatly affect the cost-effectiveness of this system.

Overall, the proposed integrated brine and desalination strategy improves the profitability of ZLD strategy, but its cost-effectiveness of desalination is lower than ZLD which only maximize water recovery. The applied methodology (CEA) assessed the cost-effectiveness on water production of the proposed strategy but cannot give a comprehensive economic assessment for the strategy. CEA only takes total cost and water production into account but excludes the economic benefits from brine mining in the studied strategy. Therefore, CEA is not the most suitable tool to assess the economic performance of the integrated brine and desalination strategy. Future research should focus on developing an integrated approach for economic assessment. The approach is supposed to balance the economic impacts of different inputs and outputs in a complicated desalination system.

Appendix

A.1. Inputs and outputs of technical models

The material and energy flows are fundamental for cost estimation, which correspond to inputs and outputs in the technical models. The inputs and outputs of the base scenario are reported in Table A1.

Table A1. Main process inputs and outputs of technical models in base scenario

PROCESS STEP	PROCESS INPUT	PROCESS OUTPUT
NANO-FILTRATION(NF)	Feed flow rate Ion concentration Feed pressure Water recovery Ion rejection	Permeate flow rate and composition Concentrate flow rate and composition Electricity requirements
MULTI-EFFECT DISTILLATION(MED)	Feed flow rate Ion concentration Feed temperature Number of effects Steam temperature	Flow rate of water Effluent flow rate and composition Electricity and thermal requirements Cooling water flow rate
BRINE CRYSTALLIZER(BCR)	Feed flow rate Ion concentration	Flow rate of water Flow rate of NaCl Electricity requirements
MULTIPLE FEED-PLUG FLOW REACTOR(MF-PFR)	Feed flow rate Ion concentration Concentration of the alkaline ion (NaOH)	Alkaline solution flow rate Flow rate of $Mg(OH)_2$ Flow rate of $Ca(OH)_2$ Effluent flow rate and composition Electricity requirements
EUTECTIC FREEZE CRYSTALLIZER(EFC)	Feed flow rate Ion concentration Feed temperature	Flow rate of Na_2SO_4 Flow rate of ice Effluent flow rate and composition Electricity requirements
BI-POLAR MEMBRANE ELECTRO-DIALYSIS(EDBM)	Feed flow rate Ion concentration Electric density	Flow rate of acid and composition Flow rate of base and composition

		Flow rate of salt and composition Electricity requirements

A.2. Economic parameters

Price of the materials and products, carbon tax and carbon emission factor, operating time, etc. are needed for annual OPEX calculation. These parameters are reported in Table A2.

Table A2. Economic parameters employed in the economic analysis

Parameter	Value	Units	Ref.
Discount rate	6%	-	
Operating hours	24	hour	
Annual working days	300	day	
Plant lifetime	20	year	
Inflation rate	2%	-	(Statista 2022)
CO_2 emission factor(electricity)	0.275	$kgCO_2$-e/kWh	(EEA 2022)
CO_2 emission factor(steam)	0.633	$kgCO_2$-e/kWh	(Nazari et al., 2010)
Carbon tax	23	€/ton CO_2-e	(Kesieme et al., 2013)
Price of electricity	0.253	€/kWh	(GlobalPetrolPrices 2022)
Price of steam	0.008	€/kWh	(Morgante et al., 2022)
Price of Antiscalant	0.002	€/ml	(Birnhack et al., 2014)
Price of HCl	125	€/ton	(Morgante et al., 2022)
Price of NaOH	330	€/ton	(Morgante et al., 2022)
Price of $FeCl_2$	5	€/kg	**

Price of $FeCl_3$	1	€/kg	**
Price of Water	1	€/m^3	(Morgante et al., 2022)
Price of cooling water	0.118	€/m^3	(Yang et al., 2021)
Price of Na_2SO_4	116	€/ton	(USGS 2011)
Price of NaCl	66	€/ton	(Morgante et al., 2022)
Price of $Mg(OH)_2$	1000	€/ton	(Morgante et al., 2022)
Price of $Ca(OH)_2$	125	€/ton	(Morgante et al., 2022)
Price of mixed salt	5	€/ton	(Panagopoulos, 2021b)

* All values expressed in $ in the quoted references were converted in € considering a currency conversion factor (April 2021) equal to 0.83€/$.

** The prices of $FeCl_2$ and $FeCl_3$ refer to industrial user's cost in Sicilian Island of Italy.

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