ZERO BRINE

D7.7: LCA and LCC of the Zero Brine Case studies

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Final

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[1] **R**=Document, report; **DEM**=Demonstrator, pilot, prototype; **DEC**=website, patent fillings, videos, etc.; **OTHER**=other

2 **PU**=Public, **CO**=Confidential, only for members of the consortium (including the Commission Services), **CI**=Classified

Executive Summary

Zero Brine aims to close the loop on industrial brine effluents through the recovery of water and valuable components contained within the effluents that include minerals (e.g. sodium chloride, sodium sulphate), regenerated acids, caustics and magnesium. Zero Brine consists of four case study projects which require different configurations of technology units:

- Demineralised water plant (DWP) effluent in The Netherlands.
- Coal mine effluent in Poland.
- Textile industry effluent in Turkey.
- Silica industry effluent in Spain.

The developed Zero Brine treatment and recovery systems (ZB systems) involve combining existing water treatment technologies and innovative units developed within the project. This report presents the final evaluation of the ZB systems using life cycle assessment (LCA) and life cycle costing (LCC). It is a follow up to preliminary analysis that was conducted in 2019 (Harris et al. 2020). The analysis follows the methodology set out in the Zero Brine report D7.1 which outlines the Unified Approach that aimed to develop consistency in the methodology and analysis of the four case studies (Tegstedt et al, 2021).

The case study assessments show that the ZB systems treat the effluents and recover by-products to a high standard going beyond current best available technology. However, the degree of environmental and economic benefits provided is highly dependent on the composition of the effluents being treated. ZB systems require the use of chemicals, membranes and energy which increase the footprint of treatment systems. This is counteracted by the recovery of salts and other compounds contained in the effluent where concentrations are high enough.

A summary of the LCA analysis of the four case studies compared to the reference cases, is shown in Figure ES1. This compares two of the most contrasting impact categories: climate change and resource depletion. It shows that the climate change impact of the ZB systems (orange bars) is lower than the reference system in all cases apart from the textile plant. It is lower due to the recovery of the brine constituents (salts, water and other compounds) that invoke credits because the analysis assumes that these will replace the production of virgin materials.

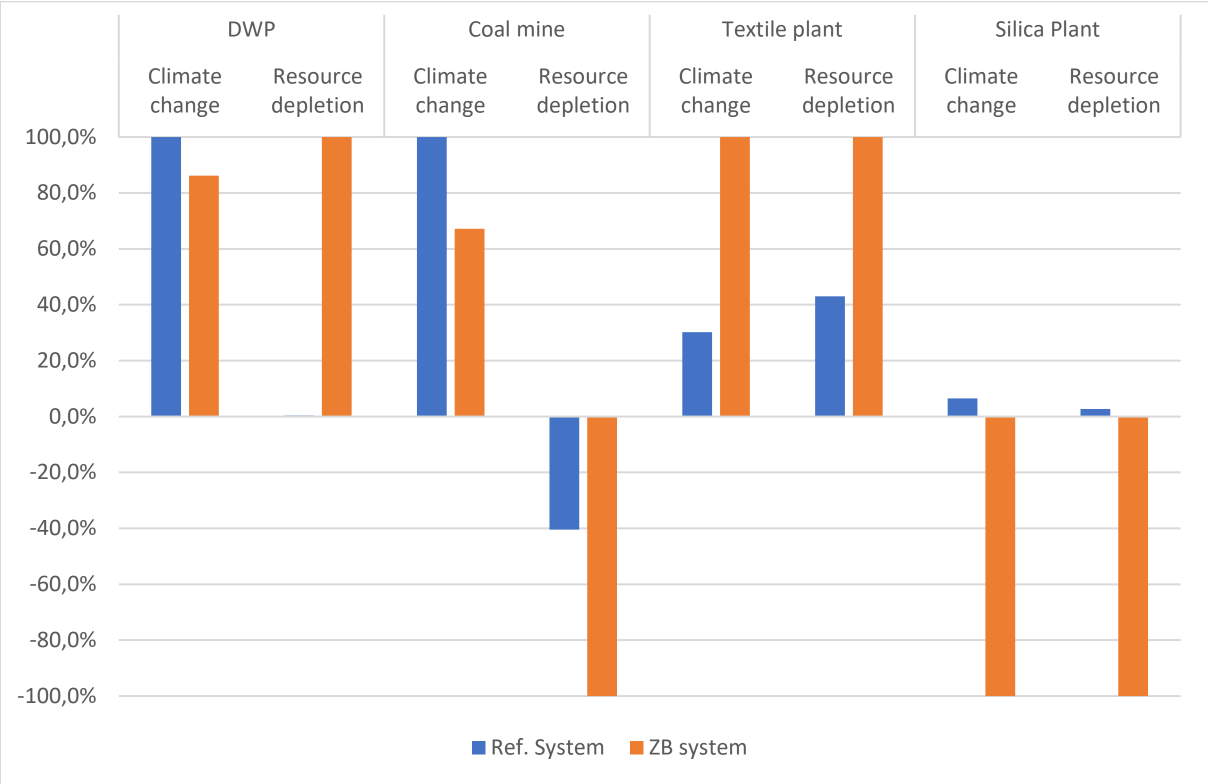

Figure ES1: Normalised percentage comparison of ZB systems with reference systems for the four case studies

However, the benefits of lower climate change need to be considered alongside the impacts of resource depletion. For the coal mine and silica plant this was also lower than for the reference case. But for the DWP and textile plant the increase in required chemicals results in a higher resource depletion. This can be expected for the DWP because currently the only treatment is dilution and discharge to the local sea.

Table ES1 summaries the environmental and economic results for the four case studies. Three of the four cases studies are expected to have lower cost than the reference system, with the coal mine actually generating a profit due to the high value of the recovered products (water, sodium chloride, gypsum and magnesium hydroxide).

Therefore, the results show that the ZB systems perform well and have the potential of providing many environmental benefits, and economic benefits. However, the results are sensitive to quantities of energy and material (especially chemicals) and to several underlying assumptions, particularly that the products recovered from the brine are utilised.

In conclusion, performance of a ZB system is largely contingent on the environmental and economic value of the constituents within the brine. Since the addition of ZB systems typically increases the use of energy and chemical use, the recovered products must counteract this in avoided environmental impacts and economic cost. This is dependent on the products being reused onsite or sold as marketable products. Future improvements in electricity and energy systems, through the use of renewable energy and lower carbon intensive systems, is likely to increase the viability of ZB systems.

Table: ES1: Relative expected change in performance of ZB system compared to current situation. Green shading signifies a reduction of impact whereas red signifies an increase in impact.

	Environmental (LCA)		**Economic (LCC)**
	Climate change	Resource depletion	
DWP	-14%	+26,800%	+274%
Coal mine	-33%	- 247% (credit)	- 6% (profit)
Textile plant	+331%	+233%	-98%
Silica plant	-1630% (credit)	-3800% (credit)	+22%*

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List of Abbreviations

CAPEX	Capital expenditure
CrIEM	Crystallization with Ion Exchange Membranes
DWP	Demineralised Water Plant
ED	Electrodialysis
EFC	Eutectic Freeze Crystallization
EPS	Environmental Product Strategies
ELU	Environmental Load Unit
FF-MED	Forward-feed evaporator
GHG	Greenhouse Gas Emissions
GFRP	Glass Fibre Reinforced Polyester
HDPE	High Density Polyethylene
IEX	Ion Exchange
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
MD	Membrane distillation
MED	Multi-effect distillation
MF	Membrane Filtration
NF	Nanofiltration
OPEX	Operating expenditure
PVC	Polyvinyl Chloride
RCE	Remote Component Environment
RO	Reverse Osmosis
TOC	Total Organic Carbon
ZB	Zero Brine

1. Introduction

This report presents the final analysis of the four case studies in the Zero Brine project using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). It is a follow up to preliminary analysis (D7.3) that was conducted in 2019 (Harris et al. 2020).

Zero Brine consists of four case study projects which require different configurations of innovative technology (developed within the project) combined with established technology units:

- Demineralised water plant (DWP) effluent in The Netherlands.
- Coal mine effluent in Poland.
- Textile industry effluent in Turkey.
- Silica industry effluent in Spain.

Brine is produced in large and growing quantities in Europe by industrial processes. The high salt content provides a challenge to wastewater management as the salinity can have deleterious effects on aquatic environments. The process industry is the largest source producing 11.5 million tonnes/year, followed by the steel industry 323,000, power sector 213,000, pulp & paper 58,000 and food & beverage for 37,000 tonnes/year (Xevgenos et al. 2018). Disposal is often made through dilution and dispersal but the efficacy and legitimacy of this approach is under increasing question. The cost effectiveness of zero discharge technology has not yet been widespread.

However, Zero Brine aims to facilitate the economic closing of the loop, using technology configurations that recover the valuable components of the brine. These can include mineral (e.g. sodium chloride, sodium sulphate), regenerated acids, caustics and magnesium.

The treatment and recovery systems developed in the Zero Brine project, involve combining existing water treatment technologies and innovative units developed within the project. Each case study utilises unique and tailored designed configurations. The technologies developed within Zero Brine are: Eutectic Freeze Evaporation (EFC), Multi Flow-Plug Feed Reactor crystallization (MF-PFR) and a Forward-Feed Multiple Effect Distillation (MED) evaporator.

The aim of work package 7 (WP7) was to apply LCA and LCC early in the project to provide insights into potential environmental and cost hotspots, and therefore aid the design and development of the case study configurations. The preliminary LCA and LCC analysis highlighted several challenges, in particular the cost and environmental impacts of the use of chemicals and energy (Harris et al. 2021). These have a high influence on the environmental and economic performance of the systems. The final LCA and LCC of the case studies are presented in this report. In the next section the methodology is briefly introduced and then the LCA and LCC assessments of each case study are presented.

2. Methodology

The methodology follows the same procedure as the preliminary analysis (D7.3; Harris et al. 2020) but using updated and improved data from pilot scale tests and simulation. A unified approach was developed to harmonise the LCA and LCC analysis (D7.1), which was conducted by three different research teams (Tegstedt et al. 2021). This should be consulted for further information on the guidelines utilised.

The assessment was intended to be performed in three stages:

1. A **preliminary assessment** - that consisted of an LCA and LCC based on bench scale data and, literature data, calculations and simulations.
2. A **draft sustainability evaluation** - using improved data from the pilot plant operations and test data, but complemented where necessary with bench scale data and some simulations.
3. **Final sustainability evaluation** - aims to be the most representative and robust LCA and LCC analysis of full-scale industrial implementation with improved data quality and less uncertainty.

Due to delays in pilot plant running and testing, partly due to the Covid pandemic, the draft sustainability evaluation was not performed. The document herein contains the final sustainability evaluation for the ZB systems of each case study.

The concepts of LCA and LCC are briefly presented below. For further information please consult the Unified Approach (Tegstedt et al. 2021).

The main goal of the assessment was to compare the ZB systems with a reference (or current) scenario in order to understand the environmental and economic performance of treating 1 m^3 of wastewater brine.

2.1 Life Cycle Assessment

Life cycle assessment (LCA) investigates the environmental impacts related to a product or a system throughout its entire life cycle. This includes evaluating energy and resource consumption as well as emissions, from all lifecycle stages including; material production, manufacturing, use and maintenance, and end-of-life.

LCA is a widely used and accepted method for studies of environmental performance of various products and systems, for more details on how an LCA is performed we refer the reader to the literature such as Rebitzer et al. (2004) and the guidelines for Product Environmental Footprint (Manfredi et al, 2012). The LCA in this report is performed in accordance with ISO 14040:2006 (ISO 14040, 2006) and ISO 14044:2006 standards (ISO 14044, 2006).

LCA consists of four stages: goal and scope definition, Inventory analysis, impact assessment and interpretation. Each of these is explained for each case study in the relevant sections.

The preliminary analysis performed on the case studies (Harris et al. 2020; 2021) highlighted the importance of five impact categories which are the focus of the analysis in this report: climate change, acidification, freshwater eutrophication, freshwater ecotoxicity and mineral, fossil and resource depletion. In particular, assessing climate change helps determine the contribution to global warming, which is currently a key global concern. Whilst, resource depletion help quantify the benefits of recovering the water and compounds from the brine, against the consumption of chemicals and energy in the ZB systems.

2.1.1 Perturbation analysis

Based on LCA results, perturbation analysis was conducted to investigate the effect of parameter uncertainties on climate change impact category results. The perturbation analysis method in Clavreul et al., (2012) was followed which recommends calculating Sensitivity Ratios (SR) to model parameter variations of +10% and –10%. SRs were calculated for chosen parameters using the below equation.

$$SR = \frac{\frac{\Delta result}{initial\ result}}{\frac{\Delta parameter}{initial\ parameter}} \qquad (1)$$

In this equation, the initial parameter and initial result are the parameter values from the base case. $^{\Delta}$parameter is the change in the parameter value and $^{\Delta}$result is the change in the LCIA result when the parameter variation is applied.

2.1.2 Scenario Analysis

Finally, scenario analysis was conducted to determine the impact of different energy mixes on the results. Firstly, a country specific projection was developed for electricity production in 2030 based on references cited in relevant case study sections. Second a scenario applied for consumption of electricity generated from 100% wind energy.

2.2 Life Cycle Costing

Life cycle costing (LCC) is an accounting technique that compiles all costs that an owner or producer of an asset will incur over its lifespan (Swarr et al, 2011a). It therefore considers both capital expenditure and operating expenditure throughout the life cycle.

LCC is defined in the International Organization for Standardization standard, Buildings and Constructed Assets, Service-life Planning, Part 5: Life-cycle Costing (ISO 15686-5, 2017) as an “economic assessment considering all agreed projected significant and relevant cost flows over a period of analysis expressed in monetary value. The projected costs are those needed to achieve defined levels of performance, including reliability, safety and availability."

The approach adopted in ZB is to include two components in line with Swarr et al. (2011b):

1) Costs linked to its development or use, such as:
    a. Costs relating to acquisition, i.e. capital expenditures (CAPEX).
    b. Operational expenditures (OPEX), such as consumption of energy and other resources.
    c. Maintenance, repair costs and others (e.g. engineering, construction fees, land, etc).
    d. End of life costs, such as collection and recycling costs.
2) Costs imputed to environmental externalities linked to the product, service or works during its life cycle (e.g. cost of emissions of greenhouse gases and other climate change mitigation costs).

For the inclusion of costs in the LCC, we make the following definitions:

- CAPEX represent costs, which are included at the beginning of the project, generally just a single time (price of the plant, taxes, fees, permits). These costs traditionally represent low contributions to the functional unit, due to the investment is repaid during the whole lifespan of the system (although may be more significant for innovative zero or circular technologies). Therefore, CAPEX costs are directly dependant on the lifespan, and its final value may vary through time.
- OPEX costs rely on continuous cashflows that the plant needs to operate. These costs have a fixed ratio per functional unit (kWh/m^3, ml/kg, etc). These values only depend on system performance, and time or lifespan do not influence on them. Generally, these costs consider energy and chemical consumption, staff, transport, waste management from operation, and products. The main exception is "spare parts" category, which is considered as OPEX: they are not introduced continuously in the system, but periodically.

To calculate the CAPEX we assume a lifetime of 35 years for the ZB systems, which is a reasonable approximation based on other research which ranges from 20 years (Resende et al. 2019) to 50 years (Raghuvanshi et al. 2017) for wastewater treatment plants.

2.3 External Costs

Environmental LCC also usually includes external costs, also referred to as externalities or damage costs. These represent the indirect costs for the society that environmental degradation and emissions cause, but are not incorporated into internal costs. In this project and report we utilize the Environmental Priority System (EPS) developed in Sweden and now available within LCA software as endpoint impact assessment. The impact is expressed in Environmental Load Units (ELUs) (equivalent to Euros) and illustrates the magnitude of the total environmental damage costs for future generations. This can be added to the internal costs to represent the total costs for the reference or ZB system.

3 Case study 1: Demineralised water plant (DWP)

3.1 System boundaries and description

The Demineralized Water Plant (DWP) is in the Rotterdam harbour area, the Netherlands, and it supplies demineralized water to local industries. This produces approximately 2.5 million m^3/year (288 m^3/hr) of brine from two sites at the plant, one from ion exchange (IEX; water softening) and another from reverse osmosis (RO). Therefore, two separate ZB systems were designed to treat the two effluents using combinations of the following technologies: nanofiltration (NF), anionic ion exchange (IX), membrane crystallisation, Eutectic Freeze Crystallization (EFC) and evaporation. Part of the energy for the brine treatment is derived from waste heat. The aim is to recover high purity magnesium hydroxide, NaCl solution, sulphate salts and clean water and reuse at the site. The LCA and LCC systems are developed for a scale of 411,720 m^3 brine/year.

3.1.1 Reference system

Currently the generated brine from the DWP is mixed with tap water and then discharged to the nearby harbour entrance (Figure 1). Hence, no additional treatment is required as the water meets discharge quality to the sea, and therefore treatment and disposal costs are minimal.

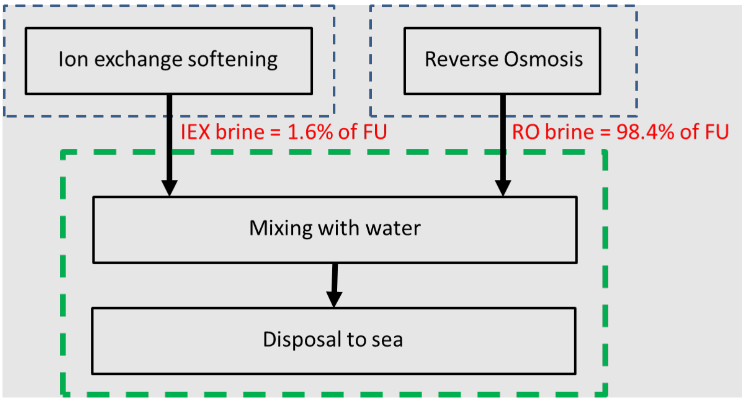


Figure 1: System boundaries of reference system

3.1.2 Zero Brine system

Figure 2 shows the designed treatment train for IEX and RO brine. The IEX treatment train is shown in Figure 2(A) and consists of NF, crystallization and evaporation units. The concentrate from the NF undergoes a crystallisation stage to recover calcium hydroxide and magnesium hydroxide. Evaporation recovers a brine solution, which is rich in NaCl, and tap-quality water from the NF permeate and MC effluent. Figure 2(B) shows the treatment train for the RO brine. It is designed to recover clean water and salts using IEX, NF, EFC, RO and evaporation units to recover sodium sulphate, brine (rich in NaCl) and deionized-quality water and tap-quality water. The by-products are reused internally with water replacing lake water input and the brine replacing high purity salt for regeneration of the IEX units.

There is abundance of waste heat potential in Rotterdam Port. Therefore, it was assumed that the evaporation processes (see Figure 2 below) will employ waste heat instead of natural gas boilers. This is a valid assumption because currently there is abundant waste heat available in Rotterdam Port, for instance Air Products and Chemicals Inc. has confirmed the existence of a waste heat stream of 3-5 MW, with a constant flow at 120°C. In addition, for processes which upscaled electricity consumption data did not exist, it was assumed that upscaling will result in a reduction of 45% based on the average of the upscaled electricity consumption data from WP5 and Task 7.2 of Zero Brine (Micari, 2020).

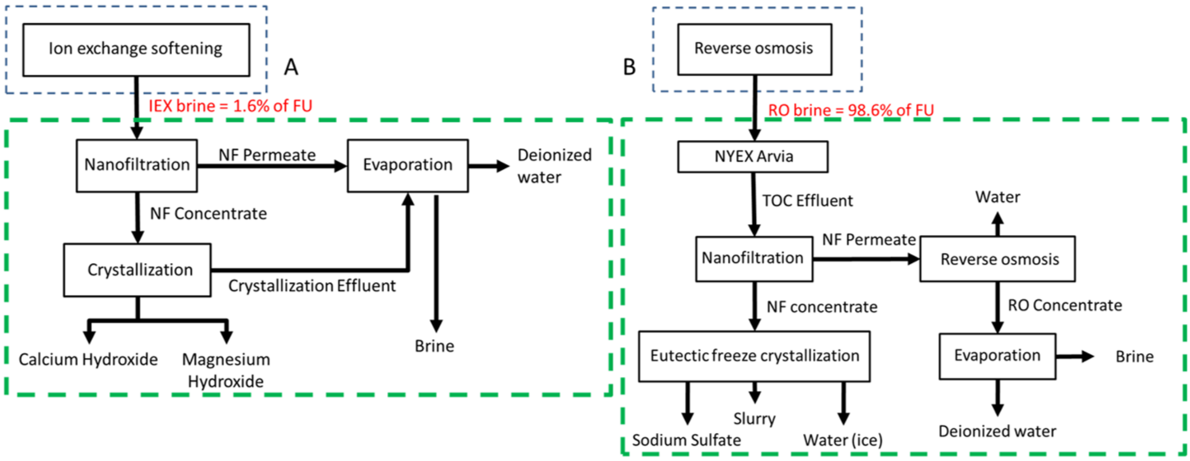


Figure 2: System boundaries of Zerto Brine system. A) ZB technologies for treating IEX brine; B) ZB technologies for treating RO brine

3.1.3 Life cycle inventory

Table 1 displays the LCA inventory data that was collected from the ZB pilot plants and upscaled from bench scale data where required. Electricity consumption data for nanofiltration, reverse osmosis and crystallization processes were upscaled from results of WP5 and Task 7.2 of Zero Brine (Micari, 2020). In the case of electricity production, the Dutch electricity mix was updated to that of annual average during 2019 based on data from the Dutch Central Statistics Bureau (CBS, 2021). Data is normalized per 1 m^3 of brine input. (https://opendata.cbs.nl/#/CBS/en/dataset/84575ENG/table).

The reference system employs only electricity to pump the brine into the sea and water to mix the brine before discharge. The ZB system employs various chemicals, such as sodium hydroxide and hydrochloric acid to adjust the pH, antiscalant to avoid scaling at the nanofiltration stage, sulphuric acid and water for cooling and cleaning purposes.

Table 1: Life Cycle Inventory of ZB system per 1m^3 brine

	Process	ZB system	DWP reference system	Unit
Energy consumption				
Electricity	All processes	8.24	5.76	kWh
Waste heat	Evaporation (Site 1)	8.72		kg

Auxiliary materials				
Sodium Hydroxide (NaOH)	Crystallization & Arvia Nyex	0.23	-	kg
Hydrochloric Acid (HCL)	Crystallization	0.03	-	kg
Antiscalant (Vitec 3000)	Nanofiltration	5.1	-	g
Sulphuric acid (H_2SO_4)	Arvia Nyex	5.57	-	kg
Cooling water (tap water)	Evaporation	250	-	L
Cleaning water (tap water)	All processes	150	-	L
Mixing water			500	L
Recovered Products				
Water (tap water quality)	Evaporation, Eutectic Freeze Crystallization & Reverse Osmosis	0.87	-	m^3
Water (deionised water quality)	Evaporation	0.07	-	m^3
Sodium sulphate ($NaSO_4$)	Eutectic Freeze Crystallization	1.95	-	kg
Calcium Hydroxide ($Ca(OH)_2$)	Crystallization	0.144	-	kg
Magnesium Hydroxide ($Mg(OH)_2$)	Crystallization	0.023	-	kg

3.1.4 LCC Inventory

The inventory data for LCC was collected after consulting technology suppliers, i.e. Lenntech, Arvia and University of Palermo for nanofiltration, NYEX Arvia and Ca and Mg crystallizer units, respectively. Whereas, for the other process unit data was collected from WP5 and Task 7.2 of Zero Brine (Micari, 2020). Table 2 shows the inventory of consumables and recovered materials per 1 m^3 of brine (see section 11.1.1 for sources of costs). In addition, maintenance is considered and is assumed to be 3% of the capital costs. Personnel cost is based on 3 employees with an average salary of 81,700 €/year spending 20% of their time at the ZB plant (calculated from average company values). Table 3 shows the capital costs per 1 m^3 of brine levelized on the entire life cycle of the plant, i.e. 35 years and a full scale plant capable of 290m^3/hr (based on average literature values, see section 2.2).

Table 2: Operational costs and revenues per 1 m3 brine

Material	**Cost** (€/1 m^3 brine)
Consumables	
Antiscalant (Vitec 3000) (Site 1)	0.00041725
HCL (Site 1)	0.00752
NaOH (Site 1)	0.02304
Clean water (Site 1)	0.006656
H2SO4 (Site 2)	1.476428335
NaOH (Site 2)	0.0887895
Antiscalant (Vitec 3000) (Site 2)	0.033153851
Clean water (Site 2)	0.409344
Electricity (Site 1)	0.002638873
Electricity (Site 2)	0.556802038

Recovered materials	
Recovered water	0.726146
Recovered deionized water	0.182823
Magnesium hydroxide	0.037162
Calcium hydroxide	0.025992
NaCl	0.045383
Na2SO4	0.293724

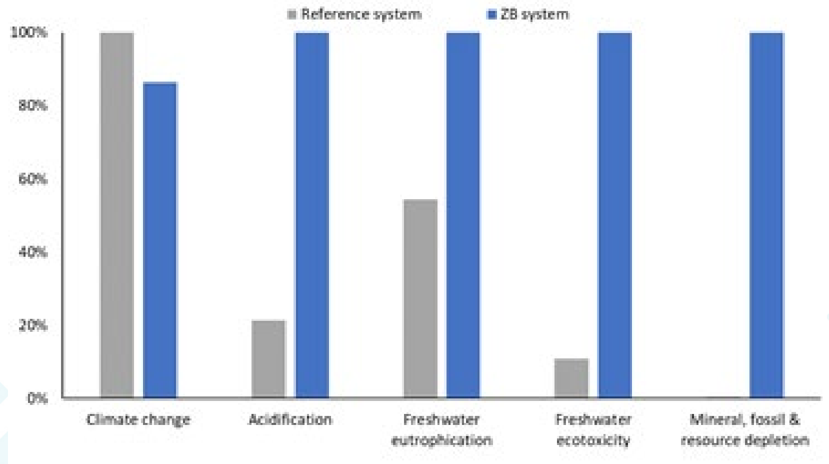
Table 3: Capital costs per 1 m^3 brine levelized in the entire life cycle of the plant

Equipment	Amount of units	Cost (€/1 m^3 brine)
Nanofiltration	1	0.006320421
Membrane Crystallization	2	0.001191851
Evaporator	2	0.037922525
Reverse osmosis	1	0.107753005
Arvia NYEX (TOC removal)	1	0.000812626
EFC	1	0.000315623

3.2 Results - Life Cycle Impact Assessment

3.2.1 Comparison with reference case

Figure 3 shows that the ZB system results in environmental benefits for Climate change and environmental burdens for Acidification, Freshwater eutrophication, Freshwater ecotoxicity and Resources depletion compared to the reference system (direct brine discharge to the sea). An environmental benefit is only expected for the climate change impact, approximately 14% lower. Whereas, the environmental burdens range from 46% higher (for Freshwater eutrophication) to 100% higher (for Mineral, fossil & resource depletion category) compared to the reference system



Impact category	Reference case	ZB system
Climate change kg CO2 eq	2.97	2.56
Acidification molc H+ eq	0.0064	0.0302
Freshwater eutrophication kg P eq	0.00012	0.0002
Freshwater ecotoxicity CTUe	0.22	2.06
Min, fossil, & res. depletion kg Sb eq (E-05)	1.485E-05	0.004

Figure 3: Percentage comparison of DWP and reference case (and absolute quantities in table) of impacts for 1 m3 of brine for impact categories

3.2.2 Contribution analysis

Contribution analysis for climate change of the ZB system is shown in Figure 4. The environmental benefits result from the recovery of sodium chloride and sodium sulphate- This occurs even though Site 2 processes are the main hotspots for environmental burdens, including Arvia (Site 2) and NF (Site 2) and to a lesser extent RO (Site 2) and EFC (Site 2). For these processes electricity production and chemical production are the cause of the environmental impacts (upstream from the ZB system). However, due to the recovered sodium sulphate at Site 2, the ZB system results in environmental benefits due to avoided production of virgin materials. Contribution analysis for the other considered environmental impacts can be found in the Appendix (section 11.1).

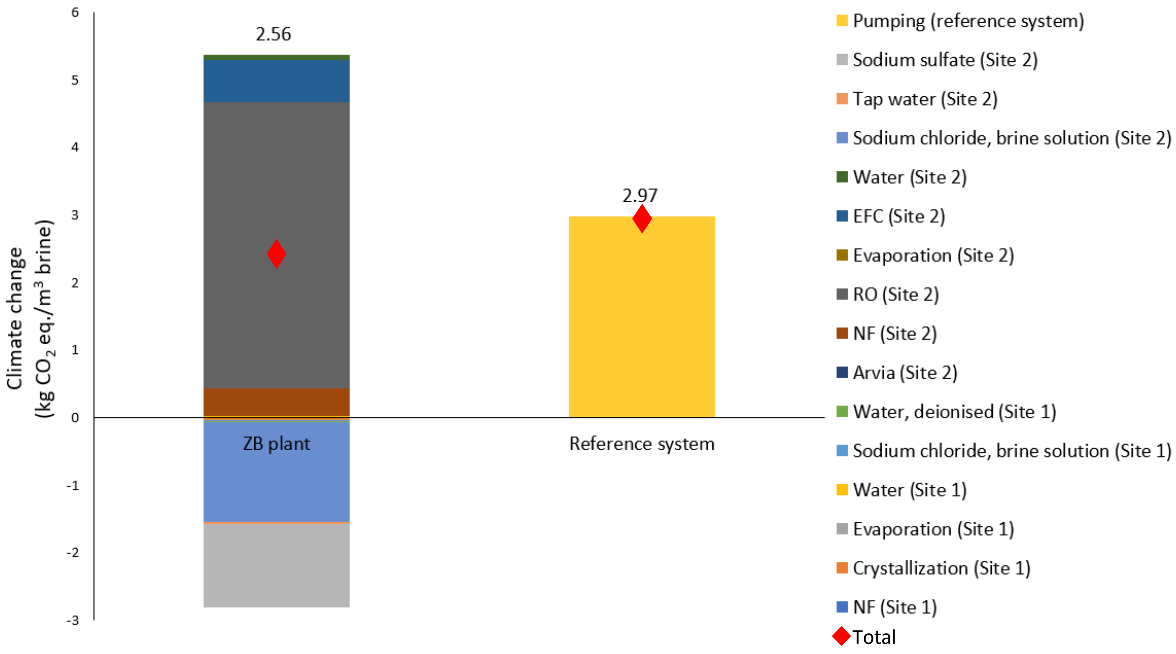


Figure 4:. Contribution analysis of ZB system and reference system at the DWP

3.3 Results – Life Cycle Costing

3.3.1 LCC

Figure 5 shows the LCC results based on the OPEX and CAPEX of the reference and ZB systems. Most of the costs are due to chemical products consumed at Site 2, particularly the sulfuric acid consumed in the Arvia Nyex unit. Economic benefits (revenue) are also expected mainly due to the recovered water and sodium sulphate. This results in a total cost of the ZB system of €1.57/m^3 compared to €0.41/m^3 for the reference system. The electricity consumption for pumping brine to the sea dominates the costs of the reference system.

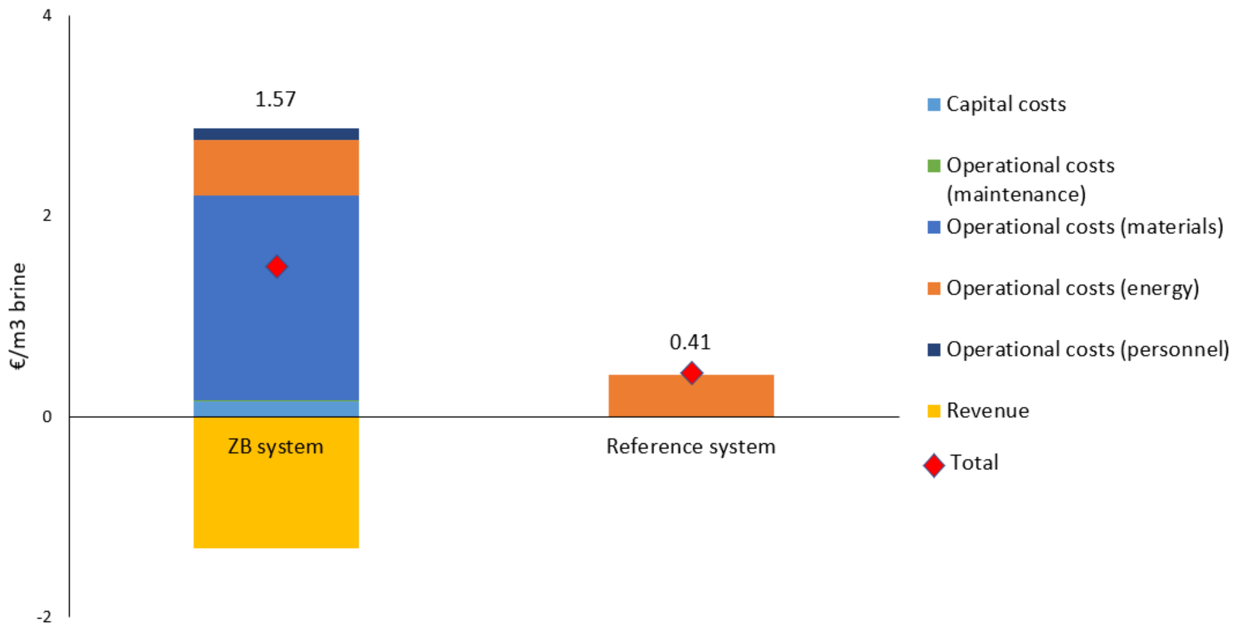


Figure 5. Contribution analysis of costs and benefits of ZB and reference systems

3.3.2 Externalities

Table 4 shows the environmental externalities based on the damage assessment of Environmental Priority System (EPS) (Steen, 2015). Site 2 is the main contributor to the ZB plant environmental externalities results. For all damage categories, the ZB plant results in significantly increases, except for "Abiotic resources" which is approx. two orders of magnitude worse. Figure 6 shows the total costs of the two systems from the summation of internal costs and externalities. It should be noted that for the purposes of this analysis it is assumed that ELU are equivalent to Euros. Therefore, the internal costs are added to the externalities to represent total costs of the systems.

Table 4: Environmental externalities for the DWP ZB system

Damage category	Unit	Site 1	Site 2	ZB system	Reference case	% change Ref to ZB system
Ecosystem services	ELU	-0.00026	0.011	0.011	0.012	10%
Access to water	ELU	-0.000016	0.001	0.001	0.001	11%
Biodiversity	ELU	-0.000001	0.000	0.000	0.000	5%
Building technology	ELU	-0.000003	0.000	0.000	0.000	37%
Human health	ELU	0.00012	0.312	0.31	0.40	21%
Abiotic resources	ELU	0.041	27.47	27.51	0.29	-9420%
Total	**ELU**			**27.84**	**0.70**	**-3890%**

**Environmental Load Unit*

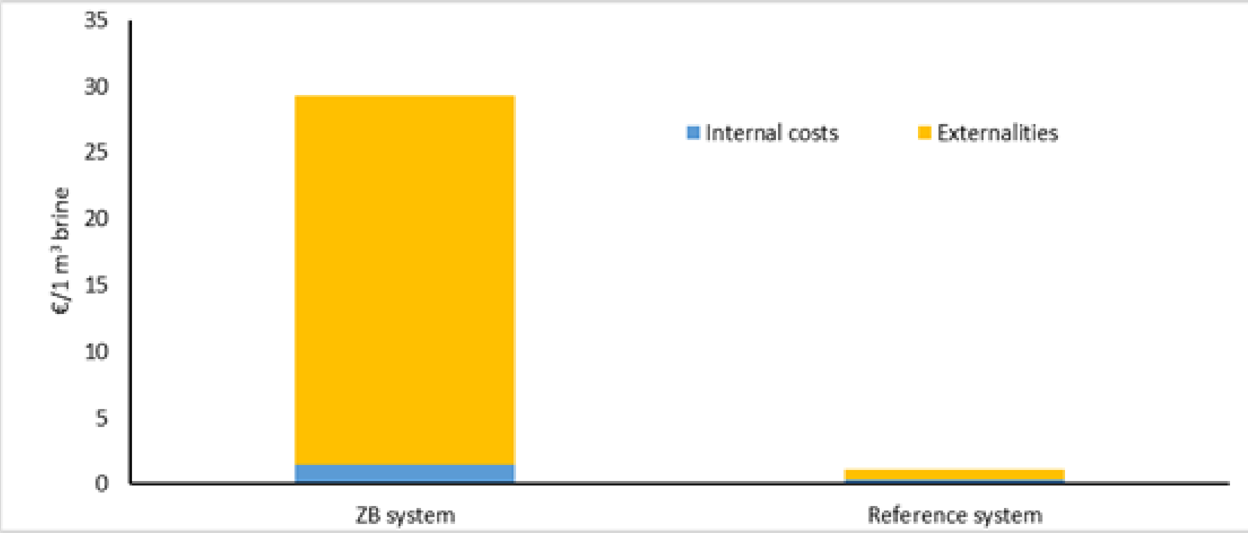


Figure 6: LCC results with environmental externalities based on EPS

3.4 Sensitivity analysis

3.4.1 Perturbation analysis

Table 5 shows the results of the perturbation analysis for climate change. Electricity consumption and sulphuric acid are the only parameters that have high sensitivity ratios, meaning they have a strong influence on the results. The other parameters have a low sensitivity ratio meaning that a change in quantity used in the system does not strongly affect the climate change impact.

Table 5: Perturbation analysis and sensitivity ratios of the climate change impact assessment for a variation of -10% and +10% in the parameter values of the DWP ZB system (Parameter amounts and impact category results are given per 1 m^3 brine)

	Original parameter		**10% decrease in parameter**		**10% increase in parameter**		
Parameter	Unit	Parameter amount	Parameter amount	Total climate change (kg CO2 eq)	Parameter amount	Total climate change (kg CO2 eq)	Sensitivity Ratio
Electricity	kWh	8.24	7.42	2.50	9.06	2.63	0.25
NaOH (Site 1)	kg	3	2.7	2.55	3.3	2.58	0.06
HCL (Site 1)	kg	2.00	1.8	2.56	2.2	2.57	0.02
H_2SO_4 (Site 2)	kg	5.66	5.01	2.52	6.23	2.61	1.7%0.17
Magnesium hydroxide (Site 1)	kg	0.02	0.021	2.56	0.026	2.56	0.0%0
Deionized water	L	70	63	2.56	77	2.56	0.1%0.01

3.4.2 Scenario analysis

In this section, the results of the scenario analysis are presented, comparing the results of the ZB system against a scenario with the projected electricity mix of The Netherlands for 2030 (Frontier Economics, 2015) and another with 100% renewable energy (in this case wind produced electricity). In 2030, the Netherlands is expected to have the electricity mix presented in Table 6. However, within this scenario we also assume that there is no waste heat available for use in the ZB system, to model the effects of other companies competing for the waste heat in the area. The heat required for the ZB system is assumed to be generated by electric boilers with electricity based on the future electricity system. In the 100% renewable energy scenario, the waste heat is also used in the ZB plant. The results of the scenario analysis are shown in Figure 7. It shows that the environmental impact increases significantly in the 2030 scenario due to the increased electricity that occurs if no waste heat is available. However, if waste heat is available and wind energy utilised (scenario 3) than the impacts are reduced considerably, particularly for climate change.

Table 6: Projection for Dutch 2030 electricity mix compared to 2017

Energy type	**Year 2018**	**Year 2030**
Nuclear power	3.1%	2.2%
Hard coal	26.8%	18.1%
Gas	51.1%	37.7%
Hydropower	0.1%	0.1%
Wind offshore	1.3%	18.1%
Wind onshore	6.3%	10.9%
Solar	3.4%	5.8%
Oil	1.2%	0%
Other RES (biomass)	3.6%	7.2%

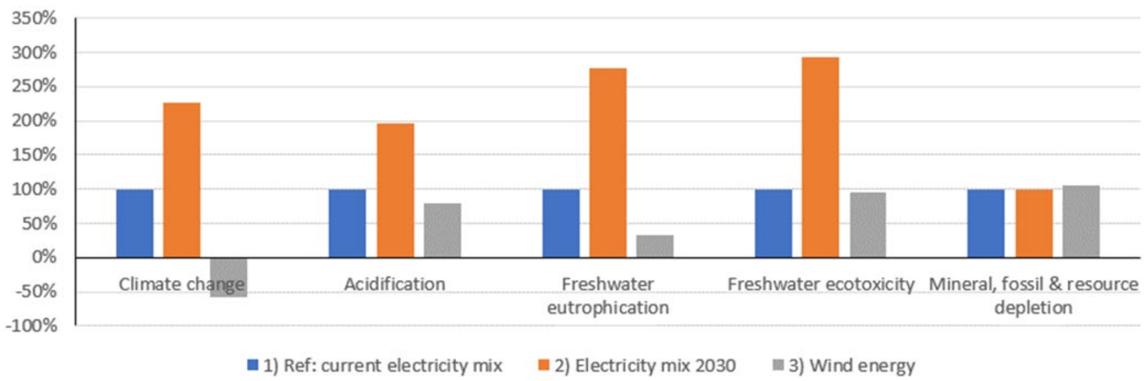


Figure 7: Scenario analysis for different sources of energy in The Netherlands, 1) Current electricity mix, 2) projected electricity mix in 2030 (no waste heat utilised) and 3) 100% wind energy, utilising waste heat.

3.5 Discussion

3.5.1 LCA

The LCIA results show that the ZB plant results in both environmental benefits and burdens for considered impact categories. This is primarily linked to the electricity consumption and chemicals used at site 2, which treats 98.4% of the brine. Further contribution analysis (not included in this report) shows that electricity consumption accounts for 25% of climate change impact but only 0.4% for mineral, fossil & resource depletion. Sulphuric acid is the most critical chemical used, accounting for 17% of the climate change impact. It also has a notable contribution to Acidification, Freshwater Eutrophication, Freshwater Ecotoxicity and Mineral, fossil & resource depletion categories. Furthermore, the tested scenario of having no available waste heat in 2030 (if additional industry competes for supply), results in significantly poorer environmental performance. This highlights the importance and criticality of waste heat usage to reduce the environmental impacts. The recovery of sodium sulphate and sodium chloride provide significant environmental benefits when compared to other recovered products, reducing climate change by 1.5 and 1.2 $kgCO_2eq$, respectively, assuming that it will be reused.

3.5.2 LCC

Total cost of the ZB system with €1.57/m^3 was more expensive than the reference system at €0.41/m^3. However, this is largely expected as the current system does not involve treatment. The results do however suggest that if regulations change and limit the ability for discharge to sea (or increase fees/penalties), then the ZB system might offer an economically viable solution. Sulphuric acid and electricity use at Site 2 are responsible for most of the costs, in addition to the environmental impacts. However, the results highlight the importance of the recovered materials at Site 1, which although small, offer considerable revenue. Nevertheless, sulphuric acid is the most significant product, as in for the LCA. Hence, despite significant revenue being attained from the recovered products, this is not enough to balance the increased costs incurred from sulphuric acid and electricity. This is emphasised in the externalities results which emphasise the impact costs of the increased resource use of the ZB system.

3.5.3 Summary and conclusions

The addition of the ZB system was shown to increase overall operating costs compared to the current system. Since the current discharge to the nearby sea is very low cost and because there are no financial disincentives for doing so, this brings into question the economic viability of the ZB system for this case.

Furthermore, although the ZB systems results in environmental benefits for climate change, the impacts for the other categories increase with the ZB system including Acidification, Freshwater eutrophication, Freshwater Ecotoxicity and Resource Depletion due to sulphuric acid consumption, and higher costs. Furthermore, the scenario in 2030 highlights the importance of waste heat for evaporation processes, especially for Site 2 which treats most of the DWP brine. If this is not available, then the cost and environmental impacts would significantly increase.

Finally, the use of sulphuric contributes to a large portion of environmental impacts and therefore lower impacting alternatives should be sought.

4. Case study 2: Coal mine

4.1 System boundaries and description

The case study of the Polish coal mine refers to the treatment of saline wastewater discharged from a Polish coal mine which is located in ZG "Bolesław Śmiały" in Poland.

The typical composition of the wastewater stream of "Bolesław Śmiały" coal mine is presented in Table 8. The functional unit of the study is defined as "the treatment of 1 m^3 of coal mine brine".

Table 7: Coal mine wastewater feed composition (data acquired from D3.1 (Mitko, 2017))

Ion	Mean concentration (g/m^3)
Li^+	< 2.5
Na^+	8,191.67
NH_4^+	< 2.5
K^+	120.42
Mg^{2+}	284.92
Ca^{2+}	342.67
Cl^-	13,450
NO_3^-	< 2.5
SO_4^+	809.83
B	2.32
HCO_3	301.08

4.1.1 Reference case

The current treatment of the coal mine brine includes a settling pond that captures the large suspended solids, followed by dilution with industrial wastewater. This ensures that the discharge conforms to regulatory thresholds to enable the discharge to a nearby river. However, the relevant emissions to water are not inventoried in the SimaPro software, and no studies could be found that document any deleterious effects on the local waterways. As a result they cannot be translated into impacts. Therefore, it was decided to select a scenario treating the brine with an alternative as reference case to compare the ZB system performance. The reference technology chosen is the desalination plant in Czerwionka-Leszczyny, Poland, formerly known as Debiensko.

The reference plant treats a mixture of saline mine water and reverse osmosis retentate from brackish water desalination. The brine mixture is concentrated in an evaporator using the vapor compression method, and the resultant salt and gypsum are crystallized. Evaporators are powered with electrical energy, which makes their exploitation expensive. Considering that the data on the reference technology are limited and for comparability purposes, it was assumed that both reference and ZB technologies have the same pretreatment and work on 50 m^3/h of coal mine water. The system boundaries of the reference plant are provided in Figure 8.

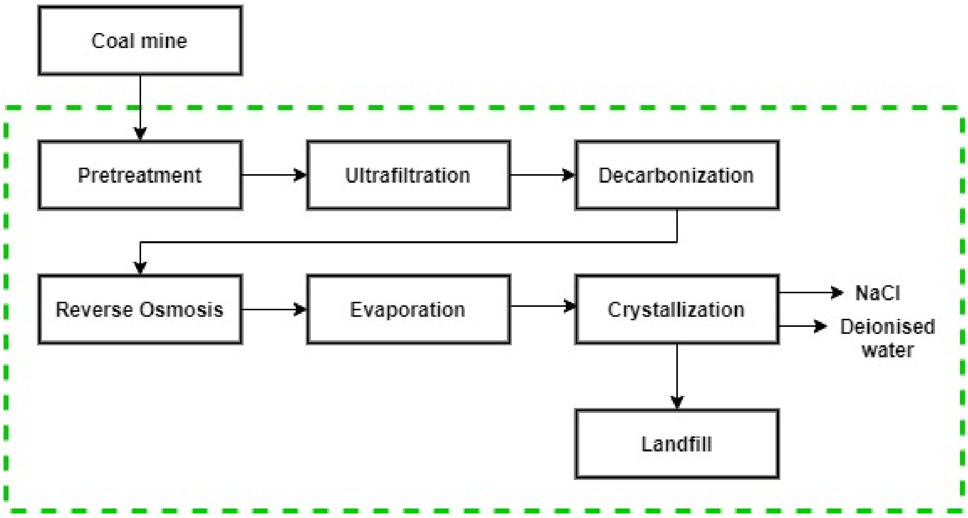


Figure 8: System boundaries of the reference system in Poland for the treatment of coal mine wastewater

4.1.2 Zero Brine system

A major driver for improved treatment is regulatory pressure to decrease the salt discharge to the river. Therefore, the ZB system is designed to avoid any discharge, optimise energy consumption, and recover marketable products. The latter include clean water, sodium chloride, magnesium hydroxide and gypsum. The ZB system and pilot plant were designed and operated by the Silesian University of Technology (SUT) within WP3.

The system boundaries of the current LCA include all process stages of the pilot ZB system for the treatment of the coal mine wastewater, while the boundaries are expanded to include the production of the recovered products (Figure 9). Clean water may be reused in the mining operations whilst other recovered products may be sold to the market.

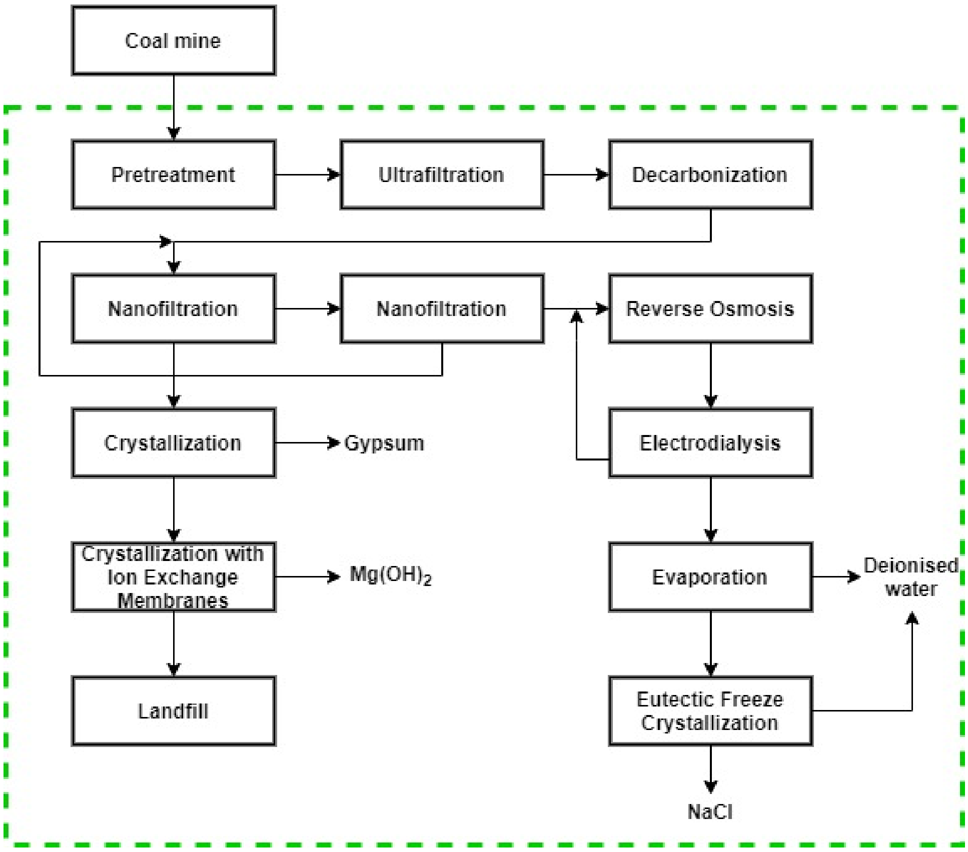


Figure 9. System boundaries of the pilot ZB system for the treatment of coal mine brine. Dotted line depicts the system boundaries

4.1.3 Life cycle inventory

The data in the LCI include the energy consumption, membrane use, chemical reagents for operational and cleaning purposes and recovered products of each unit process.

Foreground data were collected by SUT during the pilot plant operation (within WP3). The evaporator was not tested and the ecoinvent database was therefore used for this process. The ecoinvent database was used for background data, which was selected with based on the relevance and representativeness of Polish conditions such as the electricity mix..

The functional unit is "the treatment of 1 m^3 of coal mine brine-wastewater". Scaling was applied to the results received from the pilot plant operation in order to be representative of full-scale operation and so that it could be compared to the reference plant.

University of Palermo (UNIPA), as technology providers, were asked for their expert judgement on making an estimation about the process unit's energy consumption, chemicals consumption and emissions to the environment. Similarly, SUT was asked to provide a suchlike estimation for the BCr-1 operational details. To this end, simulations were carried out based on a hypothetical plant capacity of 50m^3/h brine treatment which is close to a small plant.

Aggregated life cycle inventory for the treatment of coal mine brine with the pilot ZB system and the reference system is given in Table 9.

Table 8. Life cycle inventory of the Polish coal mine case for the treatment of 1 m³ brine

	Process	ZB system	Debiensko reference case	Unit
Energy consumption				
Electricity	All processes	11.1	59.6	kWh
Auxiliary materials				
Propylene glycol, liquid	Eutectic Freeze Crystallization	850	-	mg
Lime	Crystallization with Ion Exchange Membranes	370		g
Polypropylene	Pretreatment	300	300	g
Tap water	Decarbonation, Reverse Osmosis, Electrodialysis, Crystallization with Ion Exchange Membranes	349	175	kg
Sodium sulphate, anhydrite	Electrodialysis	197	-	mg
Seawater RO module	Nanofiltration, Reverse Osmosis	36.4	8	cm^2
Ultrafiltration module	Ultrafiltration	5.60E-05	5.60E-05	p
Polystyrene	Electrodialysis	36	-	mg
Compressed air	Decarbonation	9.6	9.6	m^3
Hydrochloric acid, in 30% solution state	Decarbonation	6	6	kg
Waste disposal				
Inert material landfill	Crystallization with Ion Exchange Membranes	0.180	1090	g
Recovered Products				
Deionised water	Evaporation, Eutectic Freeze Crystallization	0.8	0.74	m^3
Sodium Chloride (NaCl)	Eutectic Freeze Crystallization	16.5	14.4	kg
Gypsum	Crystallization	0.672	-	kg
Magnesium Hydroxide ($Mg(OH)_2$)	Crystallization with Ion Exchange Membranes	0.455	-	kg

4.1.4 LCC inventory

The main aim of the LCC is to provide an assessment of the full-scale ZB system, compared to the current (reference) system, ZB treatment, or disposal. The LCC was based on the same functional unit and the system boundaries of the LCA. This created alignment between the two assessments throughout the project. Consequently, the data used in the LCA is also used as a basis in the LCC. The CAPEX and OPEX inventory values are provided in Table 10 and Table 11, respectively.

Table 9: CAPEX inventory per functional unit (m3) for the coal mine

Unit	€/FU
Nanofiltration	0.023
Crystallizers	0.004
Ultrafiltration	0.015
Reverse Osmosis (RO)	0.022
Ion Exchange Membranes (Decarbonation)	0.005
Electrodialysis	0.005
SUM	**0.074**

Table 10: Life cycle costing inventory of the coal mine case for the treatment of 1 m^3 brine

Material	Cost (€/1 m^3 brine)
Energy consumption	
Electricity	1.221
Raw & Auxiliary materials	
Propylene glycol, liquid	0.000119
Lime	0.066785
Polypropylene	0.135708
Tap water	0.36296
Sodium sulfate, anhydrite	2.96E-05
Polystyrene	0.030805
Hydrochloric acid, in 30% solution state	1.41
Waste disposal	
Inert material landfill	8.82E-06
Recovered Products	
Deionised water	2
Sodium Chloride (NaCl)	0.9405
Gypsum	0.2856
Magnesium Hydroxide (Mg(OH)2)	0.7189

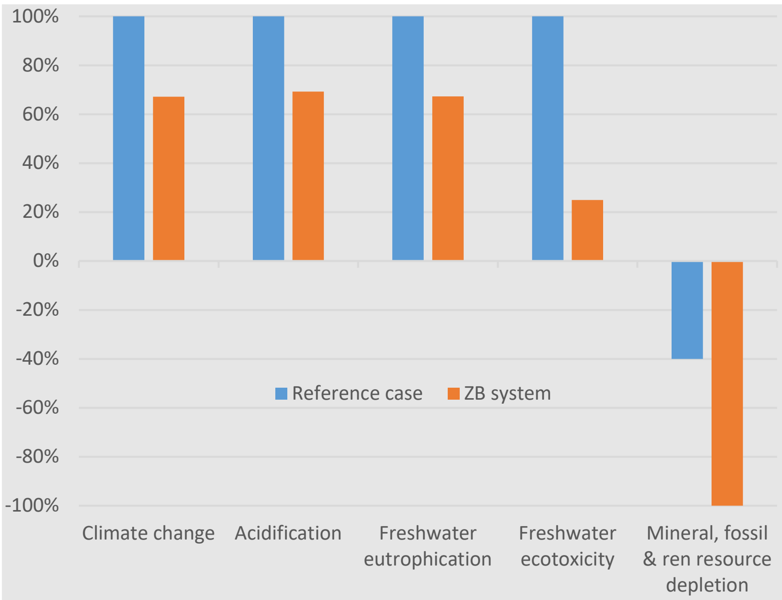
Maintenance costs cover continuous maintenance as well as periodic maintenance and investments such as replacement of membranes. Investments are assumed to be depreciated linearly for a 35-year Life Cycle. Cost of staff covers the number of full-time employees (FTE) required to operate the plant and the cost reflects site and country specific conditions.

Expected revenues from recovered products is included in the cost analysis and reflects primarily the market value of similar products in the market.

4.2 Results - Life Cycle Impact Assessment

4.2.1 Comparison with reference case

Figure 10 shows the LCIA percentage comparison of the ZB system with the reference case for the treatment of 1m^3 of coal mine brine. The ZB system performs better for all impact categories analysed, with a reduced impact of between 25-75% compared to the reference case. The largest reduction of 75% is recorded for freshwater ecotoxicity. With respect to the impact category of resource depletion where net savings are estimated for both cases, the reference case has 60% lesser savings compared to the ZB system. The improved performance of the ZB system is mainly attributed to the lower energy consumption and higher sodium chloride recovery.



Impact category	Reference case	ZB system
Climate change kg CO2 eq	18.6	12.5
Acidification molc H+ eq	0.14	0.10
Freshwater eutrophication kg P eq	0.022	0.015
Freshwater ecotoxicity CTUe	133.5	33.3
Resource depletion kg Sb eq (E-05)	-3.8	-9.4

Figure 10: Percentage comparison (and quantities in table) of impacts for 1m3 of brine for selected representative impact categories, with absolute values in table

4.2.2 Contribution analysis

In this section, the results of the contribution analysis of the different processes to the climate change impact performed for the ZB system compared to the reference system, are provided (Figure 11). The respective results of the contribution analysis for all five impact categories are presented in the Appendix section 10.2.

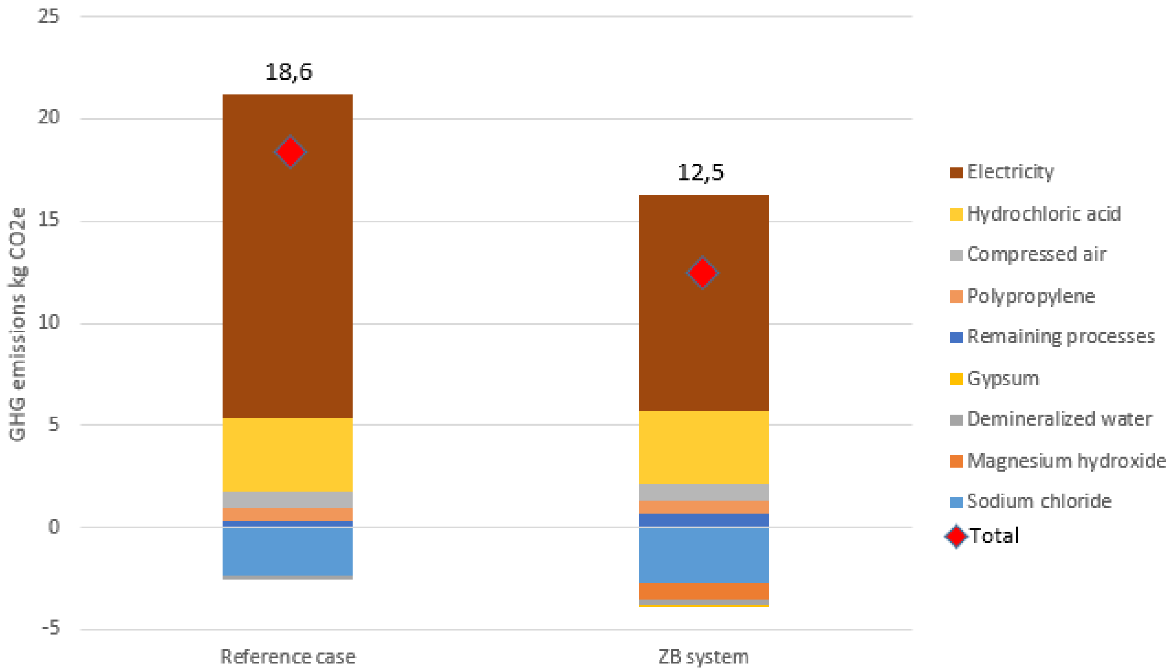


Figure 11: Contribution analysis of climate change of ZB system compared to reference system for the treatment of 1m³ coal mine brine

The contribution analysis for the reference case and the ZB system (Figure 11) shows that in both cases, the electricity consumption in the treatment of brine is the major contributor to the climate change impact, with the relevant emissions in the reference case consisting 75% of total positive emissions. In the case of the ZB system, the respective contribution lowers to 65%. The consumption of hydrochloric acid in the decarbonation step is also an important contributor of GHG emissions in both cases, with the relevant emissions contributing 17-22% to total positive emissions. With respect to the savings in GHG emissions, sodium chloride recovery provides most of the benefits amongst the recovered products, with the contribution in total savings being 91% in the reference case and 71% in the ZB system. Although the savings from sodium chloride recovery is higher in the ZB system, their contribution to the total savings is lower, as there is a contribution from the recovery of magnesium hydroxide (23%) in this case. The recovery of sodium chloride provides for a considerable reduction in net GHG emissions (16%) in the ZB system, while the recovery of magnesium hydroxide provides for a further 5% in net emissions. The contribution of water recovery in total savings is low in both cases (6-9%), while gypsum recovery in the ZB system seems to provide negligible benefits with its contribution being below 1%.

4.3 Results – Life Cycle Costing

4.3.1 LCC

The LCC results comparing the reference case with the ZB system are shown in Figure 12. Costs per cubic metre for the ZB system are considerably lower than the reference system. In addition, the increased recovery of products in the ZB system results in significant revenue, resulting in a profit of

€0.45/m³ compared to a cost of €7.97/m³ for the reference system. The main costs come from energy use and hydrochloric acid used in the decarbonation process. The most important recovered products are (in order of revenue) deionised water, sodium chloride and magnesium hydroxide, whilst the highest cost derives from polypropylene. For the reference system costs are heavily dominated by energy consumption.

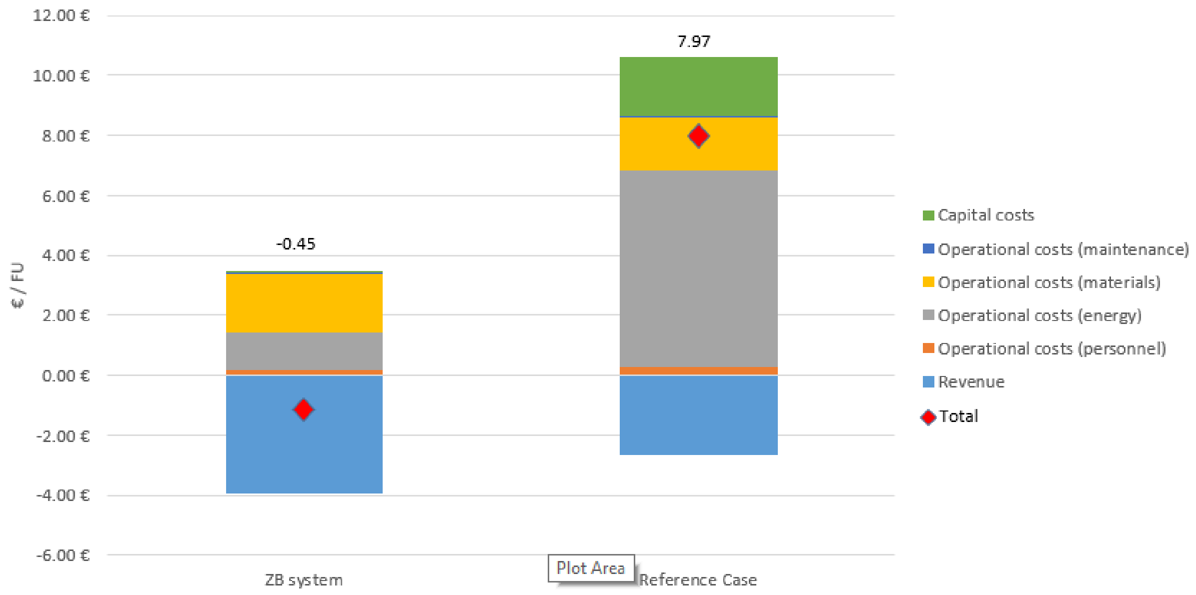


Figure 12: LCC results for the reference and ZB systems (coal mine)

4.3.2 Externalities

Table 12 shows the environmental externalities based on EPS impact costs (Steen, 2015). The externalities are combined with the internal costs in Figure 13. It should be noted that for the purposes of this analysis it is assumed that ELU are equivalent to Euros. Therefore, the internal costs are added to the externalities to represent total costs of the systems. Together they show that the ZB system has lower externalities associated with its life cycle, primarily due to the recovered resources, which provide large credits. Internal costs due to chemical use dominate the costs of the reference system.

Table 11: Environmental externalities comparing the ZB & reference system for the coal mine

Damage category	ZB (ELU)	Reference (ELU)	% change Ref to ZB system
Ecosystem services	0.0511	0.0737	-31%
Access to water	0.0031	0.0045	-31%
Biodiversity	0.0002	0.0002	-31%
Building technology	0.0004	0.0006	-31%
Human health	2.1361	3.1465	-32%
Abiotic resources	-0.3698	-0.4192	-704%
Total	**-1.18**	**2.81**	**-142%**

**Environmental Load Unit*

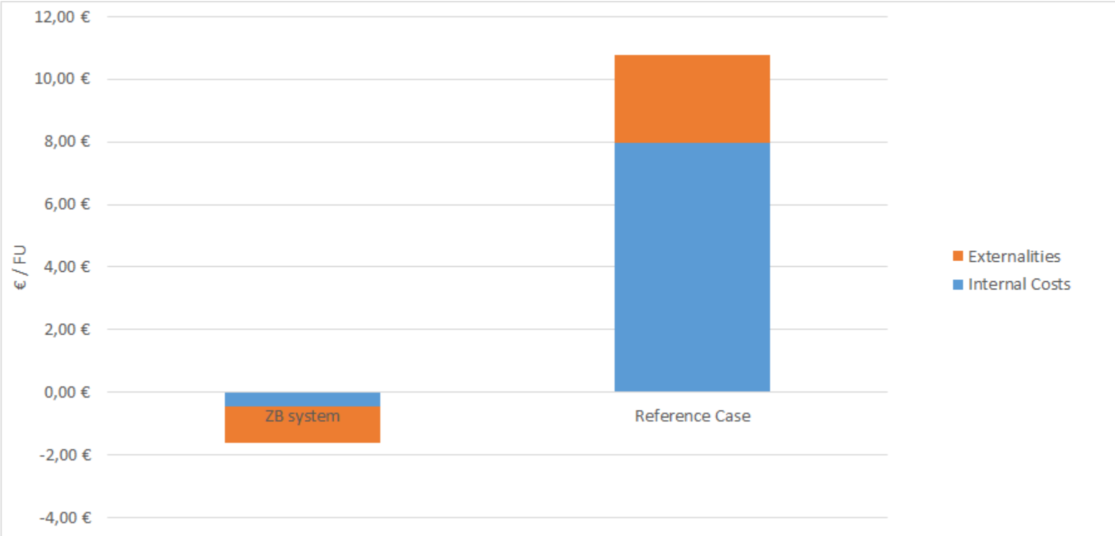


Figure 13: Internal costs and externalities for the ZB system and reference system at the coal mine

4.4 Sensitivity analysis

4.4.1 Perturbation analysis

In this section, a perturbation analysis takes place to determine the effect of a single parameter`s change on the LCIA results for the coal mine ZB system. In Table 13, the Sensitivity Ratios (SR) for those parameters/processes with the highest influence in the total LCIA results are presented. All parameters have been tested for a variation of -10% and +10% in their values and the SR have been calculated according to Clavreul et al. (2012).

Table 12: Perturbation analysis and sensitivity ratios of the climate change impact assessment for a variation of -10% and +10% in the parameter values of the coal mine ZB system (Parameter amounts and impact category results are given per 1 m³ brine)

Parameter	Original parameter value		10% decrease in parameter value		10% increase in parameter value		Sensitivity Ratio
	Unit	Parameter amount	Amount	Total climate change (kg CO_2 eq)	Parameter amount	Total climate change (kg CO_2 eq)	
Electricity, high voltage {PL}	MJ	39.81	35.83	11.45	43.79	13.57	0.85
Hydrochloric acid	kg	6.00	5.40	12.16	6.60	12.86	0.28
Sodium chloride	kg	-16.50	-14.85	12.78	-18.15	12.24	0.21
Magnesium hydroxide	g	-455	-409	12.59	-500	12.42	0.07
Compressed air	m3	9.60	8.64	12.43	10.56	12.59	0.07
Polypropylene	g	300	270	12.44	330	12.58	0.05

With respect to the parameters having the highest influence in the total LCIA results, it may be concluded from the perturbation analysis that these refer to electricity consumption, hydrochloric acid consumption and sodium chloride recovery. Hence a variation of 10% in their values results in a respective change of 8.5%, 2.8% and 2.1% to the total LCIA result (Table 13).

4.4.2 Scenario analysis

In this section, the results of the scenario analysis are presented, which compares the results of the ZB system against a scenario with the projected electricity mix of Poland for 2030 and another with 100% renewable energy (in this case wind produced electricity). These changes are only applied to the foreground system. The 2030 energy mix for Poland (Table 14) was estimated based on current available projections and 2030 country energy production targets which are 1) Electricity from coal decreases from 80% to 60%, 2) Total percentage of renewables reach 20% (IEA, 2017; https://www.iea.org/countries/poland).

Table 13: Electricity mix projection for Poland in 2030 compared to 2018

Electricity generation by energy carrier	2018	2030
Lignite	29.1%	24%
Hard coal	47.9%	36%
Oil	2.8%	5.0%
Natural gas	7.5%	14.5%
Biogas	3.8%	8.8%
Hydro	1.2%	1.6%
Wind	7.5%	9.6%
Photovoltaic	0.2%	0.1%

In Figure 14, the results of the scenario analysis is presented. The wind energy scenario generates the lowest environmental burdens for the impact categories of climate change, acidification and freshwater eutrophication (7-18% of the reference scenario). In particular, the wind energy scenario results in significant reductions for freshwater ecotoxicity, compared to the reference scenario. For resource depletion, all scenarios generate savings while the differences amongst them are small, as they are mostly related to the substitution of materials and therefore the results are not energy sensitive. The scenario referring to the projected electricity mix for 2030, lies somewhere in the middle of the two other scenarios, with its worst performance being observed in the climate change impact category (93% of the reference scenario).

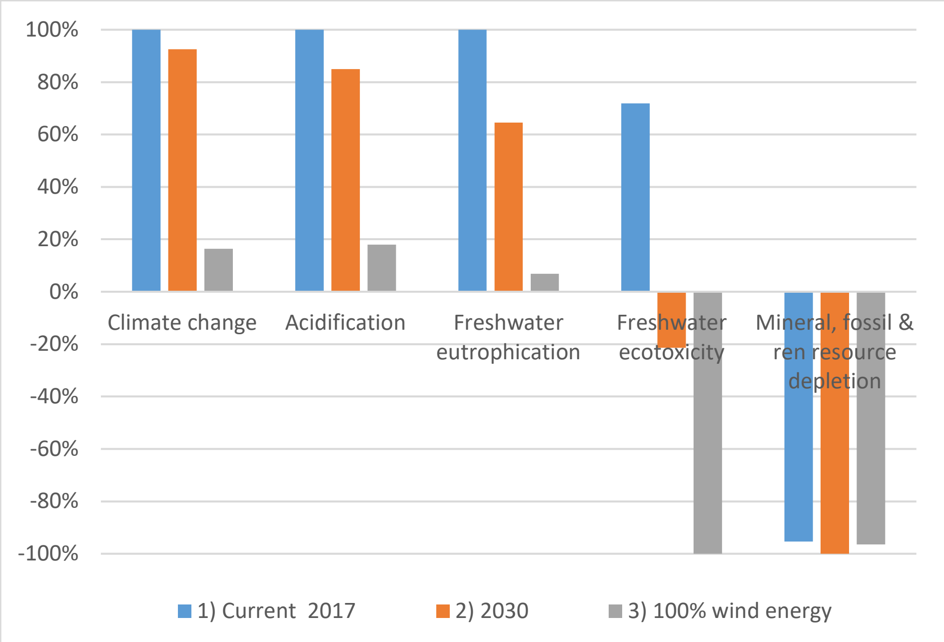


Figure 14: Scenario analysis for different sources of energy in Poland, 1). Reference scenario, 2). Electricity mix 2030, 3). Wind energy

4.5 Discussion and Summary

4.5.1 LCA

The results of the LCIA showed that the ZB system performs better compared to the reference case (i.e. the Debiensko technology) in all the examined impact categories, which is mainly attributed to the lower energy consumption achieved in the ZB system. The recovery of materials is also an important driver, as they provide for a considerable reduction in net GHG emissions. Further improvements in the process efficiency should focus on those parameters having the highest influence in the total LCIA results, such as reduction of electricity consumption and hydrochloric acid consumption and increase in sodium chloride recovery. Furthermore, the use of wind as source of energy instead of the current national electricity mix would dramatically improve the environmental performance of the ZB system.

4.5.2 LCC

The main internal cost of the ZB system is the consumption of energy and hydrochloric acid in the decarbonation stage. Economic benefits are expected mainly due to the recovered deionised water, the sodium chloride and magnesium hydroxide. In total the internal costs are negative, which mean that the system is marginally profitable at €0.45/m^3, in comparison to the reference system which has relatively high internal costs, mainly due to energy consumption. Regarding externalities, in the case of the ZB system, those are negative as well (that shows environmental benefits), while on the case of the reference system, externalities are estimated to be around 2,8 € / functional unit.

4.5.3 Summary and conclusions

In conclusion, the ZB system designed for the coal mine brine provided both environmental and economically superior performances compared to the reference system. In conclusion, the LCA and LCC provide complementary results, with the LCC suggesting that the system has potential to generate revenue.

5. Case study 3: Textile plant

5.1 System boundaries and description

The textile plant is located at Büyükkarıştıran- Lüleburgaz, Kırklareli, Turkey. The case study examines the integration of a ZB system into the textile manufacturing plant to treat brine effluent and recover by-products for reuse. Brine is recovered from the RO unit, that treats the production wastewater, and is the result of using salt in both the dyeing and water softening processes.

The functional unit of the study is considered to be the "treatment of 1 m^3 of RO textile brine". Specifically, this brine refers to a typical composition of the wastewater stream of the advanced water treatment unit (Reverse Osmosis retentate) of the ZORLU textile plant, as presented in Table 15.

Table 14: Textile RO brine composition

Ion	Mean concentration (g/m^3)
CO_3	34.9
Zn	40.,15
NH_4-N	48.8
SiO_2	49.9
Total Nitrogen	59.8
Color Pt-Co	71.8
Li^+	0.17E-3
Al^+	0.28E-3
B	0.37E-3
Sr	0.461-3
Fe^{2+}	0.73E-3
Cl^-	1598.7
SO_4^+	1987.8
HCO_3	301.08
Mg^{2+}	11.8323
Ca^{2+}	61.477
K^+	127.759
Na^+	2.392

5.1.1 Reference case

The reference case used is the current best practice applied in the industry for the treatment of brine. The textile plant currently discharges its brine to its own biological and chemical wastewater treatment plant (Figure 15). The reference case is a scenario that assumes the brine is directed to an advanced water treatment plant consisting of ultrafiltration and reverse osmosis units for the recovery of water and its reuse within the industry (comparable to the ZB system).

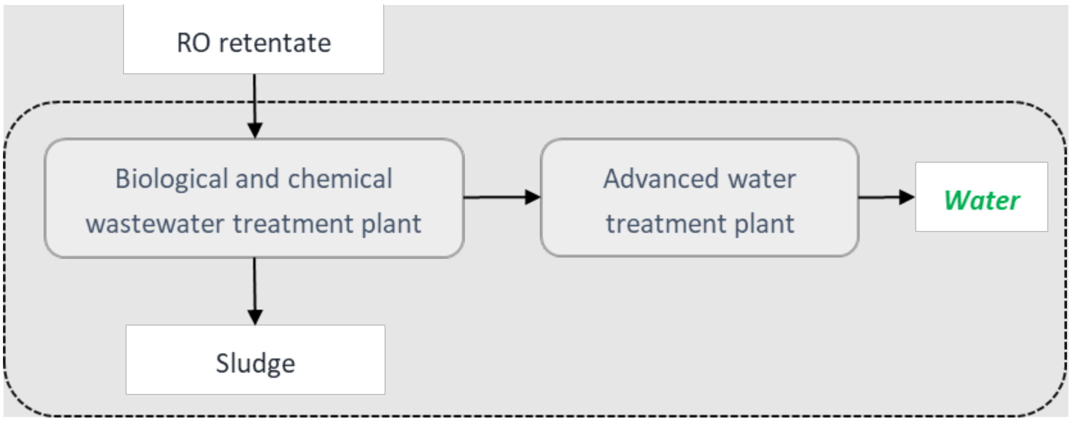


Figure 15: System boundaries of the reference system in Turkey for the treatment of textile industry brine. The avoided products of the system are highlighted with green colour. Dotted line depicts the system boundaries

5.1.2 Zero Brine system

The ZB system is designed to recover salt (NaCl) solution and clean water from the textile plant effluent. The treatment train of the ZB system has been modified since the preliminary LCA (Harris et al. 2020) with the addition of two nanofiltration units and a rearrangement of the process units. In the final configuration, deionized water and sodium chloride solution are the recovered products from the reverse osmosis and ion exchange units respectively. Figure 16 illustrates the LCA boundaries of the examined ZB system.

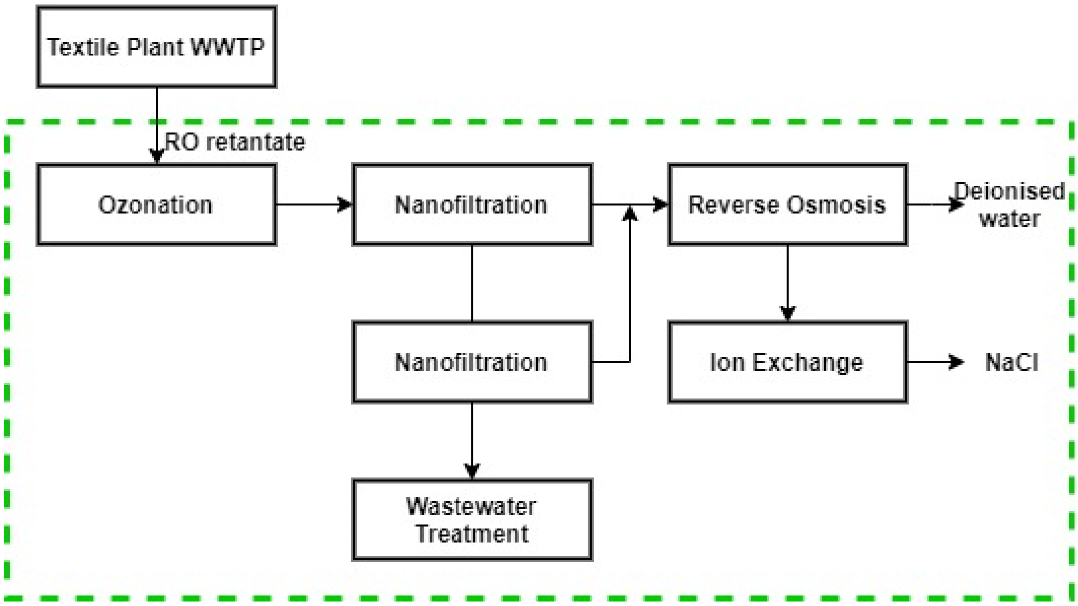


Figure 16: System boundaries of the pilot ZB system for the treatment of RO retentate from the textile industry. Dotted green line depicts the system boundaries.

5.1.3 Life cycle inventory

The final stage LCI was generated using data obtained by the experimental operation of the pilot plant in WP3 of Zero Brine. The data in the LCI includes the energy consumption, membrane use, chemical reagents for operational and cleaning purposes as well as recovered products of each unit process.

The pilot plant was designed and operated by the Scientific and Technological Research Council of Turkey (TUBITAK). Apart from the foreground data provided by TUBITAK, the inventory has also utilized experimental results and data from the pilot plant operation performed in WP3.

The University of Palermo (UNIPA) were asked for their expert judgement on making an estimation about the process unit's energy consumption at an operational scale. To this end, simulations were carried out based on a hypothetical ZB plant capacity of $100m^3/h$ brine treatment. LCI data on the reference case were provided directly by the Zorlu industry.

The ecoinvent database was utilised for background data. Cyanoguanidine was not included in the ecoinvent database, and therefore literature data was used. The background data used was selected with respect to the relevance and representativeness of the market and production conditions in Turkey. Namely, data for energy consumption was used specifically for the Turkish energy market.

The functional unit of the study is considered to be the "treatment of $1m^3$ of textile RO brine". To this end, scaling was applied to the data received from the pilot plant operation, since the pilot plant's capacity was not adequate for the continuous treatment of the above quantity.

Aggregated life cycle inventory for the treatment of the textile RO retentate with the pilot ZB system and the reference system is given in Table 16.

Table 15. Life cycle inventory of textile industry case for the treatment of 1 m³ RO retentate

	Process	Reference case	ZB system	Unit
Energy consumption				
Electricity	All processes	2.0	16.0	kWh
Auxiliary materials				
Ammonia liquid	Nanofiltration, Reverse Osmosis	-	3.6	g
Cyanoguanidine 42.5%	WWTP	90	3.6	g
Compressed air	Ozonation	-	15.65	m^3
Polyacrylamide	WWTP	2	0.08	g
Polyaluminium chloride	WWTP	10	0.4	g
Sodium hypochlorite, in 15% solution state	WWTP	12	0.48	g
Sulphuric acid	WWTP	550	22	g
Hydrochloric acid, in 30% solution state	Nanofiltration, Reverse Osmosis	-	5.1	g
Cationic resin	Ion exchange	-	66.7	g
Seawater RO module	Nanofiltration, Reverse Osmosis, WWTP	7	35.78	cm^2
Ultrafiltration module	Ultrafiltration	5.00E-06	2.00E-07	p
Waste disposal				
Waste incineration	WWTP	1.83	0.073	kg
Landfill	WWTP	-	5.184	g
Recovered Products				
Deionised water	Reverse Osmosis	-	0.861	m^3
Sodium chloride	Ion Exchange	-	2.08	kg

In the case of cyanoguanidine ($C_2H_4N_4$), which is used as a colour removal agent in the wastewater treatment plant of Zorlu industry, no relevant process was found in the Ecoinvent database. Therefore, it was modelled based on the guidance provided by CEPE LCDN node: Chemicals for Paints datasets for PEF calculations.

5.1.4 LCC inventory

The main aim of the LCC is to provide an assessment of the full-scale ZB system, compared to the current (reference) system. The LCC was based on the same functional unit and the system boundaries of the LCA. This created alignment between the two assessments throughout the project. Consequently, the data used in the LCA were also used as basis in the LCC. The CAPEX inventory values are provided in Table 17.

Table 16: CAPEX inventory per functional unit (m3) for the textile plant

Unit	(€/FU
Nanofiltration	0.017 €
Reverse Osmosis (RO)	0.017 €
Ion Exchange Membranes (Decarbonation)	0.004 €
WWTP	0.010 €
Ozonation	0.030 €
SUM	**0.078 €**

Maintenance costs cover continuous maintenance as well as periodic maintenance and investments such as replacement of membranes. Investments are assumed to be depreciated linearly for a 35-year Life Cycle. Cost of staff covers the number of full-time employees (FTE) required to operate the plant and the cost reflects site and country specific conditions.

Expected revenues from recovered products is included in the cost analysis and reflects primarily the market value of similar products in the market. The LCC inventory of the textile plant case is given in Table 18.

Table 17: Life cycle costing inventory of the textile plant case for the treatment of 1 m³ brine

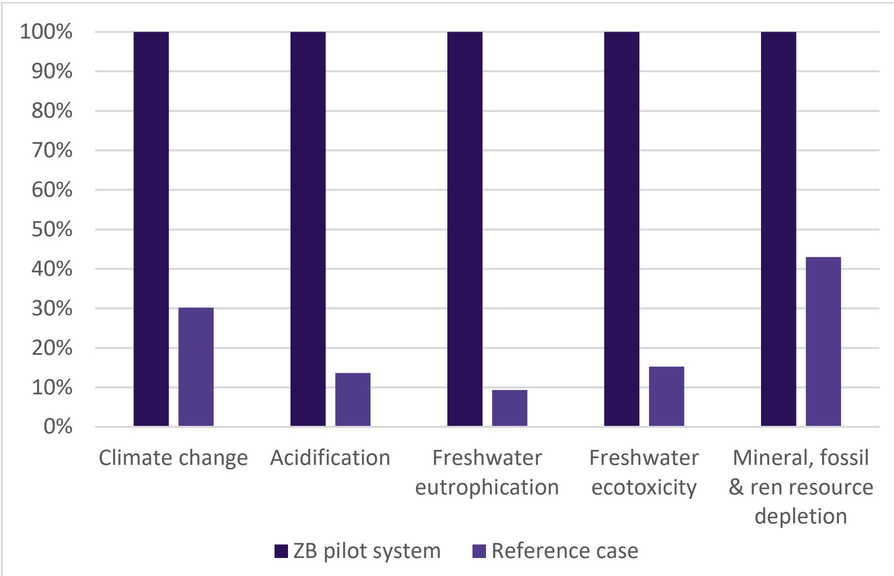
Material	Cost (€/1 m³ brine)
Energy consumption	
Electricity	1.44
Raw & Auxiliary materials	
Ammonia liquid	0.002198
Cyanoguanidine 42.5%	0.09432
Polyacrylamide	0.0052
Polyaluminium chloride	0.224
Sodium hypochlorite, in 15% solution state	0.00949
Sulfuric acid	0.00583
Hydrochloric acid, in 30% solution state	0.001199
Cationic resin	0.285803
Waste disposal	
Waste incineration	0.05195
Landfill	0.096682
Recovered Products	
Deionised water	2.1525
Sodium chloride	0.11856

5.2 Results - Life Cycle Impact Assessment

In the figures below, the total impact of the ZERO BRINE pilot plant wastewater treatment system, as well as the network of the processes that contribute more than 10% in the impact assessment can be seen.

5.2.1 Comparison with reference case

In Figure 17, the results of the LCIA for the treatment of 1m^3 of brine from the textile industry are presented in the form of percentage comparison of the reference case with the ZB system.



Impact category	Reference case	ZB system
Climate change kg CO2 eq	4.07	13.49
Acidification molc H+ eq	0.01	0.11
Freshwater eutrophication kg P eq	0.002	0.016
Freshwater ecotoxicity CTUe	175.7	1153.7
Resource depletion kg Sb eq (E-04)	2.15	5.0

Figure 17: Percentage comparison (and quantities in table) of impacts for 1m3 of brine from textile industry for selected representative impact categories, with absolute values in table.

The LCIA results for the comparison of the ZB system with the reference case (i.e. the Zorlu wastewater effluent treatment) are presented in Figure 17. It shows that the existing system for treating the RO retentate, performs better in all the examined impact categories. The environmental burdens of the reference case system are estimated to be 9-43% of the respective values for the ZB system. Freshwater eutrophication is the worst performance being, with the reference case being 91% lower. The best comparative performance of the ZB system is observed for resource depletion, where the overall impacts are reduced due to the recovery of salt and water.

5.2.2 Contribution analysis

In this section, the results of the contribution analysis of the different processes to the climate change impact performed for the ZB system, compared to the reference system, are provided (Figure 18). The respective results of the contribution analysis for all five impact categories are presented in the Appendix, section 10.3.

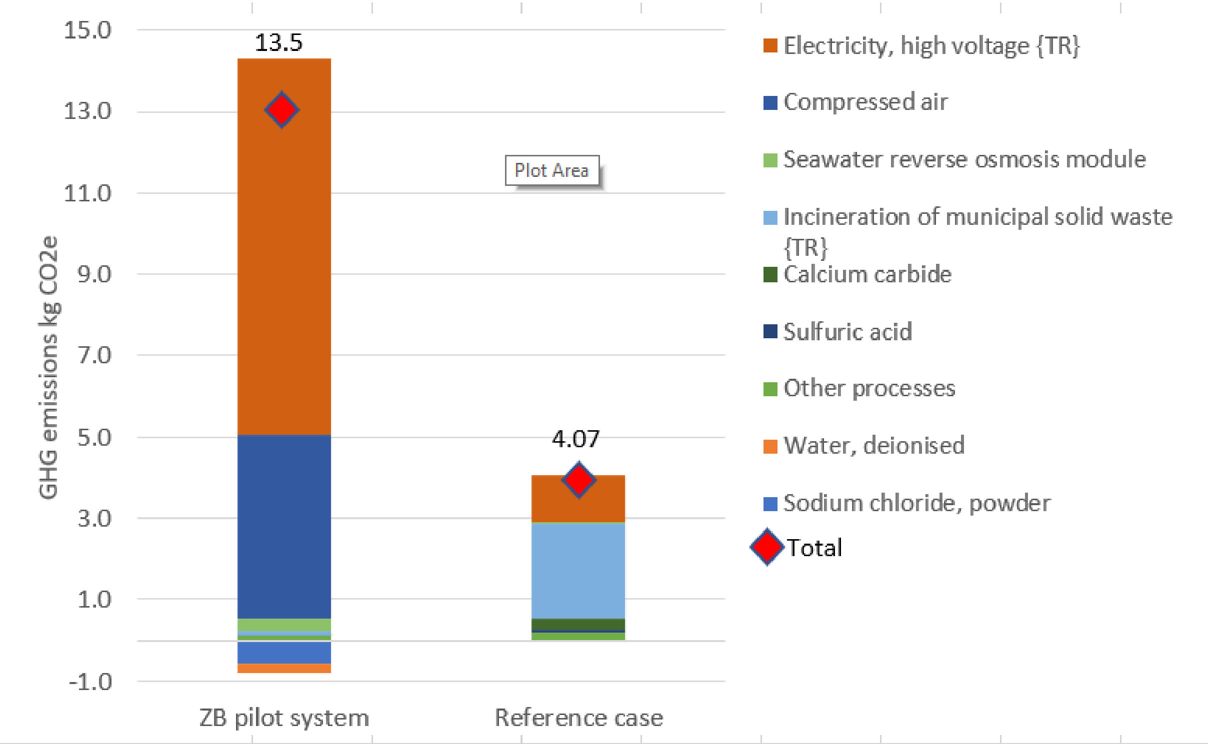


Figure 18: Contribution analysis of climate change of ZB system compared to the reference system for the treatment of 1m³ brine from the textile industry

The contribution analysis in Figure 18 shows that in the case of the ZB system, electricity consumption is the major contributor to the climate change impact, with 65% of total positive emissions. The use of compressed air in the ozonation step is also an important contributor of GHG emissions in the case of the ZB system, with the relevant emissions contributing 32% to total positive emissions. In the reference case, the treatment of sludge produced from the wastewater treatment plant is the major contributor in the positive emissions (57%), while electricity consumption contributes by 28%. With respect to the savings in GHG emissions associated to the ZB system, sodium chloride recovery provides most of the benefits, with the contribution in total savings being 69% while the remaining 31% coming from the recovery of water.

5.3 Results – Life Cycle Costing

5.3.1 LCC

Figure 19 shows the LCC results for the textile plant highlighting the much lower costs of the ZB system compared to the reference system. In addition, a revenue is generated from the recovery of deionised water means that the ZB system has a significantly lower total cost of €0.3 /m^3 compared to €12.25 /m^3. The main costs are due to energy consumption (€1.44 /m^3) and polyaluminium chloride (0.22 /m^3) and Cationic resin (0.29 /m^3).

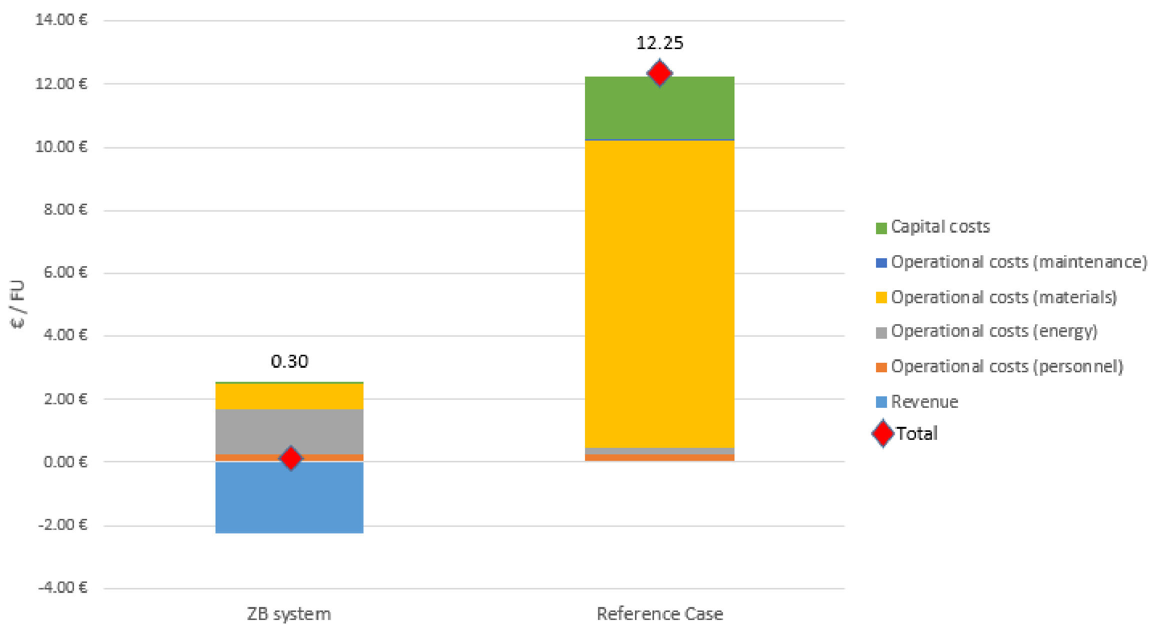


Figure 19: LCC results for the reference and ZB systems (textile plant)

5.3.2 Externalities

Table 19 shows the environmental externalities based on the Environmental Priority System (EPS) (Steen, 2015). The externalities are combined with the internal costs in Figure 20. It should be noted that for the purposes of this analysis it is assumed that ELU are equivalent to Euros. Therefore, the internal costs are added to the externalities in Figure 20 to represent total costs of the systems.

The externalities are higher for the ZB system, in contrast to the internal costs, where costs are much higher in the reference system. The total impact costs to society are therefore higher for the ZB system. The main reason for this is the large value for "Abiotic resources", which occurs mainly due to the Ozonation Stage (see Table 34 in the Appendix). This could be due to a disproportionately high value within the EPS system (or error), where ozonation represented 115% of total impact for abiotic depletion. Or it may suggest that alternative disinfection technology such as UV should be investigated.

Table 18: Environmental externalities for ZB & reference system in Turkey

Damage category	Unit*	ZB system	Reference	% change Ref to ZB system
Ecosystem services	ELU	0,016	0.0048	230%
Access to water	ELU	0,0009	0.00028	295%
Biodiversity	ELU	5.91 E-05	2.17 E-05	170%
Building technology	ELU	3.22 E-05	3.74 E-05	-14%
Human health	ELU	9.823	1.27	670%
Abiotic resources	ELU	26.42	9.73	170%
SUM		**36.25**	**11.01**	**330%**

**Environmental Load Units*

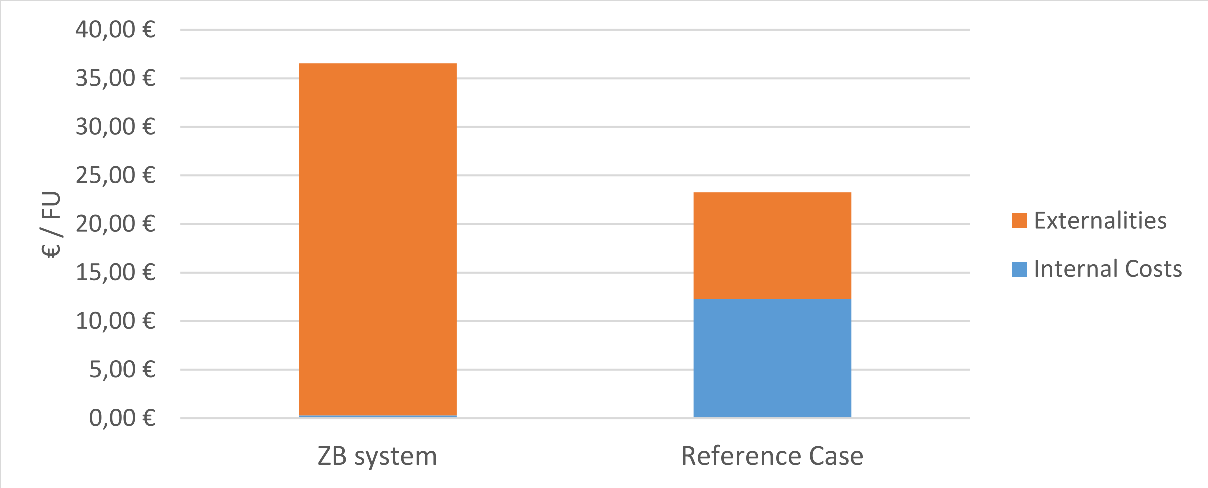


Figure 20: Internal costs and externalities for the ZB system and reference system at the textile plant

5.4 Sensitivity analysis

5.4.1 Perturbation analysis

In this section, a perturbation analysis takes place to determine the effect of a single parameter`s change on the LCIA results for the textile plant ZB system. In Table 20, the Sensitivity Ratios (SR) for those parameters/processes with the highest influence in the total LCIA results for the impact of climate change are presented. All parameters have been tested for a variation of -10% and +10% in their values and the SR have been calculated according to Clavreul et al. (2012).

Table 19: Perturbation analysis and sensitivity ratios of the climate change impact assessment for a variation of -10% and +10% in the parameter values of the textile plant ZB system (Parameter amounts and impact category results are given per 1 m³ brine)

Parameter	Original parameter		10% decrease in parameter		10% increase in parameter		Sensitivity Ratio
	Unit	Amount	Parameter amount	Total climate change value (kg CO_2 eq)	Parameter amount	Total climate change (kg CO_2 eq)	
Electricity, high voltage {TR}	MJ	57.89	52.10	12.56	63.68	14.41	0.69
Compressed air	m³	15.65	14.09	13.03	17.22	13.94	0.34
Sodium chloride	kg	-2.08	-1.87	13.54	-2.29	13.43	0.04
Seawater reverse osmosis module	cm²	35.78	32.20	13.45	39.36	13.52	0.02
Water, deionised	kg	-861.00	-774.90	13.51	-947.10	13.46	0.02

With respect to the parameters having the highest influence in the total LCIA results, it may be concluded from the perturbation analysis that these refer to electricity consumption and compressed air consumption. Hence a variation of 10% in their value results in a respective change of 6.9% and

3.4% to the total LCIA result (Table 20), while a potential increase in the amount of recovered products is not expected to significantly affect the LCIA results.

5.4.2 Scenario analysis

In this section, the results of the scenario analysis are presented, which compares the results of the ZB system against a scenario with the projected electricity mix of Turkey for 2030 and another with 100% renewable energy (in this case wind produced electricity). These changes are only applied to the foreground system. The 2030 energy mix for Turkey (Table 21) was estimated based on available projections and 2030 country energy production targets (Aksoy et al., 2020; TEIAS, 2021).

Table 20: Electricity mix projection for Turkey in 2030 compared to 2020

Electricity generation by energy carrier	2020	2030
Lignite	16.2%	13.5%
Hard coal	18.6%	15.5%
Oil	0.1%	0.2%
Natural gas	22.7%	27.3%
Biogas	1.8%	0.9%
Hydro, reservoir	18.9%	12.6%
Hydro, run-of river	6.6%	4.4%
Geothermal	3.3%	1.7%
Wind	8.1%	16.9%
Photovoltaic	3.7%	7.0%

In Figure 21, the results of the three scenarios' analysis are presented. The wind energy scenario generates the lowest environmental burdens for the impact categories of climate change, acidification and freshwater eutrophication (33-46% of the reference scenario). In the impact categories freshwater ecotoxicity and resource depletion, there are no significant differences among the scenarios, showing that the respective performance is not sensitive to different energy sources.

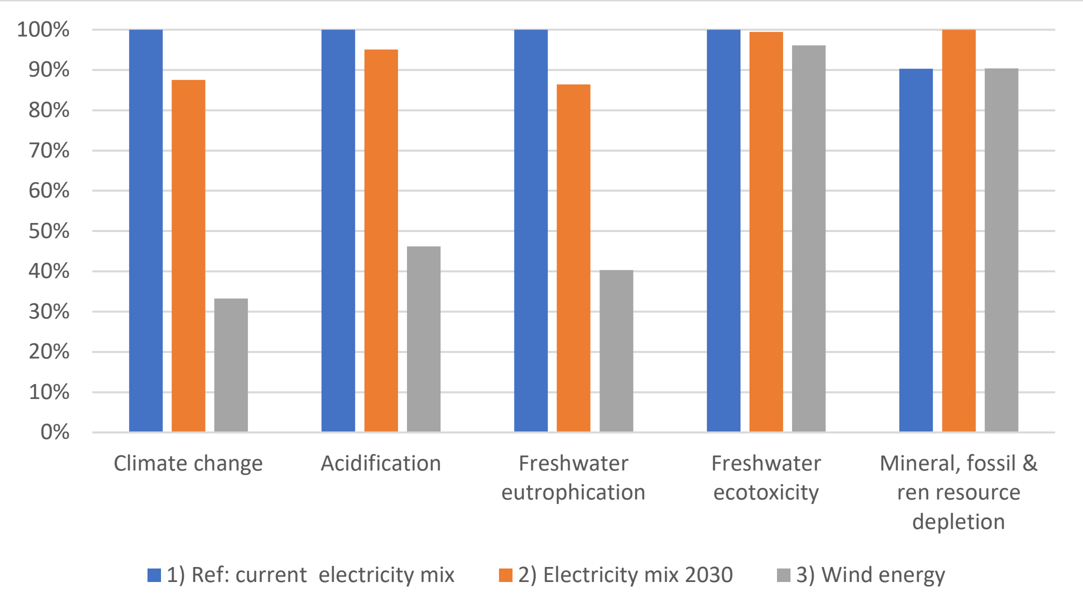


Figure 21: Scenario analysis for different sources of energy in Turkey, 1. Reference scenario, 2. Electricity mix 2030, 3. Wind energy

5.5 Discussion

5.5.1 LCA

The LCIA results comparing the ZB system with the reference case (i.e. the Zorlu wastewater effluent treatment) show that the existing treatment system for the RO retentate performs better for all impact categories. The lower performance of the ZB system is mainly attributed to the higher energy consumption compared to the reference system. Electricity consumption exerts a high influence on the LCIA results, which are not counteracted by the recovered quantities of products. Further improvements in the process efficiency should focus on a substantial reduction of electricity consumption. Furthermore, the use of wind as source of energy instead of the current national electricity mix, would further improve the environmental performance of the ZB system.

5.5.2 LCC

As previously presented, in the main internal cost of the ZB system is energy consumption, while substantial economic benefits are expected mainly due to the recovered deionised water. In total the internal costs are marginally zero, which means that the system is economically viable. Whilst the reference system has relatively high internal costs, reaching to 12,25 € / functional unit. This is mainly due to raw and auxiliary materials, specifically Polyaluminium chloride (36%) and Cationic resin (46%), that dominate the life cycle costs.

Regarding externalities, in the case of the reference system, those were estimated to be around €11,0/m^3. In the case of the ZB system, those were estimated to be higher (around 36,0 € / functional unit) leading to a higher expected environmental burden. This was shown to be primarily due to the Ozonation Stage, which suggests that alternative disinfection technology could be considered.

5.5.3 Summary and conclusions

The LCA and LCC produced contrasting results where the reference system has lower environmental impacts than the ZB system but much higher cost. In conclusion, this suggests that the ZB system could be economically viable (dependent on the economics of deionised water recovery) and efforts should be made to reduce the environmental impacts of the system by the use of renewable energy and reduction of chemical use. In addition, improvements in efficiency would be expected at full scale.

6. Case study 4: Silica plant

6.1 System boundaries and description

6.1.1 Reference case

The silica case study located in Zaragoza, involves a chemical company producing silica derivatives which results in approximately 1,200,000 m^3/year of brine effluent. This is currently sent to the municipal wastewater treatment plant (WWTP) "La Cartuja" before being discharged to the local river. The existing water cycle of Industrias Químicas del Ebro (IQE) production process entails groundwater extraction, a pre-treatment process, and a subsequent reverse osmosis (RO) process which treats the water to be used for silica production, from which brine streams are generated. Due to the potential WWTP's technical impairment because of brines high content of total dissolved solids, the discharge of these effluents to the WWTP can only be performed in pulses of small volumes (regulated by the requirements applicable to industrial discharges of the responsible authority). Thus, brine's generation and storage impose a technical limitation for IQE's productivity and a potential local environmental risk for the surrounded environment and for the normal functioning of the WWTP.

6.1.2 Zero Brine system

The ZB system aims to treat IQE's effluent to recover sodium sulphate (Na_2SO_4) for sale and water for reuse in the plant. It consists of a physico-chemical pretreatment stage (pH modification, chemical addition, sand filtering and ultrafiltration), a NF stage (regenerated membranes RO) and an EFC stage, shown in Figure 22. A novel addition is the use of exhausted RO membranes from a desalination plant, which can be used for NF by means of a regeneration process. The water recovered in the system will be used for silica production (reducing extracted groundwater), and the sodium sulphate (Na_2SO_4) will be sold in the market.

The system boundaries of ZB include the different stages of the ZB system (Figure 22), including the energy savings from the heat recovery. Listed below, a brief description of the different stages considered within the system boundaries:

BRINE TREATMENT

Pre-treatment:

- Physico-chemical wastewater treatment: Wastewater effluent coming from IQE's production process enters the ZB plant. Different chemical reagents are added (e.g., limestone, coagulants, flocculants). After settling, sludge and clarified water are separated.
- Physico-chemical sludge treatment: sludge from physico-chemical wastewater treatment is thickened and flocculants are added. After that, a centrifugal screw mashes the sludge and reduces the water content. A dried sludge is obtained as waste to be treated externally.

- Sand filtering: Clarified water from the physico-chemical wastewater treatment gets into the sand filters at high pressure. The aim of this step is to remove remaining solids before subsequent membrane filtration stages.
- Ultrafiltration: Sand filtered water is treated with sodium hypochlorite, sodium hydroxide and hydrochloric acid and thereafter is pressure-driven throughout ultrafiltration (UF) modules.

Nanofiltration:

- Reverse osmosis: Permeate from the UF stage is fed into the RO filtration module equipped with regenerated exhausted RO membranes after hydrochloric acid, sodium hydroxide and antifouling reagent are added to the stream. Permeate after this step (recover industrial water) is ready to be reintroduced in IQE's RO treatment before silica production scheme, while concentrate (brine) follows to concentration.

Concentration:

- Eutectic Freeze Crystallization: Brine concentrate from nanofiltration is submitted to eutectic freeze crystallization process, obtaining as by-product ultrapure water (to be reintroduced in IQE's silica production) and sodium sulphate decahydrate ($H_{20}Na_2O_{14}S$).
- Evaporation: Sodium sulphate decahydrate is submitted to a further evaporation process to obtain sodium sulphate (Na_2SO_4) salts.

HEAT RECOVERY

Different processes of IQE's silica production have a heat surplus which can be utilized. Although this is not used currently, it is foreseen to implement the utilisation of this heat soon, and the assessment assumes the existence of a heat recovery system. This system will couple the waste heat from IQE's silica production with the ZB plant, more specifically with the brine's concentration stage, improving the energy efficiency of the system.

RO MEMBRANE REGENERATION

Exhausted RO membranes from "El Prat" desalination plant are submitted to a regeneration process which recovers them to be used in the nanofiltration stage.

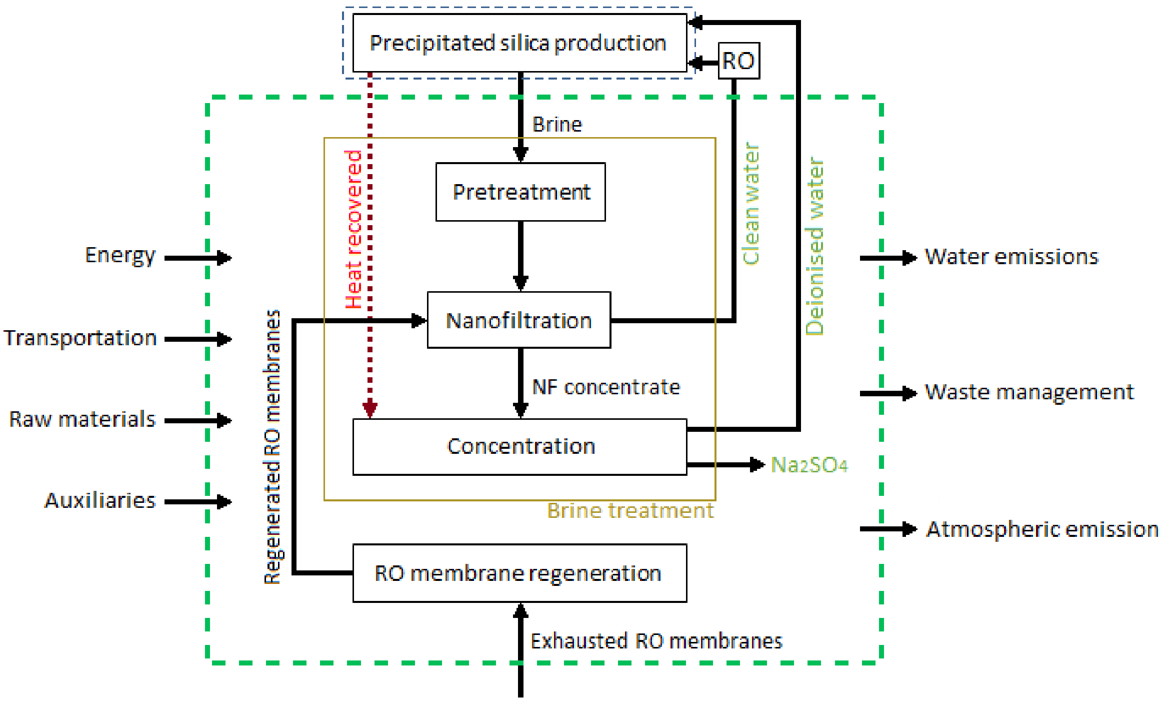


Figure 22 Technology configuration of the ZB system for the silica plant brine. Source: Adapted from Tsalidis et al. (2020)

6.1.3 Life cycle inventory and LCC inventory

The foreground inventory of the ZB technology has been built considering a full-scale industrial plant design to treat IQE wastewater, with a capacity of 150 m^3/h (3,600 m^3/day) and a lifespan of 35 years. This industrial plant design entails all the stages of the ZB technology explained in the previous section. It must be highlighted that for the reference scenario a dataset from ecoinvent has been adapted to be used. The inventory for this scenario can be found in the Appendix 10.4.1.

Table 22: includes a list of the capital goods (assets) and the related costs which have been considered in the inventory. Regarding operation inputs and outputs, Table 23 shows the chemical reagents and dosages required for the functioning of the ZB process, as well as their costs. Table 24 shows the replacement period and the allocated use of the UF and NF filter devices. Finally, Table 25 provides a breakdown of energy needs of the ZB plant and the related costs.

Table 21 Foreground inventory and economic costs considered for the capital goods of the ZB system applied to the wastewater from the silica plant

Item	Stage	Number of items per stage	Amount per FU (item/m^3)	Cost (€/m^3)
Tank	Physico-chemical treatment *(pretreatment)*	3	4.77E-8	1.74E-01*
Dosing hopper (1 m^3)		1	4.77E-8	
Dosing hopper (2 m^3)		1	4.77E-8	
Flocculation chamber		1	4.77E-8	

Settler		1	4.77E-8	
Tank	Sludge treatment (*pretreatment*)	1	4.77E-8	
Drying sludge tank		1	4.77E-8	
Sand filter housing	Sand filtration (*pretreatment*)	1	2.38E-8	
Inert filter media		1	1.24E-5	
Dosing hopper (2 m^3)	UF (*pretreatment*)	2	2.38E-8	
Dosing tank		1	7.15E-8	
Dosing hopper (2 m^3)	RO (*nanofiltration*)	1	2.38E-8	
Tank		1	2.38E-8	
Pipes	Pipping system	1	2.38E-8	
Item	**Material**	**Capacity**	**Mass (kg)**	**-**
Tank	*HDPE*	*1 m^3*	*50*	-
Dosing hopper	*GFRP*	*1 m^3*	*60*	-
Dosing hopper	*GFRP*	*2 m^3*	*90*	-
Flocculation chamber	*GFRP*	*5 m^3*	*150*	-
Settler	*GFRP*	*5.4 m^2*	*300*	-
Drying sludge tank	*GFRP*	*20 m^3*	*450*	-
Sand filter housing	*GFRP*	*2 m^3*	*20*	-
Inert filter media	*Sand*	-	*120*	-
Dosing tank	*HDPE*	*0.125 m^3*	*15*	-
Pipes	*PVC*	*100*	*meters*	-

**This figure includes only the initial costs, not the costs of the spare parts (Table 24)*

Table 22: Foreground inventory and economic costs considered for the chemical reagent used in the ZB system applied to the wastewater from the silica plant

Chemical reagents	**Stage**	**FU specific dose (g/m^3)**	**Daily dose (kg/d)**	**Annual dose (t/y)**	**Costs (€/m^3)**
Alumina sulphate	Physico-chemical treatment (*pretreatment*)	13.5	36	13.1	2.43E-03
Calcium hydroxide		135	64.8	23.6	8.89E-03
Anionic polyelectrolyte		1.35	0.648	0.243	6.36E-03
Cationic polyelectrolyte	Sludge treatment (*pretreatment*)	6.26	2.4	0.877	2.63E-02
Sodium hydroxide	UF (*pretreatment*)	1.66	2.5	0.911	3.33E-04
Hydrochloric acid		0.996	1.49	0.548	9.46E-05
Sodium hypochlorite		0.007	0.035	0.0116	1.49E-06
Hydrochloric acid	RO (*nanofiltration*)	19.9	28.9	10.6	1.89E-03
Calcium carbide		3.98	1.53	0.559	2.30E-02
Sodium hydroxide		4.32	1.66	0.607	8.68E-04

Table 23: Foreground inventory and economic costs considered for the spare parts for the operation of the ZB system applied to the wastewater from the silica plant (integrated with capital goods in the assessment)

Element	**Stage**	**Installed elements (units)**	**Annual reposition (% percentage)**	**Reposed elements (annual units)**	**Costs (€/m^3)**
UF membranes	UF (*pretreatment*)	4	20	0.8	8.34E-05
Regenerated RO membranes	RO (*nanofiltration*)	28	20	5.6	1.33E-01
Cartridge filters (process)		12	1,200 (monthly reposition)	144	8.58E-05
Cartridge filters (cleaning)		12	1,200 (monthly reposition)	144	

Table 24: Foreground inventory and economic costs considered for the energy needs of the ZB system applied to the wastewater from the silica plant

Stage	**Daily consumption (kWh/d)**	**Consumption per FU (kWh/m^3)**	**Costs (€/m^3)**
Physico-chemical treatment (*pretreatment*)	258	0.673	8.41E-02
Sludge treatment (*pretreatment*)	5	0.013	1.63E-03
Sand filtration (*pretreatment*)	63	0.164	2.05E-02
UF (*pretreatment*)	114	0.296	3.70E-02
RO (*nanofiltration*)	1,444	3.76	4.70E-01
EFC + Evaporation (*concentration*)	2,246	5.85	7.31E-01
**Heat recovery (concentration)*	*-1,617*	*-4.21*	*-5.26E-01*
Auxiliary systems	23	0.06	7.50E-03
Total	**2.536**	**6.61**	**8.26E-01**

**Energy heat recovery subtracted from Evaporation process energy consumption.*

Regarding regenerated membranes, Table 26 summarizes the operational inputs needed for the membrane regeneration considering a standard membrane of ~15 kg and including the transportation from "El Prat" desalination plant located 300 km from IQE. Finally, Table 27 shows the main outputs of the system, including the dried sludge and the by-products.

Table 25: Foreground inventory and economic costs considered for the operational data for the exhausted RO membrane regeneration of the ZB system applied to the wastewater from the silica plant. No capital goods were considered

Item	Category	Value	Units	Costs (€/m³)
Deionized water	Flow	667	l	2.45E-02
Sodium chloride	Flow	1	kg	1.31E-06
Electricity	Energy	8	kWh	3.68E-05
Deionized water	Flow	167	l	6.15E-03
Sodium hypochlorite	Flow	10	l	7.76E-02
Wastewater	Flow	167	l	3.07E-06
Electricity	Energy	0,33	kWh	1.52E-06
Deionized water	Flow	667	l	2.45E-02
Sodium chloride	Flow	1	kg	1.31E-06
Electricity	Energy	8	kWh	3.68E-05
Transport scenario	Transport	4,5	tkm	3.63E-05
	Regenerated RO membrane	**1**	**unit**	**1.33E-01**

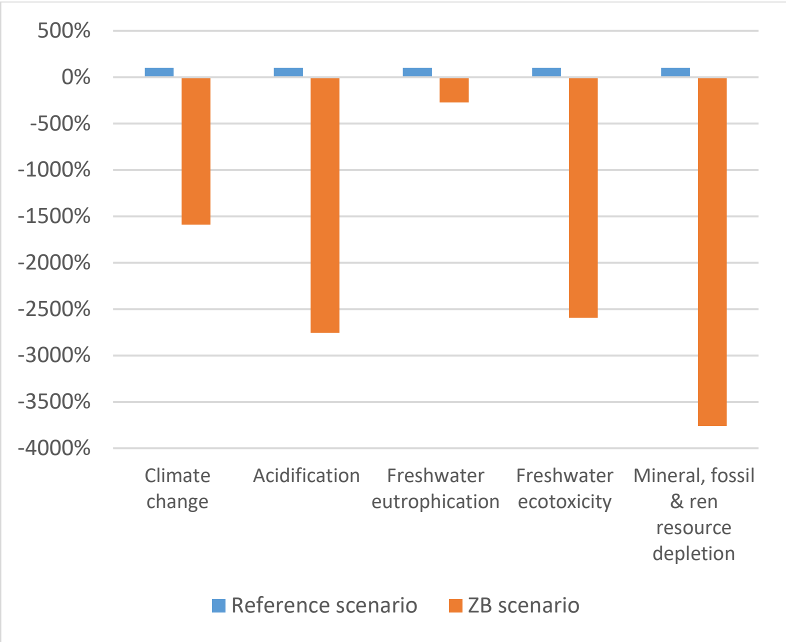
Table 26: Foreground inventory and economic costs considered for the outputs from the Zero Brine plant of the ZB system applied to the wastewater from the silica plant, including waste and by-products generated

Item	Stage	Category	Amount per FU	Units	Costs (€/m³)	Avoided Product
Dried sludge	Physico-chemical Sludge treatment (*pretreatment*)	Waste	4,5	kg/m³	2.25E-03	--
Clean water	RO (*nanofiltration*)	By-product	796	l/m³	0.00E+00	Underground water (*replace IQE's underground water*)
Deionized water	EFC (concentration)	By-product	171	l/m³	3.42E-02	Deionized water (*replace IQE's underground osmotic water*)
Sodium sulphate		By-product	16,38	kg/m³	9.83E-01	Sodium sulphate (*replace production of sodium sulphate, Mannheim process, on the external market*)

6.2 Results - Life Cycle Impact Assessment

6.2.1 Comparison with reference case

Figure 23 shows the comparison between the reference scenario and the ZB system. As can be observed, the performance is much better in the case of ZB, as it presents substantial avoided impacts in all impact categories. These avoided impacts dominate the net results, as they are several times higher than the environmental burdens. The impact category with the largest avoided impacts is resource depletion, followed by acidification and freshwater ecotoxicity. Regarding the reference scenario, the impacts are relatively low but always above zero, implying a prejudicial effect on the environment.



	Reference scenario	ZB system
Climate change kg CO2 eq	0.30	-4.69
Acidification molc H+ eq (E+03)	3.88	6.76
Freshwater eutrophication kg P eq (E+03)	1.04	-2.80
Freshwater ecotoxicity CTUe	12.98	-336.6
Min.fos. & ren. resource depletion kg Sb eq (E+06)	13.02	-489.4

Figure 23: Comparison of the environmental impacts for the treatment of 1 m3 of brine from the silica plant for the impact categories considered

6.2.2 Contribution analysis

The results for the contribution analysis are shown in Figure 24 only for the impact category of climate change, as the rest of impact categories show a similar pattern. Similar figures for the other categories can be found in the Appendix 10.4.2. The most relevant component for these results is the avoided impacts from the sodium sulphate generated in the ZB system, due to the fossil fuels used along its supply chain. For the impacts generated, the most remarkable contribution is the energy use in for the ZB scenario and the capital goods for the reference.

It must be highlighted that although other impact categories show similar results, most of the avoided impacts are generated due to the mining of copper (freshwater eutrophication and ecotoxicity), the emissions from sulphuric acid production (acidification) and the mining of zinc (resource depletion) in the supply chain of sodium sulphate.

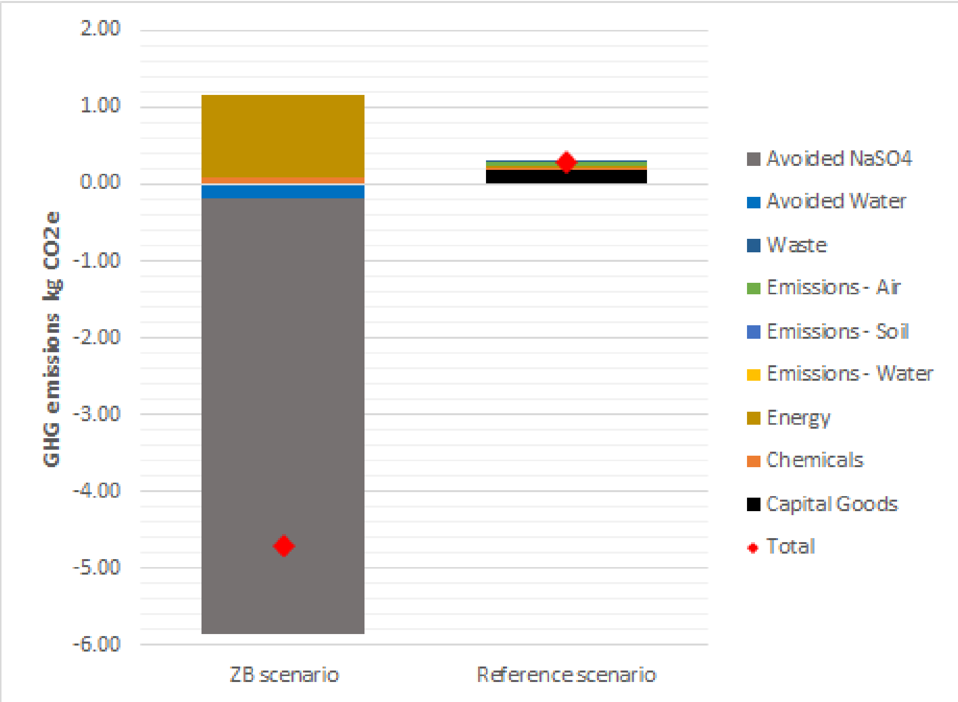


Figure 24: Contribution analysis of climate change of ZB system compared to reference system

6.3 Results – Life Cycle Costing

6.3.1 LCC

Figure 25 shows the results of the contribution analysis to the costs of the ZB system compared to the reference scenario. As can be observed, the costs are considerably higher for the ZB scenario than for the reference, but the ZB scenario also generates substantial revenues due to the generation of sodium sulphate, which is sold to the market. The resulting net cost is 0.61 €/m^3 for the ZB scenario, which is slightly lower than the reference (0.5 €/m^3).

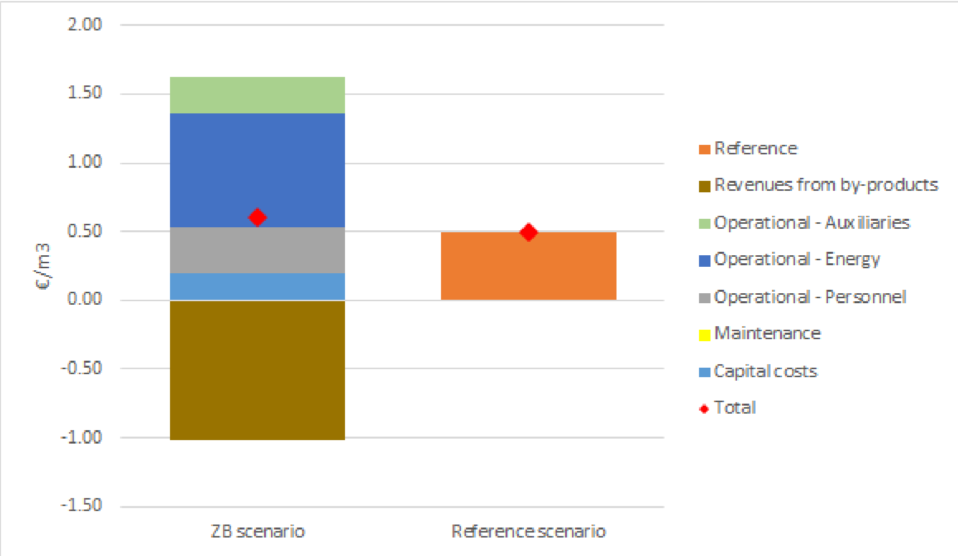


Figure 25: Contribution analysis of the costs of ZB system compared to reference system for the treatment of wastewater from the silica plant

6.3.2 Externalities

Table 28 shows the environmental externalities of the reference and the ZB scenario. As can be observed, in line with the environmental assessment, the ZB scenario presents substantial beneficial impacts due to the avoided products of the system. It must be highlighted that most of the impacts (avoided and generated) come from the abiotic resources damage category. In general, the performance of the ZB scenario is remarkably better than the reference.

Figure 26 compares the internal costs of the system (obtained in the LCC) and the costs of the environmental externalities. It should be noted that for the purposes of this analysis it is assumed that ELU are equivalent to Euros. Therefore, the internal costs are added to the externalities to represent the total costs of the systems. As can be observed, the environmental externalities account for most of the total costs, showing that most environmental impacts are not capture in the costs of the system.

Table 27: Environmental externalities for the reference and ZB scenario for the silica plant case

Damage category	**Unit**	**Reference scenario**	**ZB scenario**	**% change Ref to ZB system**
Ecosystem services	ELU	1.04E-03	-1.84E-02	-1770%
Access to water	ELU	6.43E-05	-1.07E-03	-1660%
Biodiversity	ELU	5.63E-06	-6.62E-05	-1180%
Building technology	ELU	6.08E-06	-5.92E-05	-970%
Human health	ELU	6.28E-02	-1.08E+00	-1720%
Abiotic resources	ELU	6.62E-01	-2.15E+01	-3250%
Total		**0.73**	**-22.60**	**-3110%**

**Environmental Load Unit*

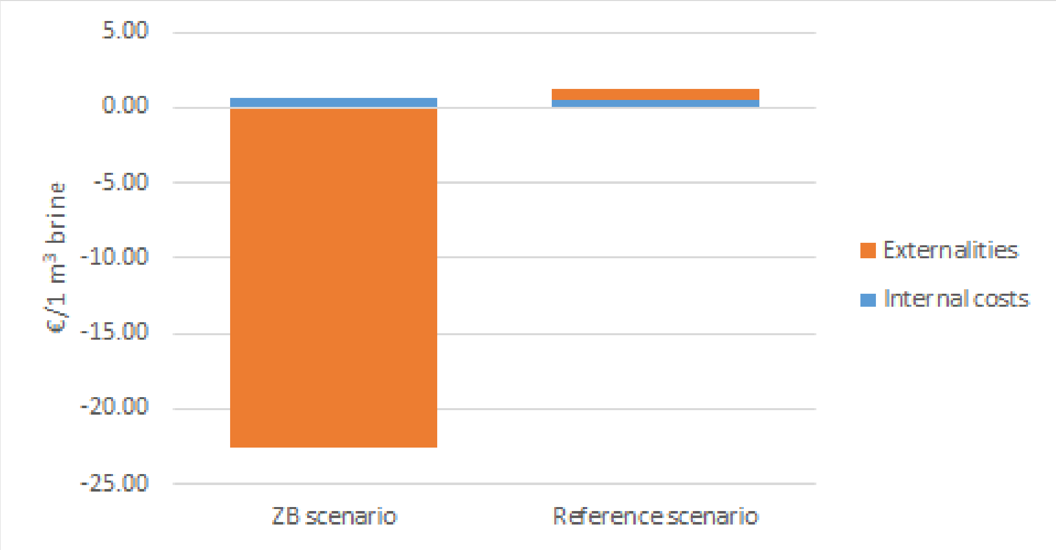


Figure 26: Comparison of the internal costs and the environmental externalities for the reference and ZB scenario for the silica plant case

6.4 Sensitivity analysis

6.4.1 Perturbation analysis

For the perturbation analysis of the silica plant case the most relevant flows of the inventory affecting the environmental impacts of the ZB scenario were considered, i.e., the production of sodium sulphate and the use of electricity (considering the electricity used for all the appliances). Table 29 shows the results of this assessment, being the sensitivity ratio 1.3 for Na_2SO_4 and –0.24 for electricity. This shows that Na_2SO_4 has the highest potential to influence the results, which makes sense because it accounts for most of the GHG emissions of the system.

Table 28: Perturbation analysis and sensitivity ratios of the climate change impact assessment for a variation of -10% and +10% in the parameter values of the silica plant ZB system (Parameter amounts and impact category results are given per 1 m3 brine)

Parameter	Original parameter value		10% decrease in parameter value		10% increase in parameter value		Sensitivity Ratio
	Amount	Unit	Amount	kg CO_2 eq	Amount	kg CO_2 eq	
Avoided Na_2SO_4	12.60	kg	11.34	-4.13	13.86	-5.26	1.30
Electricity consumption	9.44	kWh	8.50	-4.81	10.38	-4.60	-0.24

6.4.2 Scenario analysis

To assess the sensitivity of the environmental impacts of the system to the electricity mix, three scenarios were considered. Table 30 shows the prospective electricity mix that was considered for 2030 and the results of this assessment are shown in Figure 27. Notice that the percentages are negative for all impact categories and scenarios because the ZB systems resulted in negative impacts (beneficial impacts for the environment).

As can be observed, the results show a small variation for the mix from 2030, and a higher variation for the 100% renewable mix, reaching an increment of around 20% for climate change and freshwater eutrophication, being therefore more beneficial for the environment. This small variation makes sense as the Spanish electricity mix already has a substantial share of renewable electricity (44% by 2020) and includes a substantial share of nuclear energy, with negligible contribution to these impact categories (but contributes to others).

Table 29: Current and prospective electricity mix for Spain for the years 2021 and 2030

	2020 mix	2030 mix
Nuclear energy	23.0%	20.0%
Solids	2.8%	5.3%
Oil (including refinery gas)	1.4%	0.6%
Gas (including derived gases)	26.9%	17.4%
Biomass-waste	2.0%	3.1%
Hydro (pumping excluded)	13.7%	11.7%
Wind	22.2%	25.1%
Solar	8.0%	16.8%

Source: European Commission, 2016

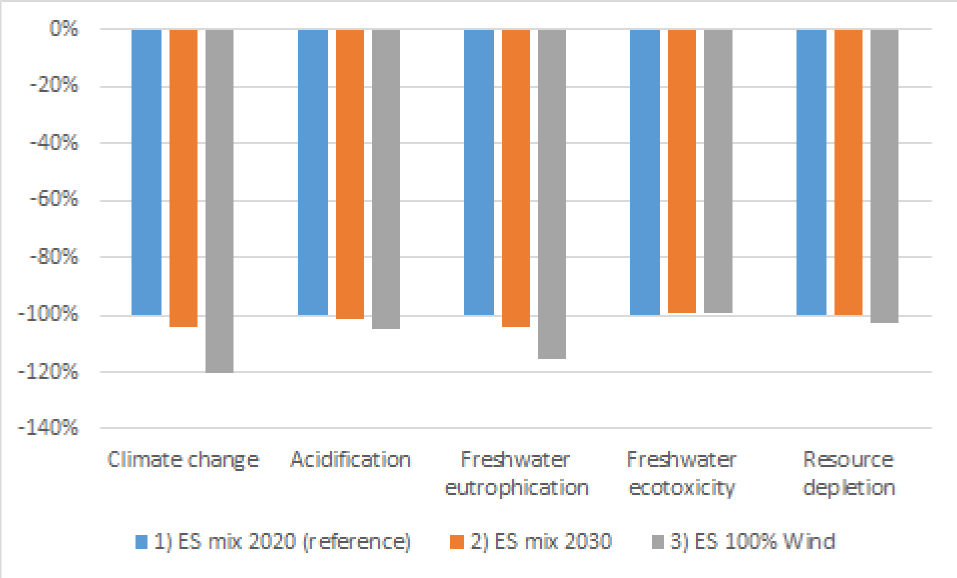


Figure 27: Comparison of the environmental impacts for the ZB scenario of the silica plant considering the 1) current Spanish electricity mix (ES mix 2020 (reference)), 2) the Spanish mix for 2030 (ES mix 2030) and 3) a mix with 100% wind energy (ES 100% Wind)

6.5 Discussion

6.5.1 LCA

The results of the environmental assessment for the implementation of ZB in the silica plant are remarkably favourable, showing an important improvement in the environmental performance of the system. The most relevant component of the life cycle is the sodium sulphate generated as a by-product, which causes the beneficial impacts due to product substitution, as it replaces conventional sodium sulphate in the market and avoids the environmental impacts of its supply chain.

It should be noted that the environmental performance of the system is highly dependent on the selling of sodium sulphate (to replace virgin sodium sulphate), as this sale generates the beneficial environmental impacts. Currently, there is market demand for sodium sulphate and the company expects to achieve a relatively high price, as the quality obtained is good. However, if this were not the case, the environmental performance of ZB would indeed be detrimental because the environmental burdens for ZB are higher than for the reference case due to electricity consumption. Although there is room to reduce the impacts from electricity through a higher share of renewables in the mix, the changes in the following years (2030) will be limited as the Spanish mix has already relatively low emissions, as shown in the scenario analysis.

6.5.2 LCC

The economic performance of the implementation of ZB is not as favourable as the environmental one, but the results are promising. A net cost of 0.61 €/m^3 was obtained for ZB, with electricity consumption as the highest contributor (51% of the costs), followed by personnel (21% of the costs). The revenues from the sale of sodium sulphate also play a relevant role in this case, as they provide 1.02 €/m^3 of revenues, which lowers considerably the net cost.

The resulting cost for ZB (0.61 €/m^3) is above the cost of the reference scenario at 0.5 €/m^3. However, two important considerations must be made regarding this comparison. Firstly, the revenues from ZB will depend on the price of sodium sulphate, which will depend on its quality and the market situation. For this assessment, a realistic but conservative choice of 60 €/t was made, but it might well end up being substantially higher. Secondly, the cost of the reference scenario depends strongly on local regulations and taxes, which will most likely increase during the following years due to more restrictive environmental legislation.

Therefore, the current economic performance of the ZB system is similar to the reference system but is likely to be better in the coming years, especially with a good price for the recovered sodium sulphate.

6.5.3 Summary and conclusions

The environmental and economic assessment of the ZB system at the silica plant suggests strong potential for improving the eco-efficiency of the system. The most critical component influencing the results is the generation of sodium sulphate as a by-product. This avoids substantial environmental impacts from product substitution and provides revenues which compensates the higher costs of ZB. The main conclusion is that it is highly advisable to implement this technology in the silica plant as it can improve the environmental performance and potentially generate a small revenue.

7. Combined analysis and discussion

The following sections summarise and discuss the findings of the LCA and LCC, and the implications for the ZB systems.

7.1 LCA

A summary of the environmental assessment of the four case studies compared to the reference cases, is shown in Figure 28. This compares two of the most revealing impact categories: climate change and resource depletion. Climate change is included because it is of central importance but it is also representative of most of the other impact categories. Conversely, resource depletion has been shown to be a critical consideration due to the use of chemicals in the ZB and reference systems, and the importance of recovering the brine constituents.

Figure 28 shows that the climate change impact of the ZB systems (orange bars) is lower than the reference system in all cases apart from the textile plant. This is primarily due to the recovery of the brine constituents (salts, water and other compounds) that invokes credits because the analysis assumes that these will replace the production of virgin materials. In addition, this is despite the energy use being higher for the ZB system.[3]

[3] It should be noted that the reference system used for the coal mine was an alternative technology and not the current situation which is dilution and discharge to local water course. This is justified as future regulations are expected to remove the availability of this discharge route.

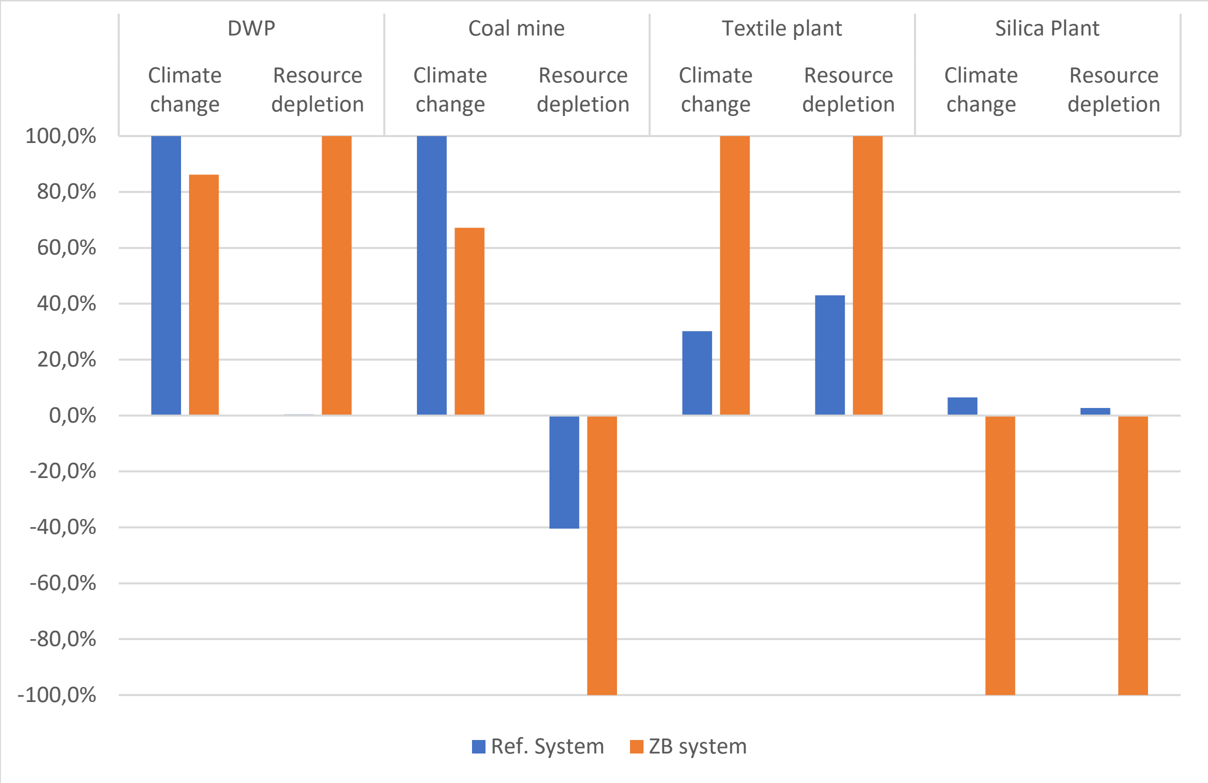


Figure 28: Normalised percentage comparison of ZB systems with reference systems for the four case studies

However, the benefits of lower climate change need to be considered alongside the impacts of resource depletion. For the coal mine and silica plant this was also lower than for the reference case. But for the DWP and textile plant the increase in required chemicals results in a higher resource depletion. This can be expected for the DWP because currently the only treatment is dilution and discharge to the local sea.

LCA also shows that results are case specific especially for resource depletion, where the quantity of recovered resources is a major influence on whether there is an overall positive or negative impact. The brine effluents had different characteristics in each case, which resulted in different recovered materials. Typically, those with larger concentrations of constituents had an overall lower impact, because the benefits of recovery can outweigh the impact of the use of resources (typically chemicals) within the ZB systems. Therefore, it is suggested to conduct LCAs in the early stages of industrial ZB applications to understand its potential according to specific brine effluent.

7.2 LCC

The LCC summary is shown in Figure 29, comparing the ZB systems with the reference systems. It shows that the ZB systems perform well and only the DWP plant exceeds the reference case costs significantly. For the silica case, the cost only slightly increases with the ZB system and since a conservative price was used for the recovered sodium sulphate it is likely to instead generate revenue. In the case of the coal mine, profit is generated due to the recovery of products (water, sodium chloride, gypsum and magnesium hydroxide).

The results highlight the importance of the recovered by-products to enable the ZB systems to be competitive. In the case of the DWP, the level and value of constituents within the water (primarily sodium chloride) is low compared to the other cases, because the original water source from a lake is relatively low in impurities.

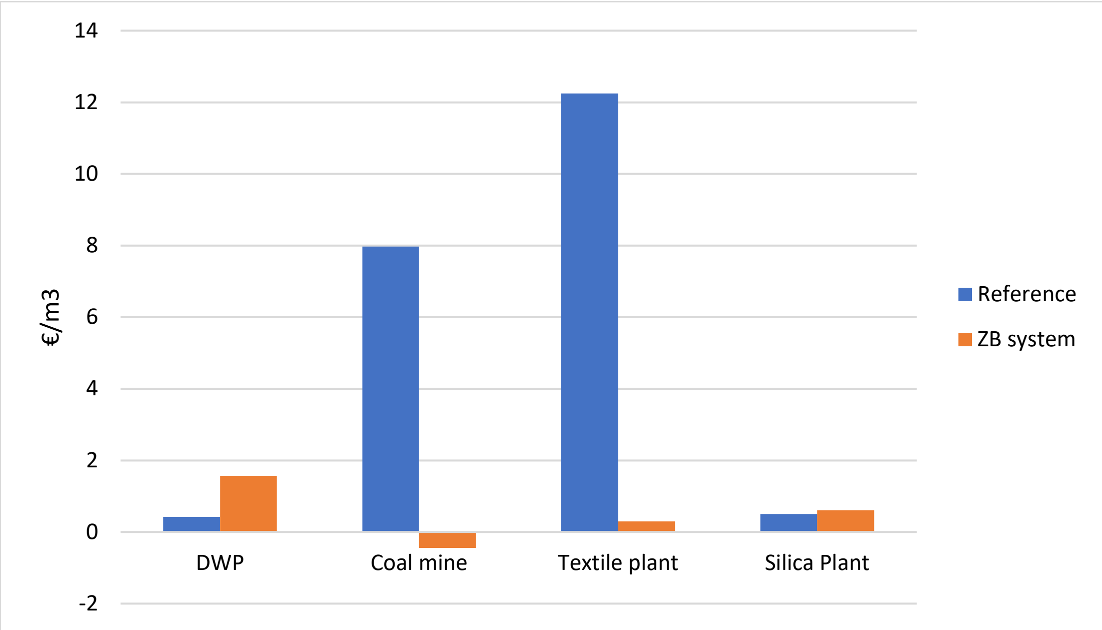


Figure 29: LCC results comparing the ZB systems with the reference systems

The externalities showed more mixed results as summarised in Table 31. This shows that the externalities were higher for the DWP and textile case studies due to an increase in resource use, mainly chemicals. Whereas, due to the recovery of products (and the associated credits) from the brine in the coal mine and silica plant case studies, the total externalities of these two ZB systems were less than the reference cases.

Table 30: Environmental externalities comparing reference and ZB systems for the four case studies

	Reference case	**ZB system**	**% change Ref to ZB system**
DWP	0.7	27.8	3990%
Coal mine	2.81	-1.18	-142%
Textile plant	11.01	36.25	329%
Silica plant	0.73	-22.60	-3110%

7.3 Implications for ZB Systems

A final comparison of the results is shown in Table 32, which shows the expected change in environmental impacts and economic costs for the ZB systems compared to the reference systems. It highlights the strong performance of the ZB systems apart from the DWP where there is an increase in resource depletion and cost which is not counteracted by the value of the recovered constituents. Nonetheless, the DWP does demonstrate lower climate change impact overall due to the products recovered from the brine.

Table 31: Relative expected change in performance of ZB system compared to current situation. Green shading signifies a reduction of impact whereas red signifies an increase in impact.

	Environmental (LCA)		**Economic (LCC)**
	Climate change	Resource depletion	
DWP	-14%	+26,800%	+274%
Coal mine	-33%	- 247% (credit)	- 6% (profit)
Textile plant	+331%	+233%	-98%
Silica plant	-1630% (credit)	-3800% (credit)	+22%*

**Based on conservative revenues for sodium sulphate, therefore this is likely to be cost positive in reality*

Therefore, the results show that the ZB systems perform well and have the potential of providing many environmental benefits, and economic benefits. These second stage results are in contrast and quite different to the results of the preliminary analysis of D7.3 (Harris et al. 2020), which suggested less favourable environmental and economic performance for the ZB systems. This is due to improved data and modelling of the systems. In addition, the analysis is now more complete, as not all technology units (within the ZB systems) were included, and the reference system data was not available for the preliminary analysis.

Despite the positive assessment, it should be noted that the results are sensitive to quantities of energy and material (especially chemicals) and to several underlying assumptions, particularly that the products recovered from the brine are utilised. This is dependent on the products achieving adequate quality (which is expected) and a market being identified.

8. Conclusions and recommendations.

The ZB systems provided an improvement in the environmental and economic performance compared to the reference systems in most of the case studies. Climate change impact was lower for the ZB systems in three out of four cases. Most other environmental impacts were lower for the ZB systems in most of the cases, but resource depletion was higher for the DWP and textile plant, due to the increased use of chemicals.

Costs were also higher than the reference case for the DWP, although the reference case used was the current situation, which is simply dilution and discharge to sea. For the textile and silica plants both ZB systems reduced costs by 98% and 6% respectively, whilst the coal mine generated a profit through the recovered products.

An important conclusion is that the environmental and economic performances of the ZB systems are largely contingent on the recovery of constituents from the brine as sellable products. This assumes a market is found and that adequate quality is achieved (which the experiments suggested was achieved and market prices used in the assessment were based on the attained quality). The recovered products counteract the associated impacts and costs of the increased use of chemicals and energy needed to operate the ZB systems, through the avoidance of producing these commodities separately. Hence the lower performance of the ZB system in the DWP case study can be explained by the lower quantities of valuable constituents in the brine, because the brine is derived from already relatively clean water.

It was also shown that future improvements of the electricity mix of countries associated with materials and energy used in the ZB systems, will further improvement the environmental performance of the ZB systems. Similarly, the use of renewable energy for ZB systems operation will also improve future performance.

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10. Appendix

10.1 DWP

10.1.1 LCC costs and references

This subsection first contains the LCC costs used for the DWP case analysis and the origins of the figures used. Secondly, figures are provided for LCA contribution analysis the other impact categories.

Table 32: Life cycle costs and references

	Cost	Unit	Reference
Benefits			
Recovered water	0.83	€/m3	(Waternet, 2021)
Recovered deionized water	2.5	€/m3	(Harris et al., 2021; Panteleaki Tourkodimitri, 2019)
Magnesium hydroxide	1.58	€/kg	(Harris et al., 2021; Panteleaki Tourkodimitri, 2019)
Calcium hydroxide	0.1805	€/kg	Mastali, Abdollahnejad and Pacheco-Torgal, (2018), Kemcore.com (2019)
NaCl (from brine solution on db)	0.057	€/kg	(Brinkmann et al., 2014)
Na2SO4	0.15	€/kg	SigmaAldrich.com (2021)
Raw Materials			
Antiscalant (Vitec 3000) (Site 1&2)	8.345	€/kg	(Wasseraufbereitung.de, 2019)
HCL (Site 1)	0.235	€/kg	(ICIS, 2019)
NaOH (Site 1)	0.48	€/kg	(IHS Markit, 2018; Panteleaki Tourkodimitri, 2019)
Clean water (Site 1&2)	0.00104	€/L	(Waternet, 2021)
H2SO4 (Site 2)	0.265	€/kg	(Kemcore.com, 2019; Panteleaki Tourkodimitri, 2019)
NaOH (Site 2)	0.48	€/kg	(IHS Markit, 2018; Panteleaki Tourkodimitri, 2019)
Energy			
Electricity (Site 1&2)	0.0679	€/kWh	(Schoots et al., 2017)

10.1.2 Contribution analysis for other impact categoires.

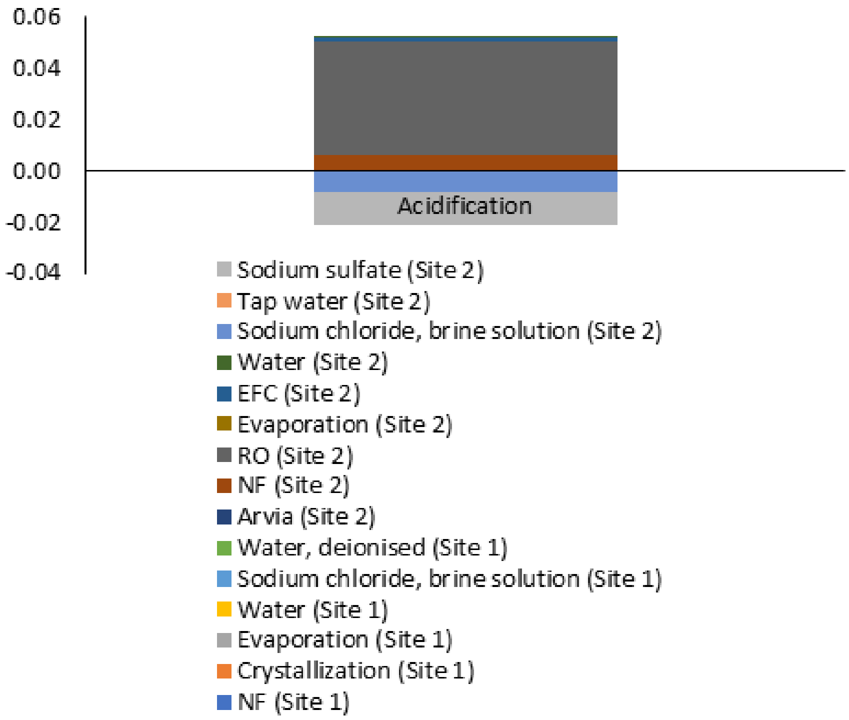

Figure 30: Contribution analysis of DWP ZB system for Acidification

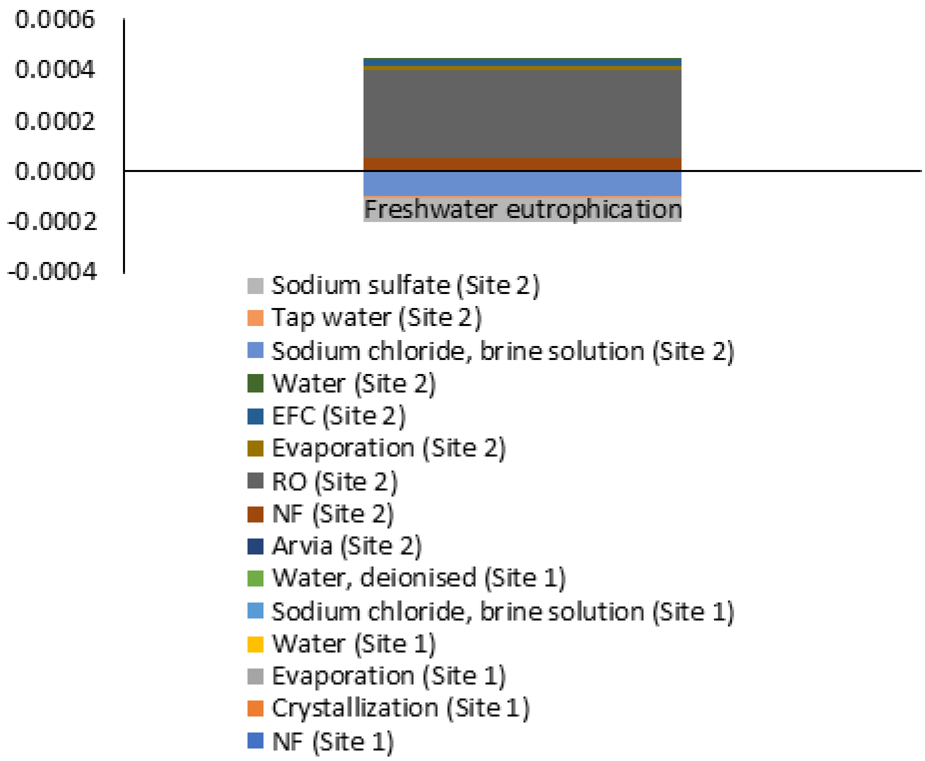

Figure 31:. Contribution analysis of DWP ZB system for Freshwater eutrophication

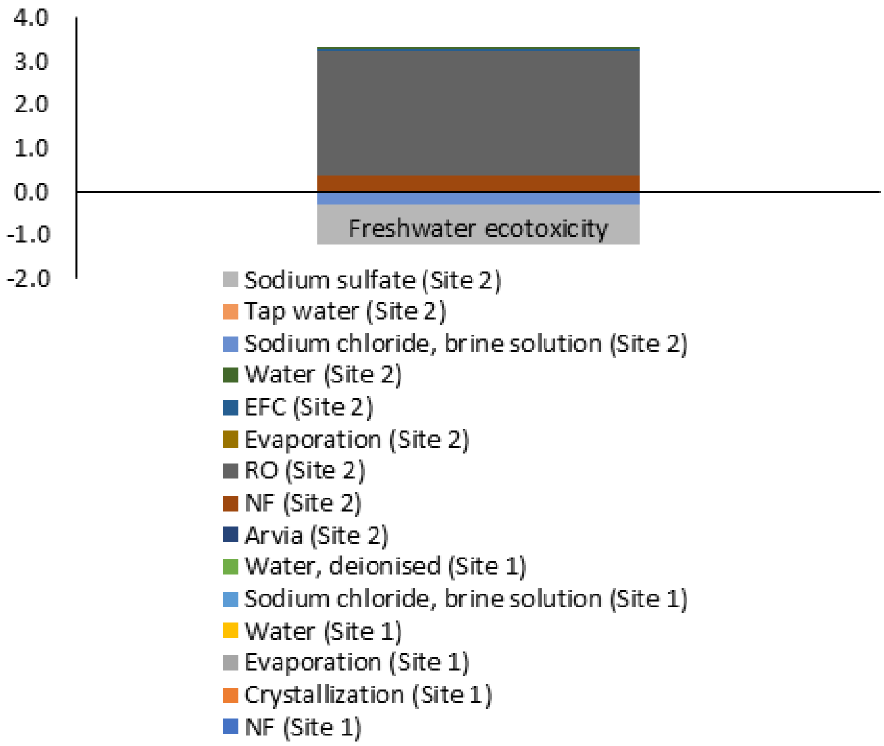

Figure 32: Contribution analysis of DWP ZB system for Freshwater ecotoxicity

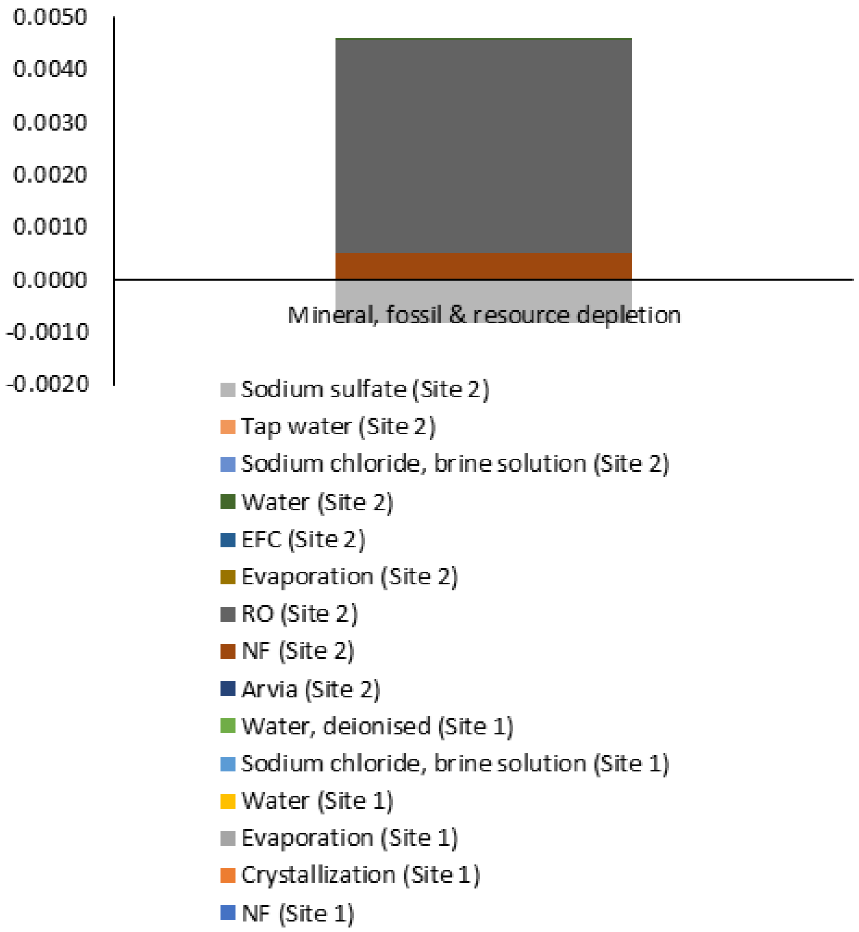

Figure 33: Contribution analysis of DWP ZB system for Mineral, fossil and resource depletion

10.2 Coal mine additional data

This subsection of the Appendix contains figures for the LCA contribution analysis of the impact categories other than climate change.

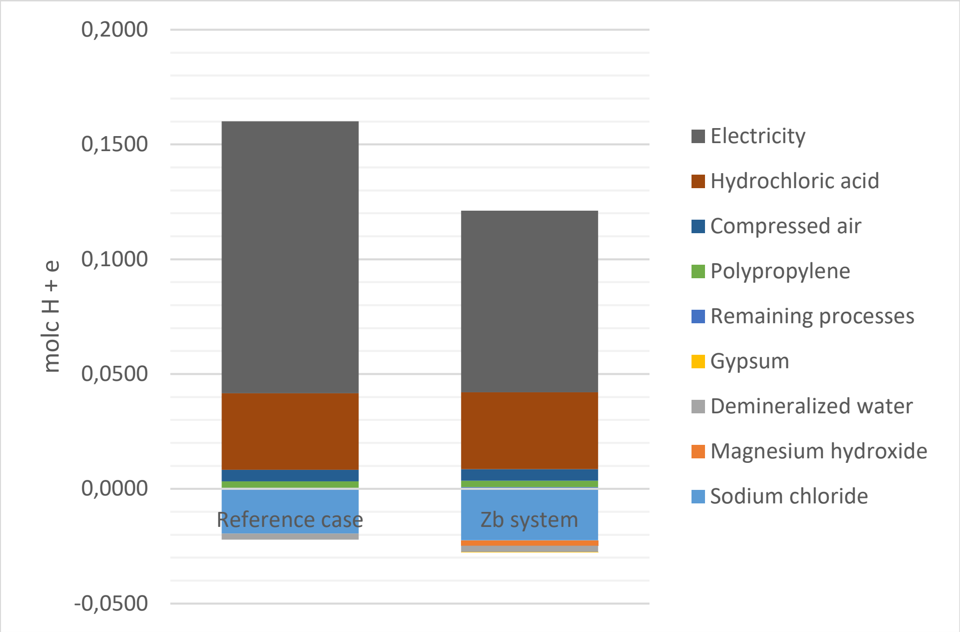

Figure 34: Contribution analysis of coal mine ZB system for acidification

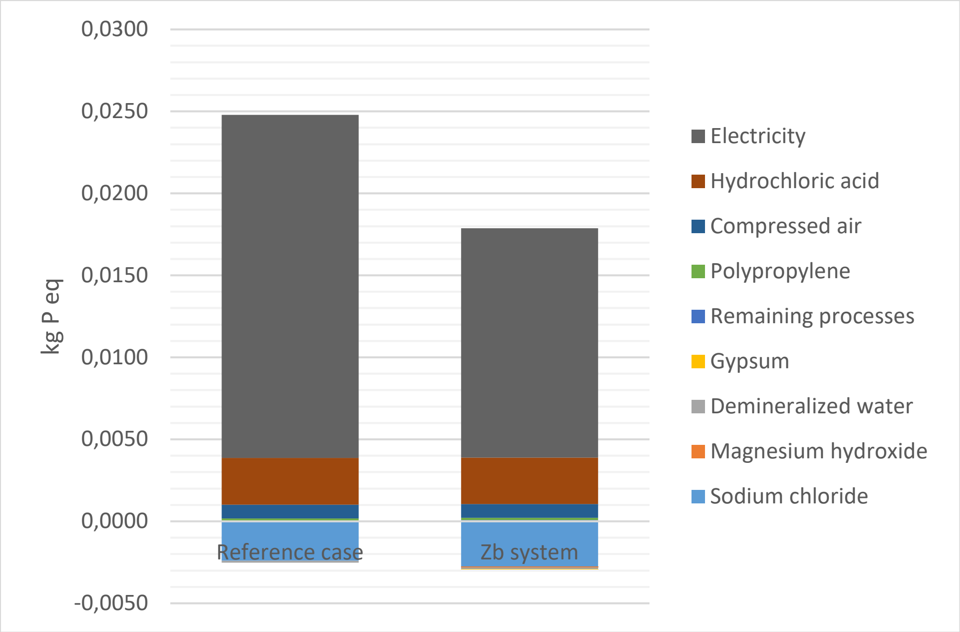

Figure 35: Contribution analysis of coal mine ZB system for freshwater eutrophication

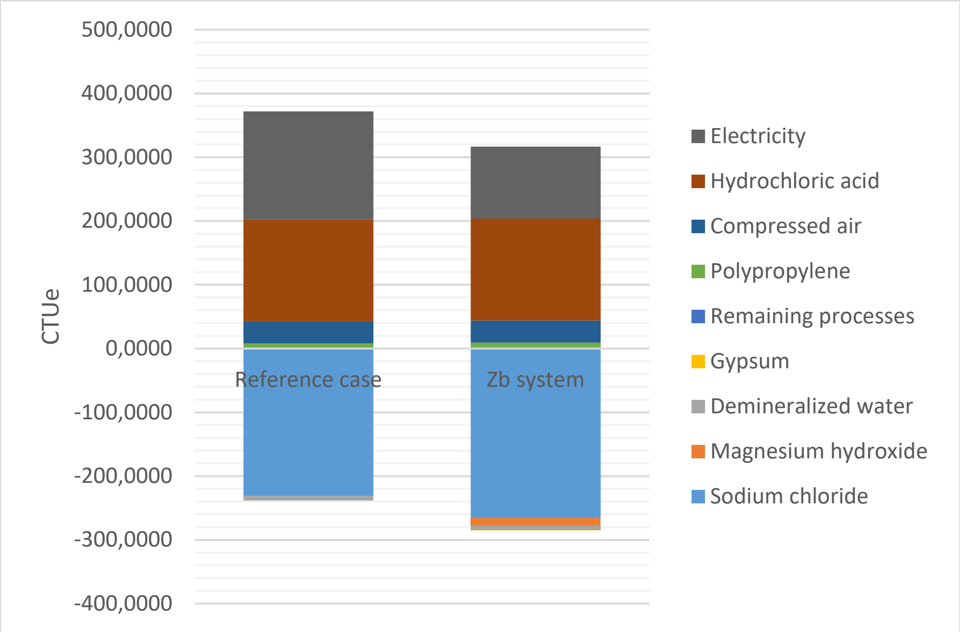

Figure 36: Contribution analysis of coal mine ZB system for freshwater ecotoxicity

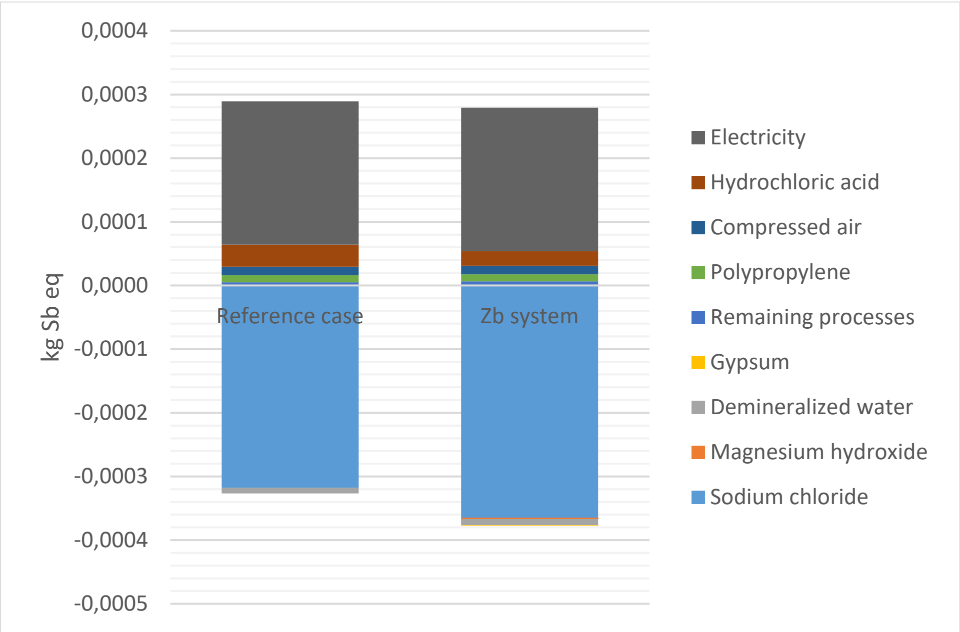

Figure 37: Contribution analysis of coal mine ZB system for Mineral, fossil and resource depletion

10.3 Textile plant additional data

This subsection of the Appendix contains figures for the LCA contribution analysis of the impact categories other than climate change. Whilst Table 34 contains detailed results for the EPS analysis of the textile plant.

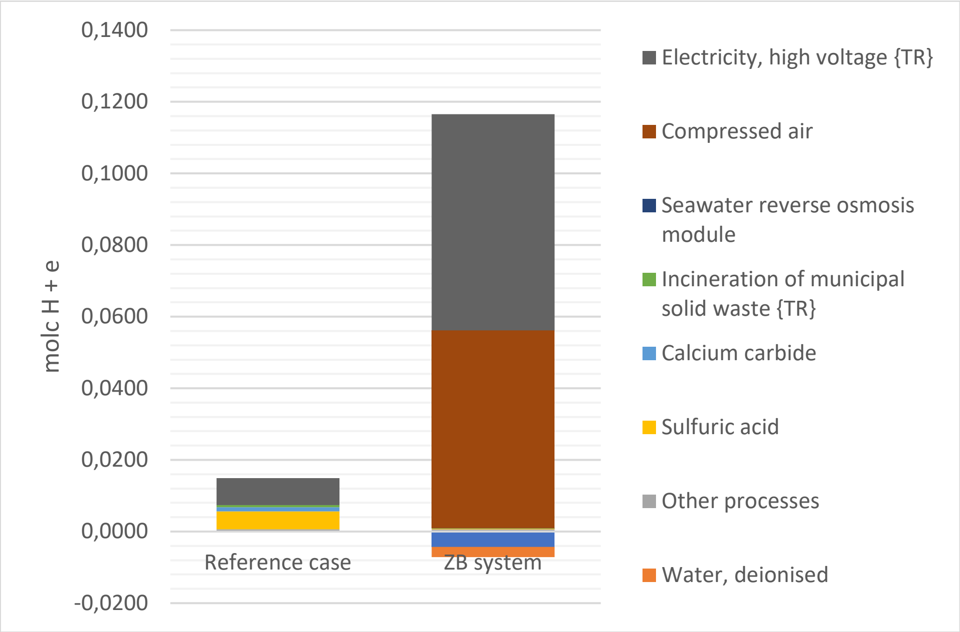

Figure 38: Contribution analysis of textile plant ZB system for acidification

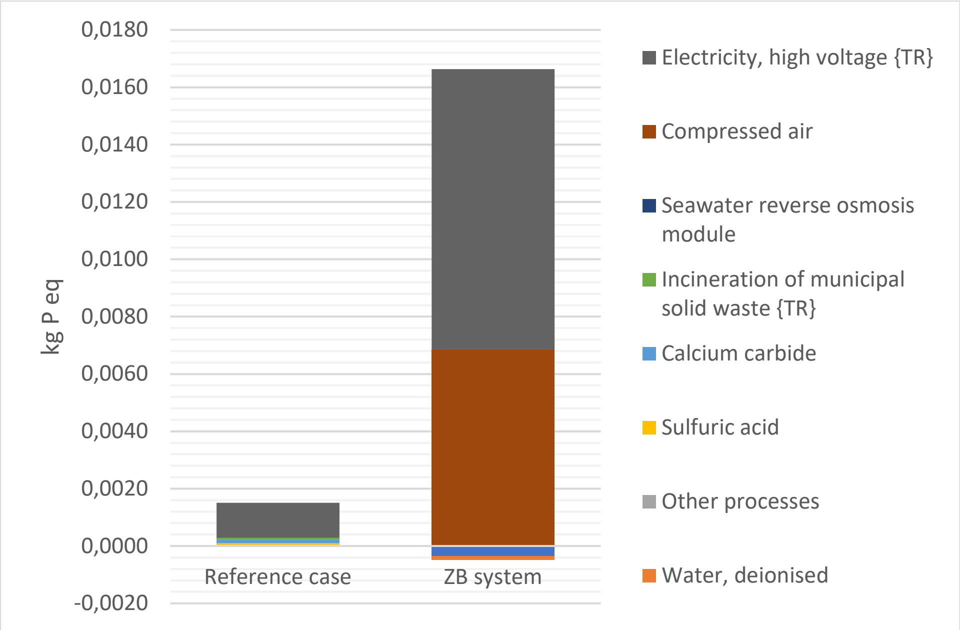

Figure 39: Contribution analysis of textile plant ZB system for freshwater eutrophication

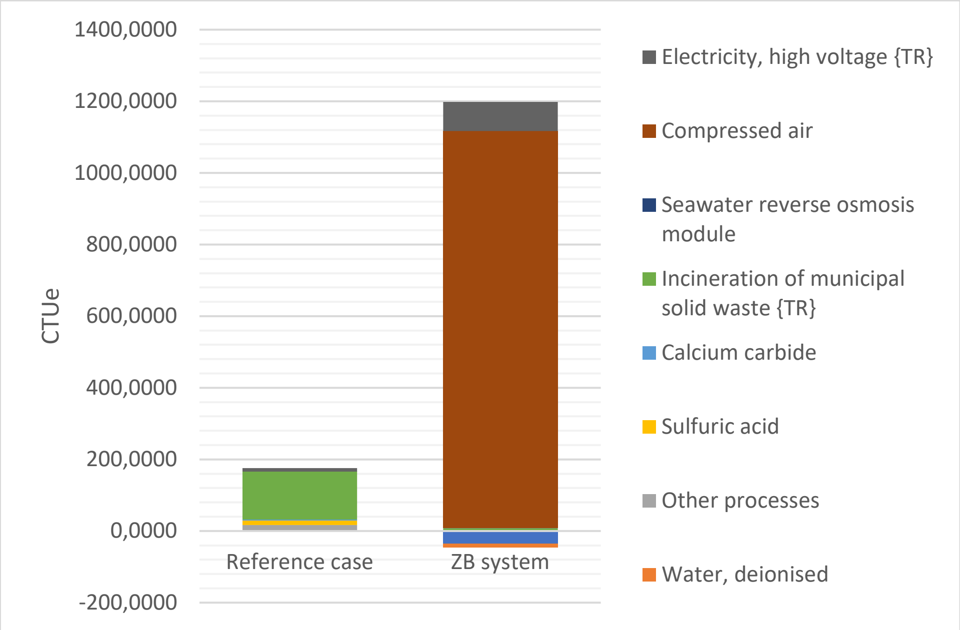

Figure 39: Contribution analysis of textile plant ZB system for freshwater ecotoxicity

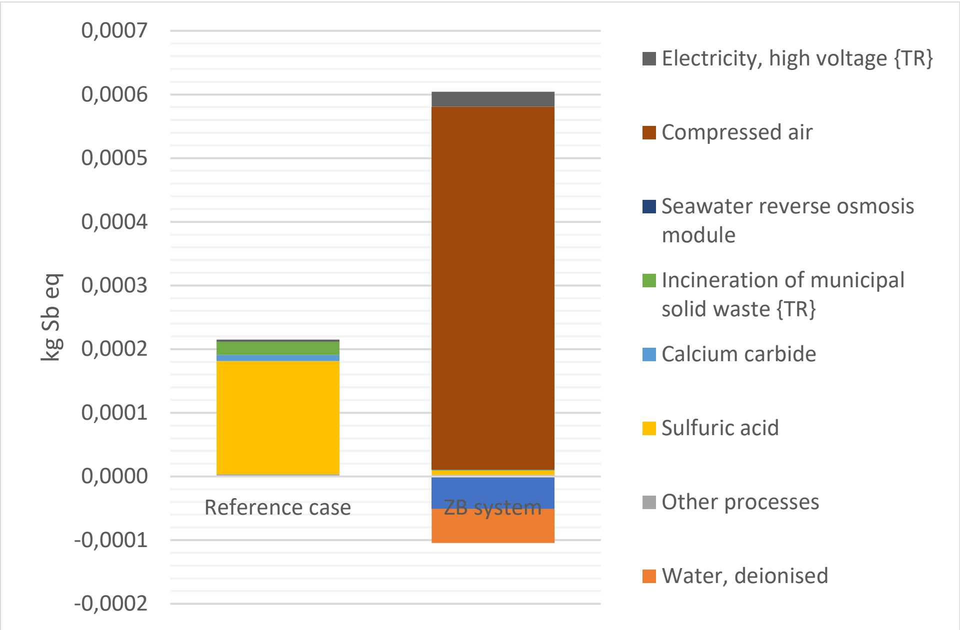

Figure 40: Contribution analysis of textile plant ZB system for Mineral, fossil and resource depletion

Table 33: Detailed results of EPS analysis for textile plant showing the individual process units and high impact of the ozonation for resource depletion.

Damage category	Unit	Total	Ozonation (Stage 1)	Nanofiltration 1 (Stage 2)	Nanofiltration 2 (Stage 3)	Reverse Osmosis (Stage 4)	Ion Exchange avg (Stage 5)	Zorlu WWTP	Zorlu advanced water treatment (RO, UF)
Ecosystem services	ELU	0.015684	0.016787	0.000360	0.000863	-0.000688	-0.001895	0.000241	0.000016
Access to water	ELU	0.000861	0.000927	0.000021	0.000054	-0.000041	-0.000114	0.000014	0.000001
Biodiversity	ELU	0.0000059	0.000063	0.000001	0.000003	-0.000002	-0.000006	0.000001	0.000000
Building technology	ELU	0.0000032	0.000041	0.000002	0.000008	-0.000005	-0.000016	0.000002	0.000000
Human health	ELU	9.815463	9.379758	0.228940	0.082355	0.001451	0.068125	0.043248	0.011587
Abiotic resources	ELU	26.416560	***30.609294***	0.044866	0.022107	-1.996384	-2.652622	0.385290	0.004010

10.4 Silica plant case study

10.4.1 Life Cycle Inventory of the baseline scenario for the treatment of wastewater from the silica plant

This subsection contains a detailed life cycle inventory for the reference case, which involves treatment at a local wastewater treatment plant.

Table 34: Foreground inventory for the reference scenario of the silica plant case study extracted from a wastewater treatment dataset from ecoinvent

Flow	Amount	Unit	Comments/ Specification
Product			
***ZEROBRINE_convenional_WWTP_Wastewater, average {CH}| treatment of, capacity 4.7E10l/year | APOS, U_ADAPTED SPAIN**	**1**	**m3**	Functional unit (1 m3)
Materials/fuels			
Aluminium sulfate, powder {RER}| market for aluminium sulfate, powder | APOS, U	3.15E-03	kg	
Ammonia, liquid {RER}| market for | APOS, U	8.43E-05	kg	
Cement, unspecified {Europe without Switzerland}| market for cement, unspecified | APOS, U	1.73E-03	kg	
Chemical, inorganic {GLO}| market for chemicals, inorganic | APOS, U	7.70E-07	kg	
Chemical, organic {GLO}| market for | APOS, U	6.15E-07	kg	
Chromium oxide, flakes {GLO}| market for | APOS, U	4.92E-08	kg	
Hydrochloric acid, without water, in 30% solution state {RER}| market for | APOS, U	4.62E-07	kg	
Iron (III) chloride, without water, in 40% solution state {GLO}| market for | APOS, U	1.59E-02	kg	
Iron sulfate {RER}| market for iron sulfate | APOS, U	1.17E-02	kg	
Liquid manure spreading, by vacuum tanker {RoW}| processing | APOS, U	2.39E-04	m3	
Municipal waste incineration facility {RoW}| construction | APOS, U	3.79E-11	p	
Process-specific burdens, municipal waste incineration {RoW}| processing | APOS, U	1.52E-01	kg	
Process-specific burdens, residual material landfill {RoW}| processing | APOS, U	4.33E-03	kg	
Process-specific burdens, slag landfill {RoW}| processing | APOS, U	2.76E-02	kg	
Quicklime, milled, packed {RER}| market for quicklime, milled, packed | APOS, U	1.47E-06	kg	
Residual material landfill {RoW}| construction | APOS, U	9.02E-12	p	
Sewer grid, 4.7E10l/year, 583 km {RoW}| construction | APOS, U	1.24E-07	km	
Slag landfill {RoW}| construction | APOS, U	4.91E-11	p	
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | APOS, U	4.12E-04	kg	
Titanium dioxide {RER}| market for | APOS, U	2.41E-06	kg	
Wastewater treatment facility, capacity 4.7E10l/year {RoW}| construction | APOS, U	6.06E-10	p	
Electricity/heat			

Electricity, high voltage {ES}| production mix | APOS, U_ADAPTED 2020	2.18E-02	kWh	
Electricity, low voltage {ES}| electricity voltage transformation from medium to low voltage | APOS, U_ADAPTED 2020	2.06E-01	kWh	
Heat, district or industrial, natural gas {RER}| market group for | APOS, U	7.40E-03	MJ	
Heat, district or industrial, other than natural gas {Europe without Switzerland}| market for heat, district or industrial, other than natural gas | APOS, U	1.27E-01	MJ	
Emissions to air			
Aluminium	1.65E-06	kg	high. pop.
Ammonia	2.80E-04	kg	high. pop.
Arsenic	2.53E-10	kg	high. pop.
Cadmium	5.52E-12	kg	high. pop.
Calcium	5.96E-06	kg	high. pop.
Carbon dioxide, biogenic	1.99E-01	kg	high. pop.
Carbon monoxide, biogenic	1.74E-04	kg	high. pop.
Chromium	3.20E-13	kg	high. pop.
Cobalt	1.81E-14	kg	high. pop.
Copper	1.47E-10	kg	high. pop.
Cyanide	1.50E-06	kg	high. pop.
Dinitrogen monoxide	1.00E-04	kg	high. pop.
Iron	3.18E-07	kg	high. pop.
Lead	2.05E-10	kg	high. pop.
Magnesium	5.53E-07	kg	high. pop.
Manganese	1.02E-13	kg	high. pop.
Mercury	3.37E-13	kg	high. pop.
Methane, biogenic	5.02E-04	kg	high. pop.
Molybdenum	6.77E-10	kg	high. pop.
Nickel	8.03E-14	kg	high. pop.
Nitrogen oxides	7.08E-04	kg	high. pop.
NMVOC, non-methane volatile organic compounds, unspecified origin	2.28E-06	kg	high. pop.
Phosphorus	1.56E-06	kg	high. pop.
Silicon	4.91E-06	kg	high. pop.
Sulfur dioxide	8.87E-04	kg	high. pop.
Tin	1.88E-09	kg	high. pop.
Water/m3	1.00E-01	m3	
Zinc	8.85E-10	kg	high. pop.
Emissions to water			
Aluminium	7.82E-04	kg	groundwater, long-term
Aluminium	6.23E-05	kg	river
Ammonium, ion	1.10E-02	kg	river
Arsenic	7.68E-07	kg	river
Arsenic	7.65E-08	kg	groundwater, long-term
BOD5, Biological Oxygen Demand	1.00E-04	kg	groundwater, long-term

BOD5, Biological Oxygen Demand	9.82E-03	kg	river
Cadmium	9.95E-10	kg	groundwater, long-term
Cadmium	1.42E-07	kg	river
Calcium	4.59E-02	kg	river
Calcium	3.11E-03	kg	groundwater, long-term
Chloride	4.05E-02	kg	river
Chromium	1.38E-08	kg	river
Chromium VI	4.58E-07	kg	groundwater, long-term
Chromium VI	6.35E-06	kg	river
Cobalt	8.21E-07	kg	river
Cobalt	5.00E-07	kg	groundwater, long-term
COD, Chemical Oxygen Demand	3.06E-04	kg	groundwater, long-term
COD, Chemical Oxygen Demand	3.02E-02	kg	river
Copper	1.61E-05	kg	groundwater, long-term
Copper	9.71E-06	kg	river
DOC, Dissolved Organic Carbon	7.54E-03	kg	river
DOC, Dissolved Organic Carbon	1.21E-04	kg	groundwater, long-term
Fluoride	3.28E-05	kg	river
Iron	3.60E-03	kg	river
Iron	4.46E-03	kg	groundwater, long-term
Lead	9.49E-07	kg	river
Lead	3.93E-07	kg	groundwater, long-term
Magnesium	5.15E-03	kg	river
Magnesium	3.71E-04	kg	groundwater, long-term
Manganese	2.69E-05	kg	river
Manganese	1.61E-05	kg	groundwater, long-term
Mercury	6.29E-08	kg	river
Mercury	5.16E-09	kg	groundwater, long-term
Molybdenum	5.44E-07	kg	river
Molybdenum	2.80E-07	kg	groundwater, long-term
Nickel	4.00E-06	kg	river
Nickel	1.74E-06	kg	groundwater, long-term
Nitrate	6.00E-05	kg	groundwater, long-term
Nitrate	4.83E-02	kg	river
Nitrite	6.44E-04	kg	river
Nitrogen, atmospheric	4.90E-04	kg	river
Phosphate	2.69E-03	kg	river
Phosphate	1.07E-05	kg	groundwater
Phosphate	1.82E-04	kg	groundwater, long-term
Potassium	3.99E-04	kg	river
Silicon	1.83E-04	kg	groundwater, long-term

Silicon	1.88E-04	kg	river
Sodium	2.19E-03	kg	river
Sulfate	1.45E-01	kg	river
Sulfate	2.77E-03	kg	groundwater, long-term
Tin	1.42E-06	kg	river
Tin	7.13E-07	kg	groundwater, long-term
TOC, Total Organic Carbon	1.21E-04	kg	groundwater, long-term
TOC, Total Organic Carbon	7.30E-03	kg	river
Water, CH	9.00E-01	m3	
Zinc	3.38E-05	kg	river
Zinc	8.40E-07	kg	groundwater, long-term
Emissions to soil			
Aluminium	4.16E-04	kg	agricultural
Arsenic	5.49E-08	kg	agricultural
Cadmium	3.91E-08	kg	agricultural
Calcium	1.41E-03	kg	agricultural
Carbon	4.89E-03	kg	agricultural
Chromium	1.70E-06	kg	agricultural
Cobalt	2.25E-07	kg	agricultural
Copper	7.84E-06	kg	agricultural
Iron	3.75E-03	kg	agricultural
Lead	2.17E-06	kg	agricultural
Magnesium	1.58E-04	kg	agricultural
Manganese	7.38E-06	kg	agricultural
Mercury	3.91E-08	kg	agricultural
Molybdenum	1.33E-07	kg	agricultural
Nickel	7.33E-07	kg	agricultural
Silicon	8.31E-04	kg	agricultural
Sulfur	4.35E-04	kg	agricultural
Tin	5.59E-07	kg	agricultural
Zinc	2.14E-05	kg	agricultural
Waste to treatment			
Waste cement, hydrated {Europe without Switzerland}| market for waste cement, hydrated | APOS, U	4.33E-03	kg	
Waste graphical paper {CH}| treatment of, municipal incineration with fly ash extraction | APOS, U	1.55E-02	kg	
Waste plastic, mixture {ES}| market for waste plastic, mixture | APOS, U	1.55E-02	kg	

10.4.2 LCA contribution analysis for all impact categories (except climate change)

This subsection of the Appendix contains figures for the LCA contribution analysis of the impact categories other than climate change for the silica plant.

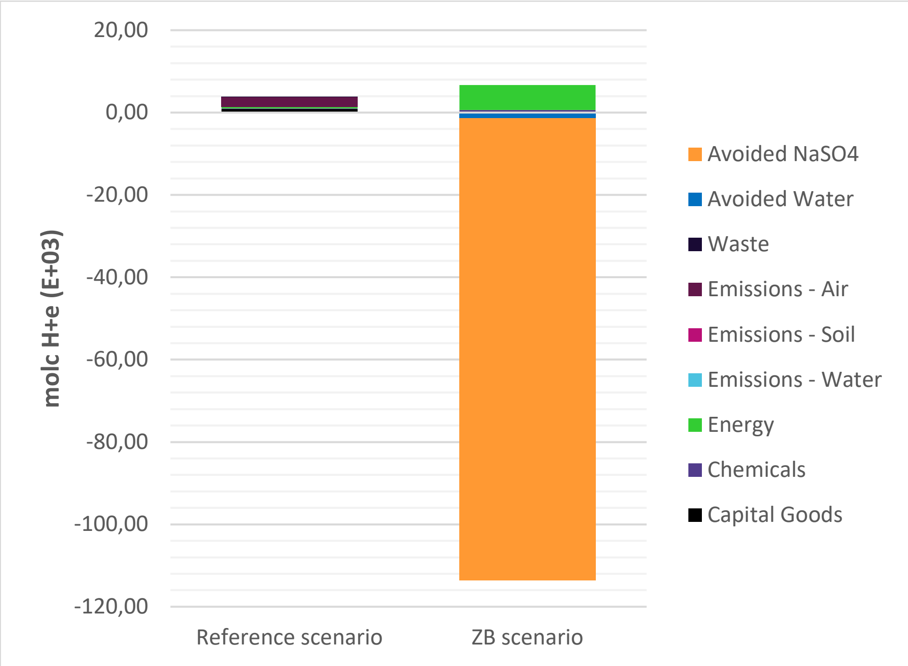

Figure 41: Contribution analysis of acidification of ZB system compared to reference system for the silica plant

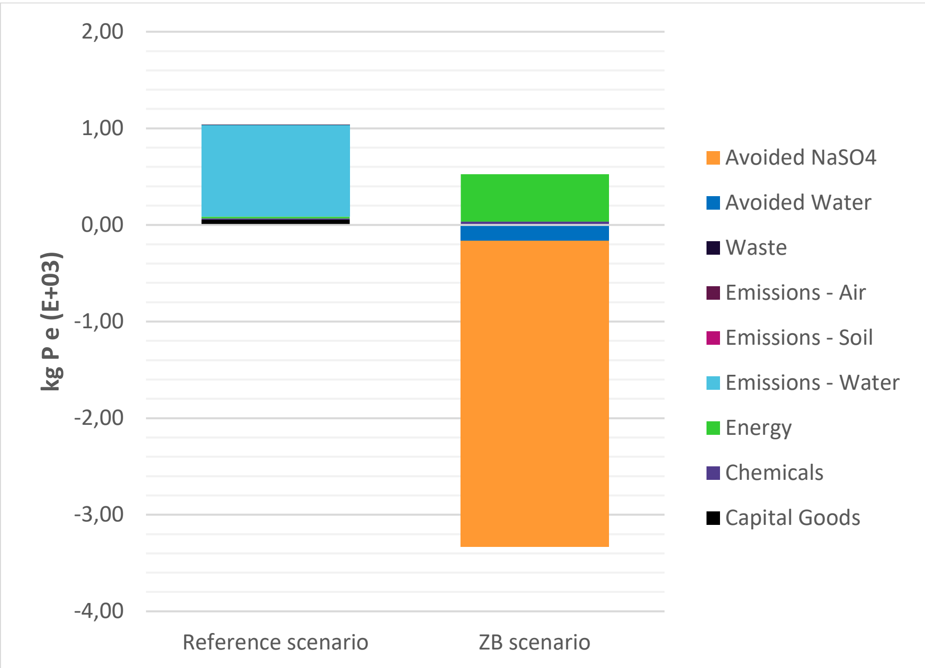

Figure 42: Contribution analysis of freshwater eutrophication of ZB system compared to reference system for the silica plant

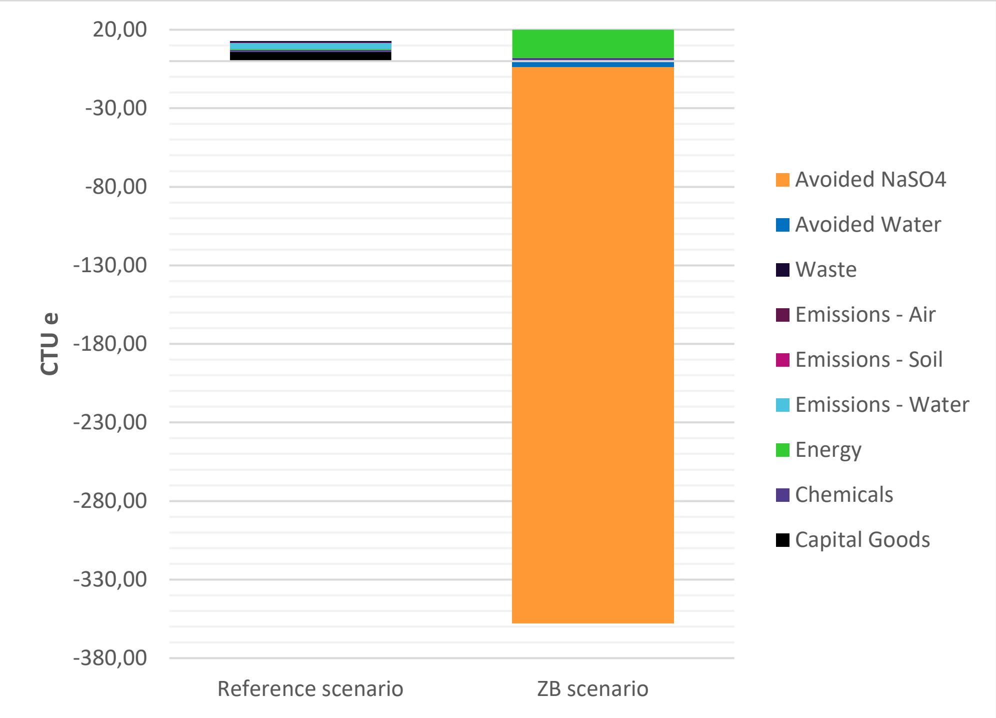

Figure 43: Contribution analysis of freshwater ecotoxicity of ZB system compared to reference system for the silica plant

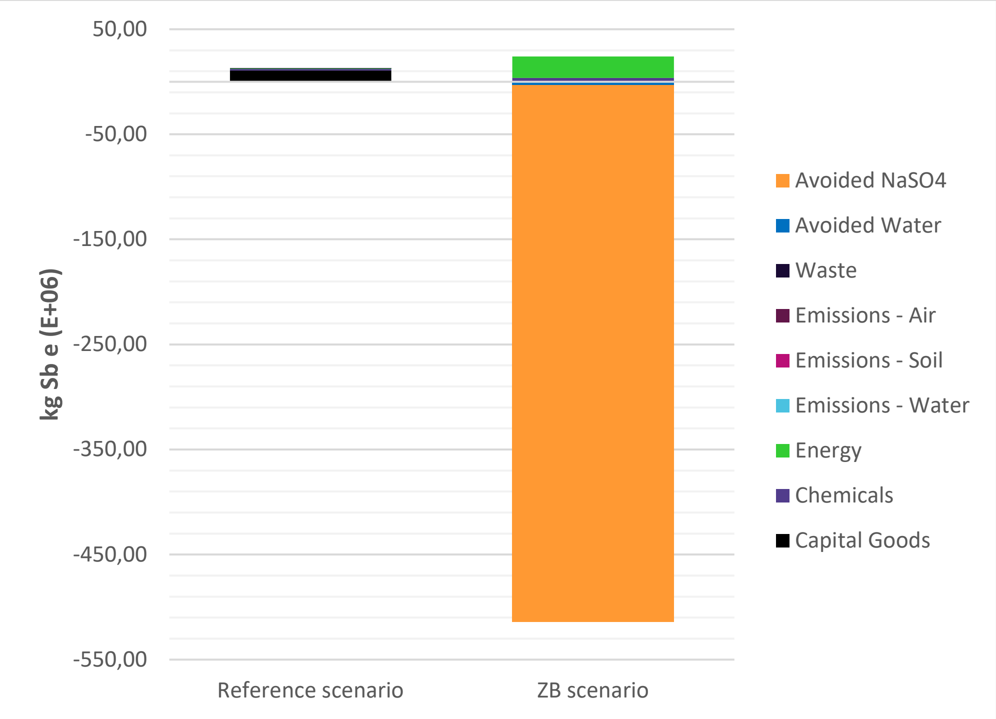

Figure 44: Contribution analysis of mineral, fossil and renewable resource depletion of ZB system compared to reference system for the silica plant