ZERO BRINE

D7.3 Preliminary LCA and LCC of the Demonstration Projects

An initial analysis

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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 of 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.

This report presents the first of three stages of evaluation using life cycle assessment (LCA) and life cycle costing (LCC) that will be conducted on each case study. A unified approach is also developed during this process to ensure consistency of approach across the three LCA teams conducting the analysis. The purpose of the three-stage evaluation approach is to aid the design and development process to ensure the optimum environmental and economic solution is developed.

The initial results are based on bench scale data for the LCA and are therefore of a preliminary nature, with the efficiencies and impacts expected to improve with larger full-scale operations. Nonetheless, the results already identify potential hotspots of concern. In addition, data availability varied across the case studies and therefore each one required a different approach or focus.

For the DWP, a comparison was made with and without the Zero Brine system. For the impact categories considered the Zero Brine system increased overall impacts, with climate change impacts doubling. This was due to the increased use of chemicals and the associated energy involved in their production. In addition, the electricity of the DWP also increased. However, in contrast the release of brine to the local harbour is avoided, although at this stage it is not known how much benefit this provides. This leads to the suggestion that the next phases of development should focus on reducing the use of the chemicals in the TOC removal or utilising lower impact chemicals should therefore be considered.

The LCA for the coal mine revealed that a large share of the impacts that result from chemical and energy use in the ZB system are negated by the benefits of recovering magnesium hydroxide and sodium chloride. Similarly, in the textile case study the recovery of materials has large benefits, particularly for recovered brine for reuse in the dyeing process. The LCC's for both cases showed that there could be significant revenues generated from by-product recovery, but this is highly sensitive to the market price that can be obtained.

In the silica case study, the RO was shown to be the main environmental hotspot, accounting for 80% of the impacts. Design recommendations therefore centre around reduction energy use and ensuring renewable sources are utilised. Further, design suggestions are expected when data for the complete system becomes available.

In summary, the Zero Brine systems are expected to greatly improve the quality of local discharge to local water bodies or stop them altogether. However, there is a risk for some systems that the overall impacts in terms of climate change and resource depletion could increase without careful design considerations and sourcing of sustainable resources.

The next phases of the evaluation will focus on collecting the data for the complete systems, and the reference systems, and upscaling the data to represent full scale plants. The final results will be reported in D7.7: "Report on LCA and LCC results of case studies and technologies involved in the ZERO BRINE project". This will be complemented with D7.2 that provides an evaluation of the results from the demonstration activities with a more techno-economic focus.

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List of Abbreviations

CrIEM	Crystallization with Ion Exchange Membranes
ED	Electrodialysis
EFC	Eutectic Freeze Crystallization
GHG	Greenhouse Gas Emissions
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventiry
IEX	Ion Exchange
MF	Membrane Filtration
NF	Nanofiltration
RO	Reverse Osmosis
SLCA	Life Cycle Social Assessment
TOC	Total Organic Carbon
ZB	Zero Brine

1. Introduction

The Zero Brine (ZB) project is focused on developing innovative recovery solutions to close the loop of saline impaired effluents (brines) generated by the process industry. It aims to eliminate wastewater discharge and minimise environmental impact of industrial operations through the integration of several existing and innovative technologies. These technologies are targeted to recovery high quality end products with high purity to provide optimum market value.

The largest source of chloride effluent releases in Europe is the process industry, with the chemical industry's being the predominant source with 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). Economic treatment of the brine effluents is a major challenge due the various composition and complexity of the treatment solutions. Industry is also the second largest water consumer accounting for 22% of global demand and can therefore play a significant role in tackling water stress. In many countries, the chemical industry is the most water intensive industry accounting for over 30% of industrial water consumption.

Zero Brine therefore aims to close the loop of these problematic effluents through the recovery of water and valuable components of 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 aim to develop and demonstrate the Zero Brine approach under different industrial circumstances:

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

The different case studies utilise different configurations of water treatment technologies to treat and recover the various constituents of the water. The Zero Brine approach is to combine existing technologies such as reverse osmosis and nanofiltration with newly developed innovative technologies: eutectic freeze evaporation, crystallisation with ion exchange membranes and a forward-feed multiple effect distillation (MED) evaporator. Each case study requires different configurations of these technologies.

Work package 7 of the ZB project involves a comprehensive sustainability assessment of the ZB systems to verify the sustainability performance of the industrial applications. The assessment will combine life cycle assessment (LCA), life cycle costing LCC) and a Social LCA (SLCA). The ultimate aim is to compare the ZB system against the existing treatment process.

This report details the preliminary LCA and LCC of the case studies utilising bench scale and pilot scale data, as well as data from literature and other sources. The objectives are to:

- Provide a preliminary assessment of the environmental hotspots of the ZB system.
- Provide a preliminary LCC that gives an initial indication of the life cycle costs of the ZB processes.
- Utilise the results of the LCA and LCC to inform the design process of the ZB systems to improve the environmental performance where possible (in terms of aspects such as optimisation, choice of chemicals and materials etc.).

At this stage in the development process the data (bench scale and pilot plant scale) is not fully representative of how the full-scale plants will perform. This is considered as much as is currently possible in the analysis. In addition, at this stage of the project, adequate data was not available on the existing treatment processes that would allow a comparison with the ZB systems. Therefore, in this report the most of analysis is only of the ZB systems. Some cursory comparisons were possible however, for the LCC, which are described in the individual case studies.

2. Case Study Introductions

2.1 Water Plant in The Netherlands

The Demineralized Water Plant (DWP) in the Botlek area owned by EVIDES is a large-scale demonstration of the ZB project using a combination of ion exchange and membrane technology: Dissolved Air Flotation (DAF), Cationic Exchange Resin, Reverse Osmosis and Mixed Bed Ion Exchange. There are two sites at the DWP that both generate a brine stream. The first brine is generated at Site 1 from a water softening process, whilst the second brine stream is generated at Site 2 by the reverse osmosis process.

The aim is to demonstrate the Nanofiltration – Evaporation concept for the treatment of ion exchange (IX) regenerate and RO concentrate at large industry scale as well as to demonstrate the Anionic Ion Exchange (IX) – Nanofiltration (NF) – Evaporation – Eutectic Freeze Crystallization (EFC) concept at demonstration scale. Part of the energy for the brine treatment is derived from waste heat. Waste heat and wastewater streams will be combined in a multi-company site environment eliminating brine effluent (target: zero liquid discharge) of the industrial water supplier, recovering high purity magnesium products (target: magnesium purity >90%), NaCl solution and sulphate salts and recycling streams within the site (target: >70% internal recycling of materials recovered).

2.2 Coal Mine in Poland

The pilot plant for the Polish case study will be located at the ZG Bolesław Śmiały Coal Mine operated by PGG. The aim is to demonstrate the benefits of the ZB system to effectively treat the mine water salinity, whilst recovering several valuable constituents from the water. The aim is to decrease the energy consumption by 50% compared to the energy consumption of a reverse osmosis-vapour compression system, which represents current best practice. The coal mine water, with a salinity of ca. 23 g/L and rich in calcium sulphate, will be treated using integrated system consisting of nanofiltration, reverse osmosis and electrodialysis with the aim to recuperate valuable raw materials, such as concentrated brine, magnesium hydroxide, and high-quality RO permeate.

2.3 Textile Industry in Turkey

The Turkish case study examines the potential of a ZB system to be integrated into a textile manufacturing plant to treat the brine whilst recovering valuable components for reuse. The pilot plant will be located at the ZORLU Textile and Energy Groups at Büyükkarıştıran- Lüleburgaz, Kırklareli, Turkey. The methodology involves physical and chemical characterization studies, followed by bench scale treatability studies. Technology options that are tested include nanofiltration, oxidation and ion exchange.

Initial analysis suggested that the ZB system together with waste heat recovery from the textile operation, will reduce the water consumption by 50 kt/year through water reuse, recover 400 tonnes of NaCl per year for use in production processes and lead to a reduction of 200 t/year of CO2 emissions.

2.4 Silica Industry in Spain

The pilot plant will be located at IQE in Zaragoza, Spain, a producer of chemicals and silica. The aim is to demonstrate the technical and economic feasibility of a ZB system to recover water, sodium sulphate, waste heat and alkalis from silica industry brine. The case study includes the technologies nanofiltration, eutectic freeze crystallization, forward feed evaporation and electro dialysis with bipolar membranes. The case study will also examine the benefits of using regenerated membranes derived from a desalination plant.

3. Approach and Methodology

3.1 Introduction

This report presents the preliminary LCA and LCC analysis using the best available data to date. Although the aim of WP7 is to compare the ZB systems with the existing treatment solutions this has not been possible at this stage in the project due to data limitations, partly due to the development stage of the project. The following sections provide a brief introduction of LCA and LCC and the approach used in this report.

Concurrent to this preliminary analysis has been the development of a Unified Approach for the sustainability assessment. The aim of the unified approach is to provide a framework to ensure consistency across the LCA and LCC research on the case studies. This will help to ensure that the analysis is done to the highest standard and that the results can be compared across the case studies. The Unified Approach also aims to compare the ZB systems with the reference system so that the advantages of installing such a system in other similar industrial situations can more easily be assessed.

However, part of the development of the Unified Approach is to first understand the systems, challenges, data limitations and other LCA relevant aspects, of the case studies. Unfortunately, due to the timing of the preliminary analysis and many challenges getting the initial data, it has not been possible at this stage to fully develop the Unified Approach. Therefore, each case study in the present analysis has been required to utilise the available data and information and therefore there are some differences across the case studies.

In the next phase of the ZB project, the focus will be on developing the Unified Approach so that consistency is applied across the next stages of the LCA, LCC and Social LCA analysis.

3.2 Life Cycle Assessment

Life cycle assessments (LCA) investigate the environmental impacts related to a product or a system throughout its complete life cycle. This includes evaluating energy and resource consumption as well as emissions, from all life cycle 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 a LCA is performed we refer the reader to the literature such as Rebitzer et al. (2004) and the draft guidelines for Product Environmental Footprint (PEF, 2012). The LCA in this report is performed in accordance with ISO 14040:2006 (European Committee for Standardization, 2006) and ISO 14044:2006 standards (European Committee for Standardization, 2006). A schematic overview of a life cycle is shown in Figure 1.

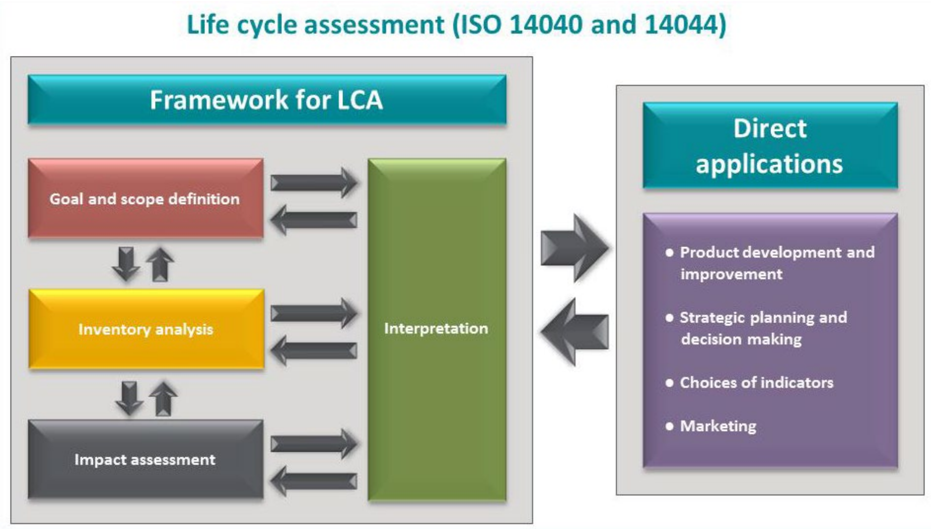

Figure 1: The LCA framework (ISO 14040:2006)

Full data on the ZB systems and reference (current) systems is not yet available to enable full comparisons of the reference system with the ZB system. Therefore, each case study currently takes a different approach in this report and assesses different aspects of the treatment process as follows:

1. **Demineralised water effluent in The Netherlands** – compares the current system that produces desalinated industrial process water, with and without the ZB system.
2. **Coal mine effluent in Poland** – compares four configurations of the ZB unit operations, in order to inform design choices based on environmental and economic performance.
3. **Textile industry effluent in Turkey** – assesses the unit processes of the ZB system to assess their contribution to environmental impacts and economic implications of the system
4. **Silica industry effluent in Spain** – is limited to an assessment of the ZB filtration technology, comparing the use of regenerated membranes (effectively reused/recycled membranes that have reached the end-of-life at a separate desalination plant) with utilising new membranes

Further information on the goal, scope and system boundaries is provided in the individual case study chapters.

3.3 Life Cycle Costing

Life cycle costing is an accounting technique that compiles all costs that an owner or producer of an asset will incur over its lifespan (Swarr et al, 2011). It therefore considers both capital expenditure and operating expenditure throughout the life cycle. This is in contrast with traditional cost-accounting systems that only for example consider the initial capital costs of purchasing a building. They fail to properly account for operating costs or end-of-life activities such as demolition and recycling (Gluch and Baumann, 2004)

LCC has a considerable history that predates LCA and exists in different forms with different approaches (Swarr et al, 2011)). Gluch and Baumann (2004) identified at least ten different techniques that fall under the remit of life cycle costing and which address environmental concerns at varying degrees. However, it is only within the last 20 years that it has begun to be aligned with and associated with LCA. LCC has not been standardised as has LCA, but the Society of Environmental Toxicology and Chemistry (SETAC) developed a code of practice (Swarr et al. 2011b).

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) 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."

Typical LCC analyses are therefore are based on (IISD, no date):

- purchasing costs and all associated costs such as delivery, installation, commissioning and insurance;
- operating costs, including utility costs such as energy and water use and maintenance costs;
- end-of-life costs such as removal, recycling or refurbishment and decommissioning;
- longevity and warranty time frames of the asset.

IISD (no date) identify several inconsistencies in the application of LCC. Furthermore, they note that there is too much emphasis on financial returns and wider socio-economic benefits need to be more fully included (IISD, no date). This can include both social benefits and avoided social costs enabled by a project or tender. They note however, that this can be extremely challenging to forecast with an acceptable degree of certainty. For example, avoided unemployment benefits or health care costs are especially difficult to forecast.

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.
    b. Operational costs, such as consumption of energy and other resources.
    c. Maintenance and repair costs.
    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)

However, as in the LCA approach, at this stage in the project there are several limitations in the data availability and the development stage of the project that limit the current analysis. Therefore, in the current report the LCC is limited to the first component.

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 tend to represent low contributions to the functional unit, due to the investment is repaid during the whole lifespan of the system. Therefore, CAPEX costs are directly dependant on the lifespan, and its final value may vary through time.
- OPEX costs rely on continuos 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.

However, at this stage the individual case studies have taken different approaches based on data availability. For the Turkey and Polish case studies, the analysis only includes the operating costs, as data on capital expenditure was not currently available.

Therefore, due to the timing of the preliminary analysis and challenges in obtaining data each case study has taken a slightly different approach to the LCC. Inclusion of aspects such as replacement of equipment, maintenance and end-of-life costs are only included where stipulated and as shown in Table 1 and Table 2. This shows that the inclusion of different elements is at this stage in the project the LCC's are at a very cursory level, are very different and therefore no cross comparisons can yet be made.

Table 1: Inclusion of CAPEX elements in the different case study analysis

CAPEX element	The Netherlands	Poland	Turkey	Spain
R&D	-	-	-	X
Total plant cost	X	-	-	X
End	-	-	-	

Table 2: Inclusion of OPEX elements in the different case study analysis

OPEX element	The Netherlands	Poland	Turkey	Spain
Staff	X		-	X
Consumables (chemicals, water etc)	X	X	X	X
Energy/electricity	X	X	X	X
Replacement parts	-	-	-	X
Revenues /products	X	X	X	-
NPV /discounted cash flows	-	-	-	-

4. Case Study 1: Demineralised water, The Netherlands

4.1 Intro

Environmental pollution, resource scarcity, and freshwater shortage are critical world challenges facing humanity in this century. The process industry is the major source of brine production in Europe. Brine is a high-concentration solution of salt in water, and Its disposal is problematic due to environmental pollution and brine's share in critical raw materials (European Commission, 2014). Therefore, processing industrial brine may result in decreasing environmental pollution and recovering scarce resources and clean water.

Brine consists of water with high salt concentration. Brine can be a waste product of various industrial processes, but it is also a product in salt solution mining. Solution mining involves drilling one or several wells down to a salt layer. Hot water is pumped down the well, resulting in dissolving the salt in the salt layer, and producing saturated brine. The brine is transported to a salt production plant, where it is purified in a brine purification facility to produce specialty salt, vacuum salt and low-purity salt (Sediyi, 2006; Warren, 2016). The vacuum salt consists of high purity salt and is manufactured for industrial use. This industrial use covers chemical production, such as chlorine and caustic soda, sodium carbonate, sodium chlorate etc., and water treatment facilities (Roskill, 2018). As a result, the salt consumed in these processes ends-up as brine effluent. European regulation prohibits organizations from disposing industrial brine to surface water (US EPA, 2014). Additionally, brine contains substances that European Union has identified as critical raw materials (European Commission, 2014) and is a priority in the Circular Economy Package (Bourguignon, 2016), such as magnesium.

One of the industries that participates in the project is Evides Industriewater (Rotterdam, the Netherlands). Evides Industriewater produces ultra-pure demineralized water (demi water), which is purchased by the chlor-alkali industry in the port of Rotterdam area, and brine as a waste product. Brine derives from two sources in the demineralized water plant (DWP), the ion exchange softening units and reverse osmosis units. The ion exchange softening units regard the use of high purity salt during the regeneration process. The high purity salt that is employed is the vacuum salt that is described above. In reality, brine is generated in a salt plant, then it is dried to acquire high purity salt and the high purity salt is transported and put into water for resins regeneration purposes. Evides Industriewater currently discharges the brine affluent to the sea water nearby, but it considers improving its environmental performance by recovering and reusing the sodium salt in the regeneration process. The ZB project aims at treating brine from Evides Industriewater to recover distilled water, sodium salt and other salts. For this purpose, a demo plant will be built. The demo plant will consist of Site 1 and Site 2, with each site processing brine from one of the two brine sources in the DWP.

Site 1: The main objective of Site 1 (treating brine from IX Softeners) is to achieve Zero Liquid Discharge, to recover high purity magnesium compounds with potential commercial value, as well as to recover a sodium chloride solution that will be recycled for the regeneration of the ion exchange resins. The total flow per regeneration is 80 m^3, while the resins are regenerated every 18 hours, which results in an equivalent flow of 106 m^3/day (per unit, total 8 units). The demo plant that will be developed will be able to treat 5.3 m^3/day, thus accounting for 0,6% of the total brine volumes generated. This system comprises a large scale (industrial) demonstration. The system is optimized in a way to be able to make use of waste heat, thus the optimal combination of membrane and thermal evaporation steps will be determined. The membrane crystallizer has already been demonstrated at pilot scale, resulting in high purity of recovered products.

Site 2: The main objective of Site 2 is to achieve Zero Liquid Discharge, to produce sulphate salts (while dealing with organic contamination), as well as to recover a sodium chloride solution that can be recycled for the regeneration of the anionic ion exchange resins. The system will be able to treat approximately 1 m^3/h of the brine generated by the reverse osmosis unit. The existing reverse osmosis unit of the DWP runs continuously producing approximately 250 m^3/h, which means that the demo plant will treat 0.4% of the total brine flow. The evaporator unit that will be demonstrated in Site 1 will be used also in Site 2.

4.2 Goal and Scope

4.2.1 Goal and functional unit

The goal of the study is to investigate the effect on the environmental performance of the DWP with and without the ZB pilot system. The aim of the ZB system is sodium salt recovery in order to replace 75% of the high purity (HP) salt purchased by AkzoNobel in the norther part of the Netherlands. Due to the goal of this report, the functional unit is the “generation of 1 m^3 of total brine”, that corresponds to 0.5 m^3 brine deriving from the IEX softener unit and 0.5 m^3 brine deriving from the reverse osmosis unit. The LCA modelling was performed with the Simapro software (Consultants, n.d.) and Ecoinvent database 3.5 (Wernet et al., 2016) was used. The environmental impacts indicators under investigation were calculated with the CML 2001 Impact Assessment Method: abiotic depletion, global warming, human toxicity, fresh water aquatic ecotoxicity, terrestrial ecotoxicity, acidification, eutrophication and photochemical oxidation potentials.

4.2.2 Allocation

Allocation was avoided when possible, and substitution was applied as suggested by the ILCD handbook (Wolf et al., 2010). Substitution was applied in membrane crystallization 1 and 2 processes of Site 1 and nanofiltration and evaporation in Site 2 of the ZB system. On the other hand, applying substitution was not possible for the AkzoNobel plant which produces the high purity salt that the DWP uses for resins regeneration, therefore economic allocation was used based on the current prices of the Dutch market (Brinkmann et al., 2014).

4.2.3 System boundaries

The system boundaries are gate-to-gate for the DWP with and without the installation of the ZB system. Figure 2 illustrates the DWP current operation and Figure 3 illustrates the DWP with the ZB system. The DWP is presented in an abstract way in Figure 3 showing only the two processes, which are the brine sources, as no modifications happen in the DWP. The system boundaries start with water pumped to the DWP from the Breelse lake and processed to produce ultra-pure demineralized water and brine. The lake water is processed firstly with coagulation and floatation processes, filtration and then with ion exchange (IEX) softening, reverse osmosis and lastly using a mixed bed polisher before distribution to the water network. Both the IEX softener and reverse osmosis unit produce brine. In the IEX this is derived during the resin regeneration process. Currently, brine is disposed into the sea. The ZB system will process the brine to produce distilled water, magnesium and sodium salts. Figure 3 illustrates the two ZB systems, where brine from the IEX at Site 1 and brine from the RO at Site 2 are treated with different solutions. In both sites, nanofiltration, evaporation, membrane crystallization, eutectic freeze crystallization, ion exchange and reverse osmosis technologies are employed. The recovered sodium chloride will be reused internally in the DWP, recovered water will replace the current lake source water, whilst the by-products can be sold externally.

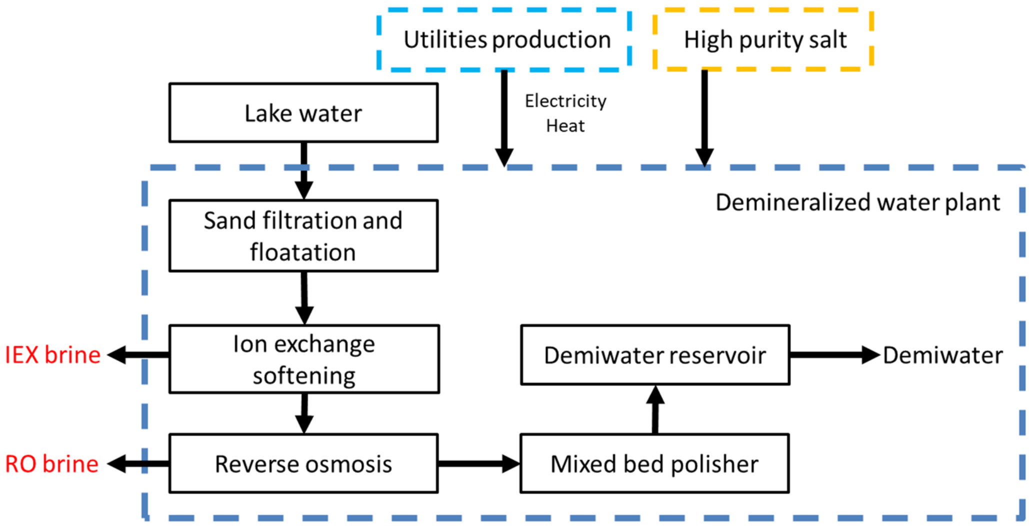

Figure 2. System boundaries of DWP without the ZB pilot system

![ZERO BRINE]

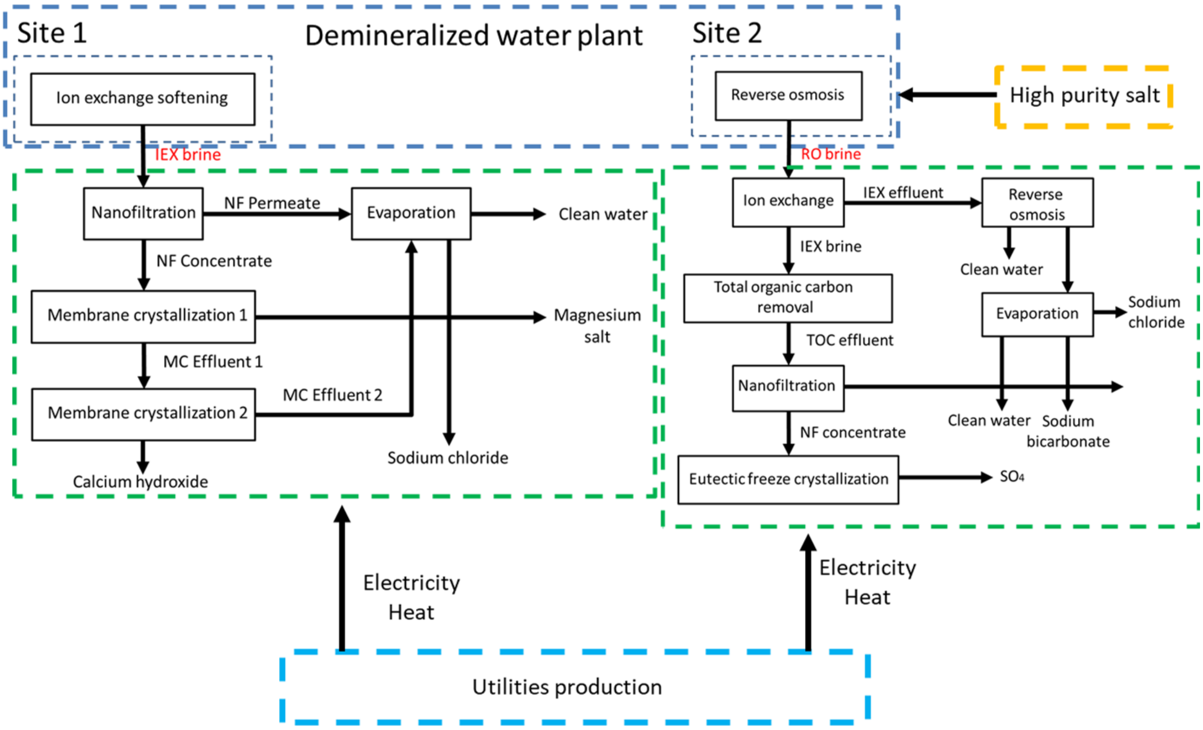

Figure 3. System boundaries of DWP with the ZB pilot system

4.2.4 Study assumptions

In this work we assumed that no regeneration is taking place in the IEX softening unit of Site 2. For regeneration a sodium chloride solution would be needed, the same product that is recovered in both Sites 1 and 2. Furthermore, we assumed that the evaporator in Site 1 will use waste heat, as it is indicated in the Grant Agreement document. However, until the finish of this report, it was not confirmed the source of the waste heat. Therefore, a scenario is presented in the "Design recommendations" subsection, where needed heat is generated via natural gas combustion. Last, one limit of the Life Cycle Impact Assessment models is their limit to assess the effect of brine, and even saline, effluents to the environment. It is expected that brine disposal results in environmental burdens when disposed in surface water, but when this was modelled in Simapro software, no effects were identified in toxicity impact indicators. Therefore, it is expected that the aquatic toxicity indicator will be underestimated in the DWP (without the ZB plant) system.

4.3 LCI

4.3.1 Demineralized water plant

Data for the current operation of the DWP is presented in Table 3. The data concerns the whole plant operation, they are not per unit process and they are per 1000 m^3 of demi water production. Data for the DWP were collected from Evides Industriewater.

Table 3. Life Cycle Inventory of DWP operation

Inflow		
Lake Breelse Water	1261	m^3/1000 m^3 demi water
HP Salt	467	kg/1000 m^3 demi water
Sodium hydroxide (NaOH)	43	kg/1000 m^3 demi water
Hydrochloric acid (HCL)	36	kg/1000 m^3 demi water
Iron(III) chloride (FeCl3)	13	kg/1000 m^3 demi water
Polyacrylamide	0,23	kg/1000 m^3 demi water
Steam (200°C, ca.18 bar)	2375	kg/1000 m^3 demi water
Electricity	1269	kWh/1000 m^3 demi water
Outflow		
Demineralized water	1000	m^3
Waste	1057	Kg/1000 m^3 demi water

4.3.2 Zero Brine system

The life cycle inventory of the ZB system with all the inputs and outputs of the life cycle stages is presented in Table 5 and Table 6. The data regarding inflows and outflows of Site 1 and Site 2 are based on results from bench scale tests and PhreeqC simulations, respectively. Bench scale tests were performed regarding nanofiltration and membrane crystallization technologies for Site 1 processes. PhreeqC is a computer program designed to model a wide variety of aqueous chemical reactions. The simulation results will be used to fine-tune the process flow diagrams. Data from PhreeqC simulations exist on the Grant Agreement document. Furthermore, data regarding capacities of equipment used in Site 1 and Site 2, were collected based on internal communication with the consortium partners that are providing the technologies. Table 4 shows the technology providers.

Table 4.Technology providers in ZB project

Technology	Provider
Ion exchange softening unit	Lenntech
Reverse osmosis unit	UNIPA
Nanofiltration unit [a]	Lenntech
Membrane crystallisation units	UNIPA
Evaporator unit [a]	NTUA
Total organic carbon (TOC) removal unit	Arvia
Eutectic freeze crystallisation unit	TU Delft

[a] in Figure 3, two of these units are shown, however, it is one unit that will run on two different time periods

Table 5. Site 1 process inflows and outflows for LCA modelling

SITE 1	Inflow					Outflow				
Nanofiltration	IEX brine	1000	L/h	36000	g/h	NF Permeate	700	L/h	7700	g/h
	Electricity for pump			10.57	kWh	NF Concentrate	300	L/h	28200	g/h
	Antiscalant (Vitec 3000)			0.5	kg/h					
Membrane Crystallization 1	NF Concentrate	300	L/h	28200	g/h	Magnesium		L/h	666.4	g/h
	Electricity for pumps and control			1.5	kWh	MC1 effluent	300	L/h	29400	g/h
Membrane Crystallization 2	MC1 effluent	300	L/h	29400	g/h	Calcium hydroxide		L/h	8.42	kg/h
	Hydrochloric acid (HCL)			0.8	kg/h	MC2 effluent	300	L/h	29700	g/h
	Electricity			3.7	kWh					
	Sodium hydroxide (NaOH)			6.6	kg/h					
Evaporator	MC2 effluent	300	L/h	29700	g/h	Evaporator effluent	582	L/h	37830	g/h
	NF Permeate	700	L/h	7700	g/h	Condensate	418	L/h	0	g/h
	Waste heat			3,9	kWh					

Table 6. Site 2 process inflows and outflows for LCA modelling

SITE 2	Inflow					Outflow				
Ion exchange	RO brine	1000	L/h	3000	g/h	An. IEX effluent	950	L/h	2850	g/h
	Evaporator effluent	13.84	L/h	2823	g/h	An. IEX brine	50	L/h	4950	g/h
	Antiscalant (Vitec 4000)			625	g/h					
	NF permeate	40	L/h	3560	g/h					
	Electricity for pump			5	kWh					
Reverse osmosis	An. IEX effluent	950	L/h	2850	g/h	RO concentrate	95	L/h	2850	g/h
	Electricity for pump			5	kWh	RO permeate	855	L/h	25.65	g/h
TOC removal	An. IEX brine	50	L/h	4950	g/h	TOC removal effluent	50	L/h	4950	g/h
	Electricity for pump			7.37	kWh	Waste			40.5	kg/h
	Sulfuric acid (H2SO4)			36.1	kg/h					
	Sodium hydroxide (NaOH)			24.4	kg/h					
Evaporator	RO concentrate	95	L/h	2850	g/h	Condensate	81.17	L/h	0	g/h
	Electricity			5	kWh	Evaporator effluent	13.84	L/h	2823	g/h
	Waste heat			0.38	kWh	Sodium bicarbonate (NaHCO3)			16600	g/h
Nanofiltration	TOC removal effluent	50	L/h	4950	g/h	NF concentrate	10	L/h	1370	g/h
	Electricity			5	kWh	NF permeate	40	L/h	3560	g/h
Eutectic Freeze Crystallization	NF concentrate	10	L/h	1370	g/h	Sodium sulfate (Na2SO4)			240	g/h
	Electricity			4	kWh	Water (ice)	10	L/h		

4.4 LCIA

4.4.1 Results

Figure 4 and Figure 5 show the performance of the DWP with and without the ZB system. It is obvious that the environmental performance becomes worse when the ZB system is implemented. The current analysis suggests some environmental impacts are higher in the DWP (with the ZB plant) case but the impact of brine effluent from the current system has not been considered at this stage, as it was assumed that the "freshwater aquatic ecotoxicity" indicators is not affected by brine disposal. The difference between the LCA systems Figure 4 and Figure 5 is mainly due to the operation of the ZB system, as the improved efficiency of the DWP due to the recovery of distilled water and the environmental benefits due to sodium chloride and magnesium recovery are negligible when compared with the chemicals needed for the ZB system operation. In the discussion section, an analysis of environmental hotspots of the ZB system will be presented.

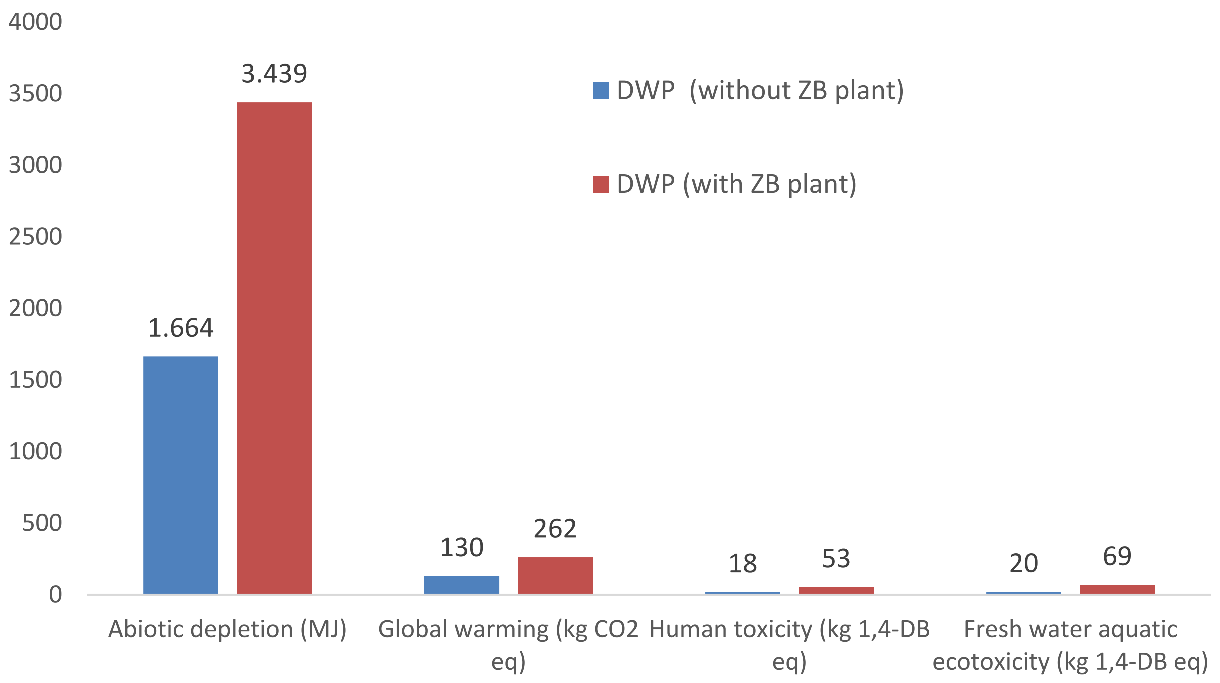

Figure 4. LCIA results for 1 m³ of brine

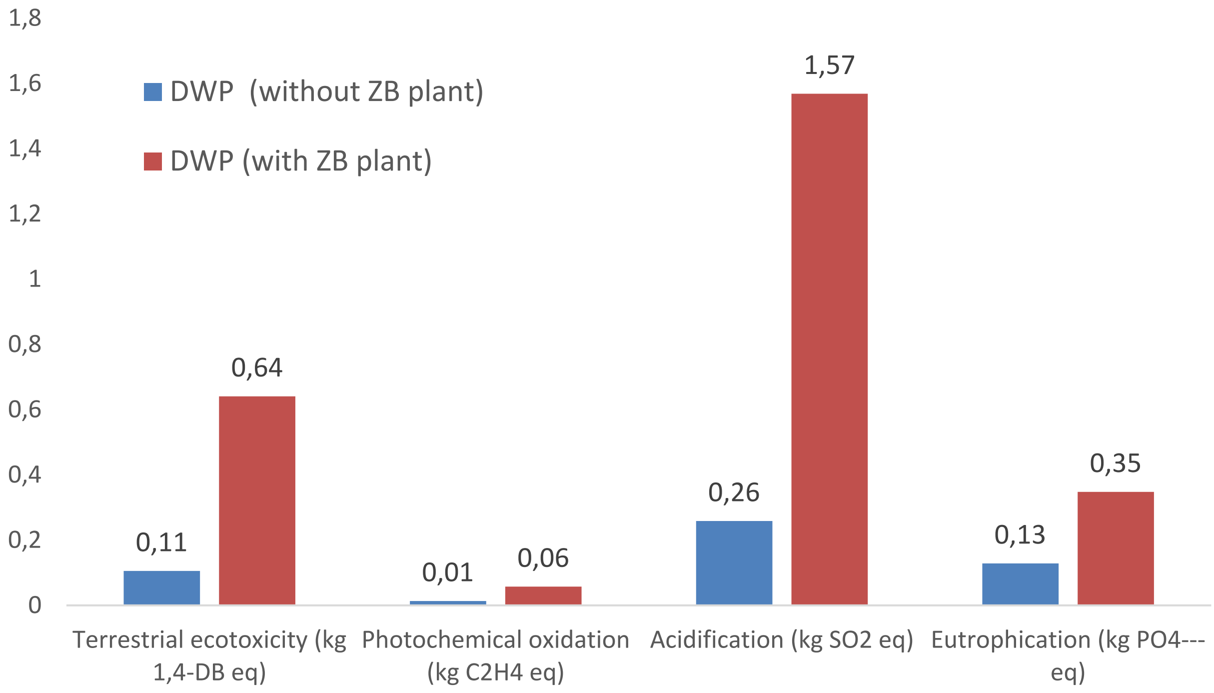

Figure 5. LCIA results for 1 m^3 of brine

4.5 Life Cycle Interpretation

4.5.1 Contribution analysis

The contribution of processes in the ZB system performance is presented in Figure 6 and the process tree of ZB system for Global Warming Potential (for 100 years) is presented in Figure 7. The cut-off was performed at 1% for the process tree. This was selected to have a good visual result of the contributions. Figure 6 shows that electricity generation is the main contributor to the GWP score. However, when complemented with Figure 7, electricity consumption does not occur in the ZB system itself. Electricity is consumed to produce chemicals needed for the ZB system, especially the neutralising agent (sodium hydroxide) for the TOC removal process. Furthermore, the mined coal to produce electricity is also contributing to the GWP result. In Figure 7, the red arrows refer to contributing in increasing the GWP score, whereas the green arrows refer to contributing in mitigating the GWP score. Site 1 contributes to environmental benefits due to the recovered products, magnesium and calcium hydroxide, and the avoided production of the same products in the global market. Nevertheless, the recovered amounts are very low in order to have a significant impact when compared with the chemicals needed for the TOC removal process.

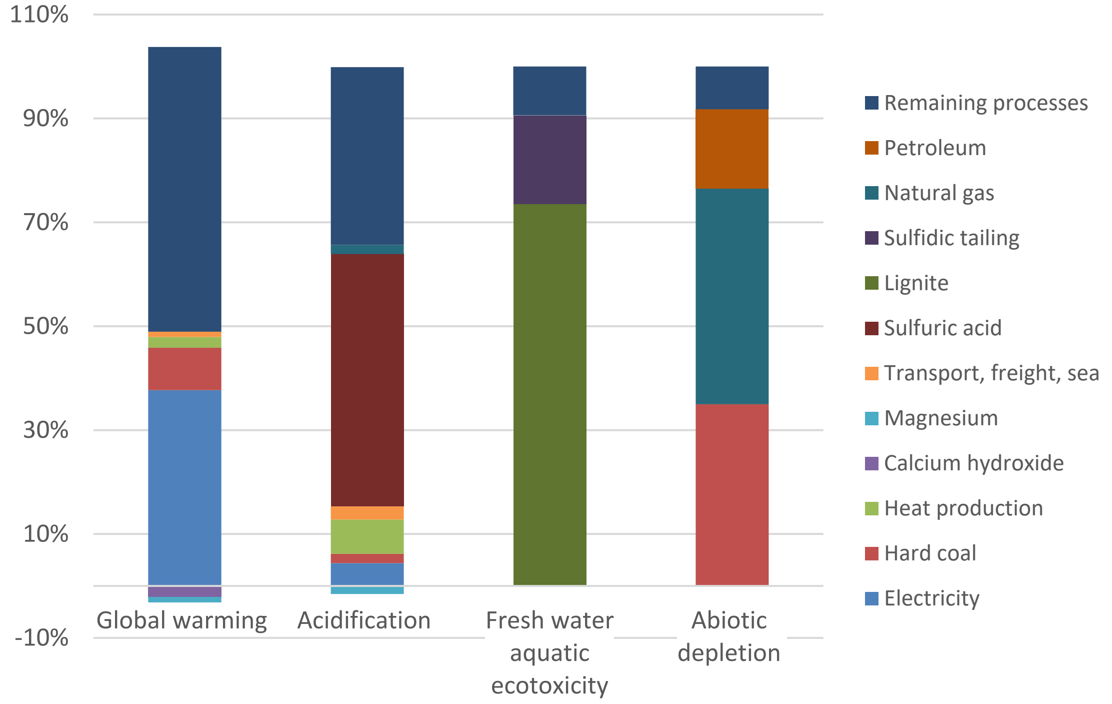

Figure 6. Contribution analysis of environmental impacts of ZB system (cut-off processes<1%)

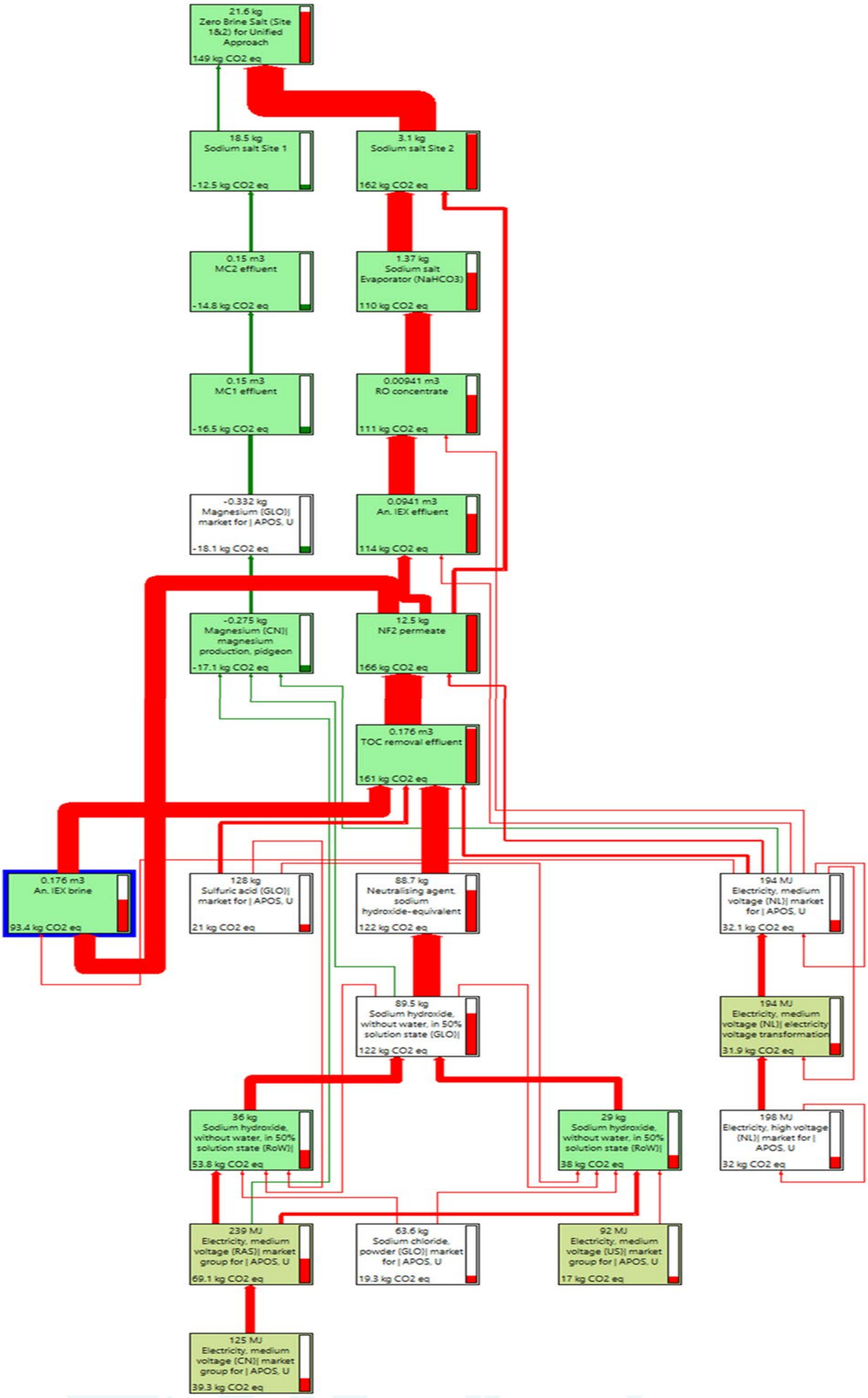

Figure 7. Process tree of Global warming (GWP100a) for Zero Brine system (cut-off at 8%)

4.5.2 Design recommendations

Several aspects of the ZB plant design need to be optimized in order to improve the environmental performance of the system. First of all, the consumption of chemicals (i.e. sulphuric acid and sodium hydroxide) at the TOC removal process is a large contributor to impact indicators, as illustrated in Figure 7. Different chemicals with better environmental performance or a reduction in the consumption of sodium hydroxide will greatly benefit the environmental performance. The LCA modelling was based on the assumption that waste heat is used in the evaporator, but quantities are relatively low and so not critical. Figure 8 shows how the impact of selected environmental indicators change waste heat is not utilized. In this scenario, heat was generated from natural gas combustion. Finally, the recovery of materials of high purity in Site 1 is important to improve the environmental performance of the system. Low quality recovered materials will result in materials that is not clear if they can replace existing products on the market.

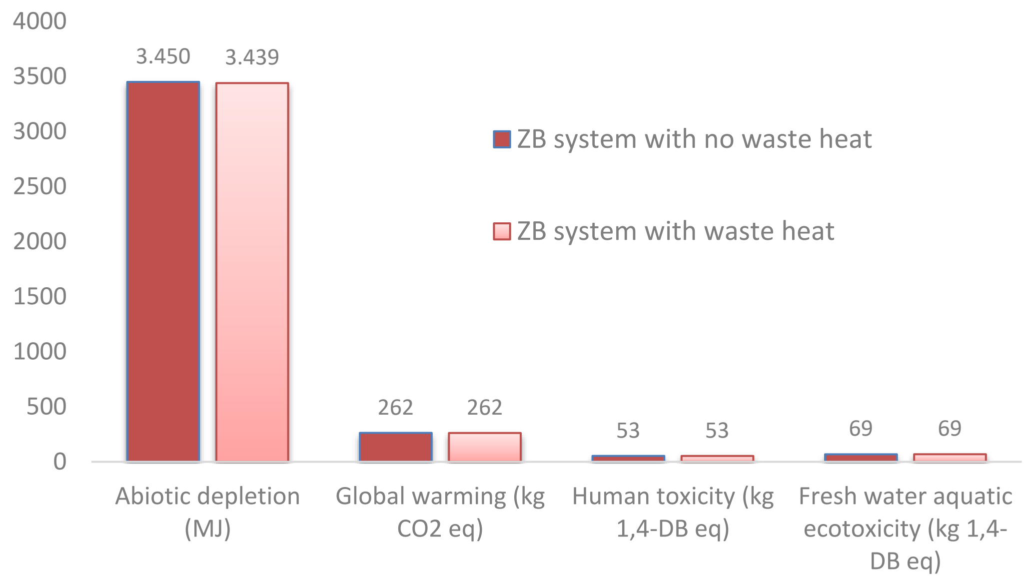

Figure 8. Selected environmental indicators in case no waste heat is available in Site 1 of Zero Brine plant

4.6 LCC

This section concerns the economic performance of the ZB system in the Evides Industriewater context. This is performed by applying the Life Cycle Costing (LCC) method. The system built based on the LCC follows the recommendations by SETAC (SETAC, n.d.) and a similar approach to the LCA modelling is followed. Therefore, both approaches share the same functional unit, "generation and treatment of 1 m^3 of total brine" and spatial system boundaries.

The system boundaries cover the capital goods (CAPEX) and the operational cost (OPEX) of the DWP and ZB system. The CAPEX data for the DWP were estimated from Evides Waterbedrijf 2017 annual report (Evides Waterbedrijf, 2017) based on a fraction of the total capital financial value of Evides. CAPEX for the ZB system and internal communication with the ZB technology providers (see Table 5) for the DWP and technologies used in the ZB system, respectively. The OPEX data for the DWP and ZB plant concerned the conversion of the operational mass inflows and outflows of the LCA models into monetary flows. Operational inflows and outflows regarded mainly the chemicals and electricity consumption, and the demi water production and recovery of magnesium oxide, calcium hydroxide and sodium chloride, respectively. The quantities of used chemicals were collected via internal communication with the technology providers, and prices were collected from literature and online specialized chemical wholesalers. Last, data regarding the personnel cost was collected from the Evides Waterbedrijf annual report and via internal communication with Evides Industriewater confirmed that the ZB plant will result in increasing employment. Table 7 presents, CAPEX and OPEX results, the expected quantities for chemicals consumption and their prices and, prices for recovered products. Additional information for the LCC modelling of the ZB system is presented in Appendix 1.

Table 7. LC Inventory of LCC modelling

Cost	Unit cost	Unit	Price	
CAPEX (DWP)	0.02	Euros/m^3 brine		
CAPEX (Zero Brine)	0.17	Euros/m^3 brine		
OPEX (personnel)	3.28	Euros/m^3 brine		
OPEX (materials)	4.9	Euros/m^3 brine		
DWP consumables	0.76	Euros/m^3 brine		
NaCl	0.24	Euros/m^3 brine	0.057	Euros/kg
NaOH	0.08	Euros/m^3 brine	2.36	Euros/kg
HCl	0.03	Euros/m^3 brine	2.8	Euros/liter
FeCl3	0.02	Euros/m^3 brine	4.2	Euros/kg
Polyacrylamide	0.00	Euros/m^3 brine		
Steam (200°C, ca.18 bar)	0.33	Euros/m^3 brine		
Electricity	0.01	Euros/m^3 brine	0.082	Euros/kWh
Zero brine consumables	5.9	Euros/m^3 brine		
Antiscalant (Vitec 3000)	0.36	Euros/m^3 brine	13.5	Euros/kg
HCL	0.02	Euros/m^3 brine	37.8	Euros/liter
NaOH	2.62	Euros/m^3 brine	0.165	Euros/kg
Antiscalant (Vitec 4000)	1.34	Euros/m^3 brine	144.4	Euros/kg
H2SO4	0.06	Euros/m^3 brine	0.5	Euros/kg
Electricity	1.55	Euros/m^3 brine	0.082	Euros/kWh
Zero Brine products				
Magnesium Oxide	0.02	Euros/m^3 brine	924	Euros/kg
Calcium hydroxide	0.02	Euros/m^3 brine	89.6	Euros/kg
NaHCO3 (soda ash)	0.00	Euros/m^3 brine	73.3	Euros/kg
Demineralized water	9.62	Euros/m^3 brine	2.5	Euros/m^3

Based on the CAPEX and OPEX estimations, it is shown that the CAPEX of the ZB plant is negligible when compared to the DWP, see Figure 9. The OPEX estimations for the DWP with the ZB plant is shown in Figure 10. Furthermore, the quantity of the recovered materials can influence the LCC results, as their prices are high when compared to the consumed chemicals (Figure 11). Most of the expected profit derives from the magnesium oxide recovery since its market price is 924 Euros/kg, considerably higher than any other material consumed or recovered.

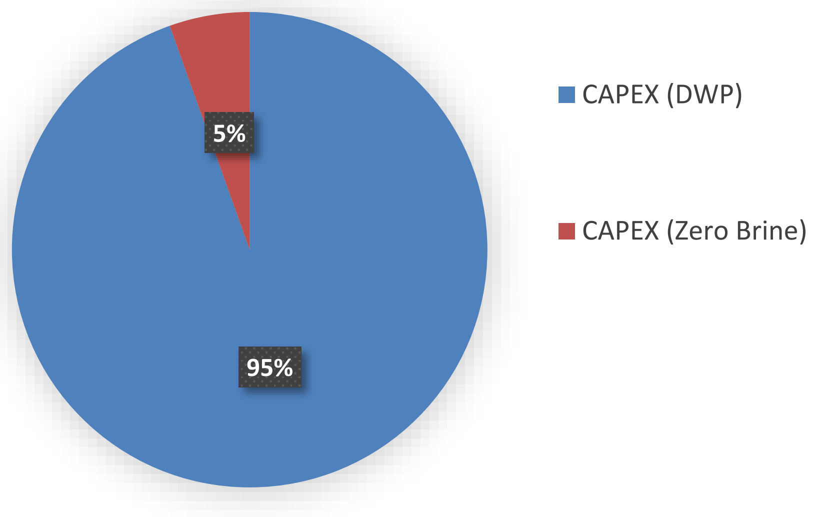

Figure 9. CAPEX estimations

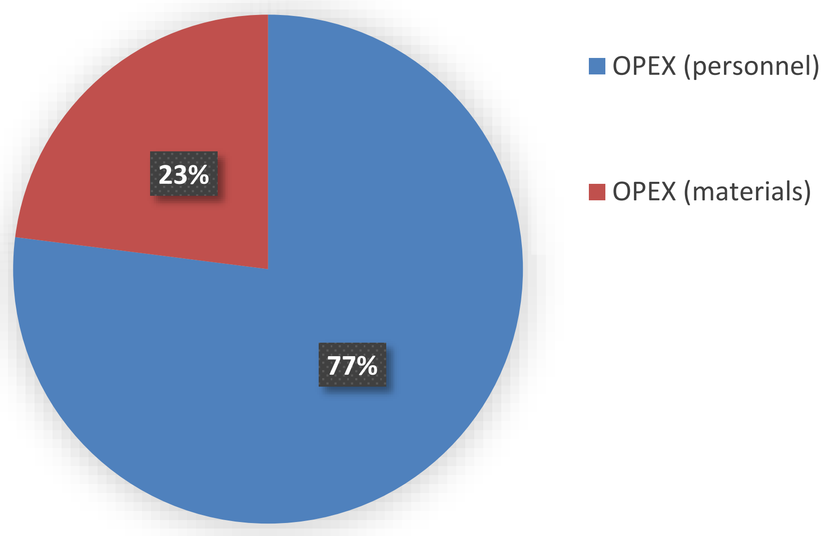

Figure 10. OPEX estimations

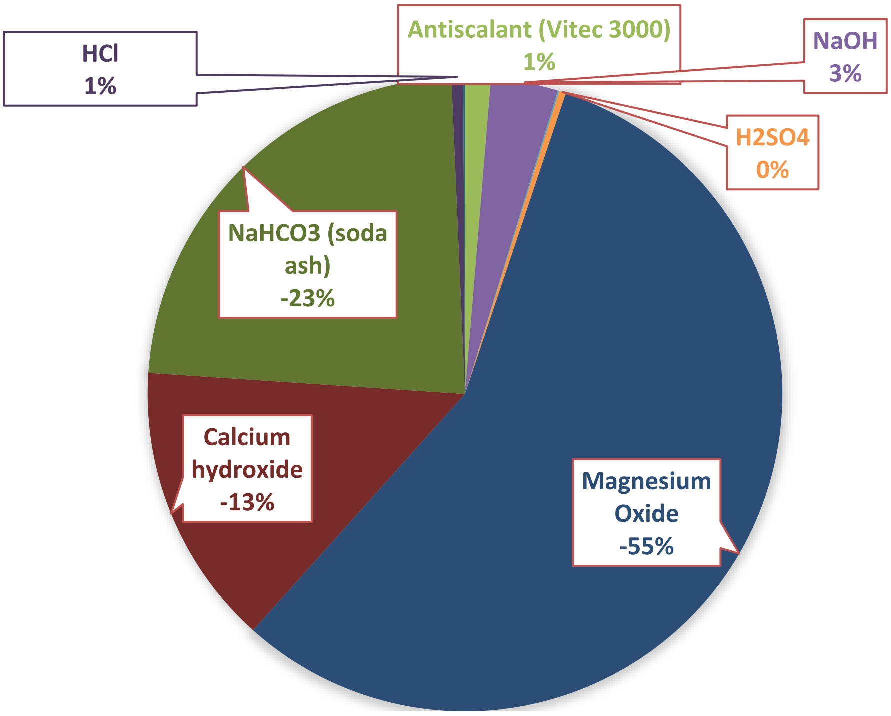

Figure 11. Contributions of consumables and recovered materials

4.7 Conclusions

Based on the current design for the ZB system and data from bench scale tests and computer simulations, the addition of the recovery of products with the ZB system will result in environmental burdens for the DWP. However, the calculated environmental burdens for the "fresh water ecotoxicity" indicator should be taken with a pinch of salt, as brine disposal does not result in any environmental burdens in Life Cycle Impact Assessment models. Environmental burdens derive mainly from the chemicals consumed in the TOC removal process. Therefore, in order to improve the environmental performance of the ZB system the first issue to be tackled in the sodium hydroxide consumption in the TOC removal process. Based on the LCC, the CAPEX of the ZB system is negligible when compared to the CAPEX of the DWP, so there should not be any issue for Evides Industriewater acquiring and employing the ZB system. Last, the purity of the recovered products is crucial, especially for magnesium, as high purity recovered products result in commodities with a high financial value.

4.8 Further work

The future work of the LCA and LCC modelling of the ZB system in the Netherlands should comprise of confirming the purity of the recovered materials via pilot scale tests. In addition, data collection from the pilot plant, and update, will provide LCA and LCC results of larger scales, comparable to industrial standards. In this case, the consumption of electricity and heat of the ZB technologies is expected to decrease due to upscaling. Last, part of the tasks of WP9 is the "Assessment of environmental impacts associated with brine discharge". Therefore, these activities will be coupled with the development of a Life Cycle Impact Assessment model explicitly for the brine composition produced by Evides Industriewater. This model will be implemented in future LCA calculations.

5. Case Study 2: Coal mine, Poland

5.1 Intro

The purpose of the Polish pilot plant is to investigate the benefits and ability of the ZB system to process wastewater from a coal mine. The process uses an integrated membrane system, to treat the wastewater to acceptable discharge standards whilst recovering valuable products including sodium chloride, magnesium hydroxide, calcium chloride, clean water and gypsum.

The successful treatment of coal mine wastewater represents a significant challenge as coal mining activities generate large amounts of saline wastewaters. Their direct drainage to water bodies would result in salination, that could cause significant harm to the ecosystems and river life, impair its use for society downstream (Gzyl et al.,2017). Poland is the largest coal producer in the EU (EURACOAL, 2017). Currently, the drainage from the Polish coal mine undergoes a basic two stage treatment process. First it is fed into settlement ponds that removes the suspended solids. The remaining effluent is then diluted so that the thresholds of its remaining constituents conform to discharge standards in surface water bodies.

The pilot plant will be located at ZG "Bolesław Śmiały" in Poland, a coal mine owned by PGG (Polska Grupa Górnicza S.A.), the EU's largest black coal mining company, producing approximately 30 million tons of black coal annually (total EU production: ~100 milliontons) (PGG,2019). The "Bolesław Śmiały" coal mine currently generates over 730,000 m^3 of saline wastewater annually. To conform to the discharge limits, the largest particles are removed in a settling pond and the wastewater is then diluted with wastewater from the co-located energy plant There, is currently no further treatment before wastewater discharge in a near river. However, due to the tightening environmental regulations, the company is seeking new methods for decreasing the salt load in their wastewaters.[3]

After its startup, the pilot system will be evaluated against the following objectives:

- To demonstrate circular economy solutions in coal mining sectors at a pilot scale through innovative brine treatment.
- To decrease energy consumption by 50% compared to the energy consumption of reverse osmosis-vapour compression system, which represents current base practice.
- Increase the recovery of resources and lost products through advanced selective separation technologies.

[3] Deliverable 3.5: Report on the operation and optimization of the pilot system for the treatment of coal mine.

A LCA and LCC study has been carried out for the ZB coal mine case study and is presented in the following sections.

5.2 Goal and Scope

The goal of the preliminary LCA study is to assess the performance of the ZB pilot coal mine system by comparing four possible configurations of the unit operations. The four different configurations all contain the same process stages and are presented in the LCI section. The LCA results will primarily be used to help the design procedure by providing initial environmental and sustainability input to the plant design and operation. It will be examined which stages of the wastewater treatment life cycle contribute most to the total impact of the process and how the process performance can be improved. The results of this study will be used by the technology providers and practitioners of the ZB project as input to the design and operation procedure.

- The functional unit of the study is "the treatment of 1 m^3 of coal mine wastewater". Specifically, this wastewater refers to a typical composition of the wastewater stream of "Bolesław Śmiały" coal mine. The functional unit is described by the composition presented in Table 8.

Table 8: Coal mine wastewater composition (data retrieved from D3.1[4])

Ion	Mean concentration (g/m^3)
Li^+	< 2.5
Na^+	8,191.67
$NH4^+$	< 2.5
K^+	120.42
Mg^{2+}	284.92
Ca^{2+}	342,67
Cl^-	13,450
NO^{3-}	< 2.5
SO_4^{2-}	809.83
B	2.32
HCO_3	301.08

Allocation

In line with the recommendations of ISO 14044, allocation was avoided in the present study by expanding the product system to include the recovery of by-products. The treatment of the coal mine wastewater with the ZB pilot plant is a multifunctional process resulting in the recovery of valuable products. The pilot plant is evaluated with a focus on the treatment of the wastewater. In the LCA

4 Deliverable 3.1: Characterization of waters from three coal mines owned by TAURON

analysis, a systems expansion has been performed to include the production of the avoided products: Sodium Chloride, Gypsum, Magnesium Hydroxide and clean water (RO permeate).

The system boundaries are presented in Figure 12. The system boundaries include the input of the brine wastewater to the treatment train and the technologies involved in the treatment of the wastewater. The steps included in the system boundaries are the operation units (namely: nanofiltration, reverse osmosis, electrodialysis and crystallization), the needed electricity and auxiliary materials as well as the produced products (Sodium Chloride, Gypsum, Magnesium Hydroxide and clean water) and the emissions to the environment.

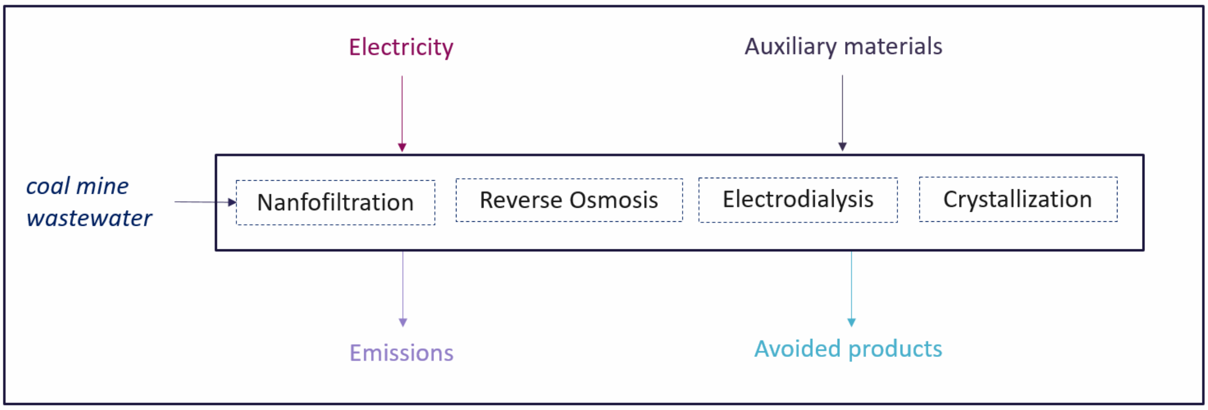

Figure 12: Coal mine case study: System boundaries

Data quality

The pilot plant is designed by Silesian University of Technology (SUT). Foreground data are collected with the purpose to address the goal of the study. Foreground data are mainly results of laboratory and bench scale experiments (derived from the ZB project deliverables D3.2 [5]and D3.3[6]), combined with simulation data Primary data providers were SUT partners and published data from WP3. Data gaps and uncertainty of information were overcome with the use of literature data (mainly Ecoinvent database). Literature data were used for the input of dolime in the treatment train as explained in the LCI section (5.3). The background data used were selected in order to be recent and representative for Poland. Specifically, data for energy consumption were retrieved from Ecoinvent v.3 database for Poland.

5 Deliverable 3.2: Database of data collected during WP3 demonstration activity
6 Deliverable 3.3: Report on the preliminary design and the simulation model results

Assumptions and limitations

- The present study is conducted with the use of experimental (bench scale) and simulation data resulting to some limitations that will affect the results of the study.
- The pretreatment of wastewater before the ZB pilot plant is not included as sufficient data was not available.
- Construction of the individual units is not taken into account.

The LCA study is conducted with the use of SimaPro v.9 software and Ecoinvent v.3 database.

5.3 LCI

The LCI of the coal case study has been built for the pilot scale treatment of $1m^3$ of coal mine wastewater. Four different configurations for the treatment of 1 m^3 of wastewater were evaluated and compared (illustrated in Figure 13 to Figure 16).

1. Two stage nanofiltration (NF), dilute from electrodialysis is recycled before the NF.
2. Single-stage NF, ED diluate is recycled back to the NF.
3. Two-stage nanofiltration, 75% of NF retentate is recycled, ED dilute is recycled back before the RO.
4. Single stage nanofiltration, 75% of NF retentate is recycled, ED diluate is recycled back before the RO.

The data in the LCI includes: the energy consumption of the pilot unit, chemical reagents for operational and cleaning purposes and recovered products. However, the use of spare parts is not included in the present study as projections of energy consumption of individual units is not yet available.

Dolime is not included in the Ecoinvent v.3 database. For this reason, the use of dolime suspension in the magnesium recovery unit it was assumed the following. Dolime (CaO.MgO) is the result of the chemical transformation of dolomite ($CaCO_3.MgCO_3$) by heating it above 900°C (equation 1) and requires energy.[7]

$$(CaCO_3.MgCO_3)_{(s)} + \text{heat } (>900°C) \rightarrow (CaO.MgO)_{(s)} + 2CO_{2\,(g)} \quad (1)$$

[7] https://www.lhoist.com/want-know-more-about%E2%80%A6#dolime

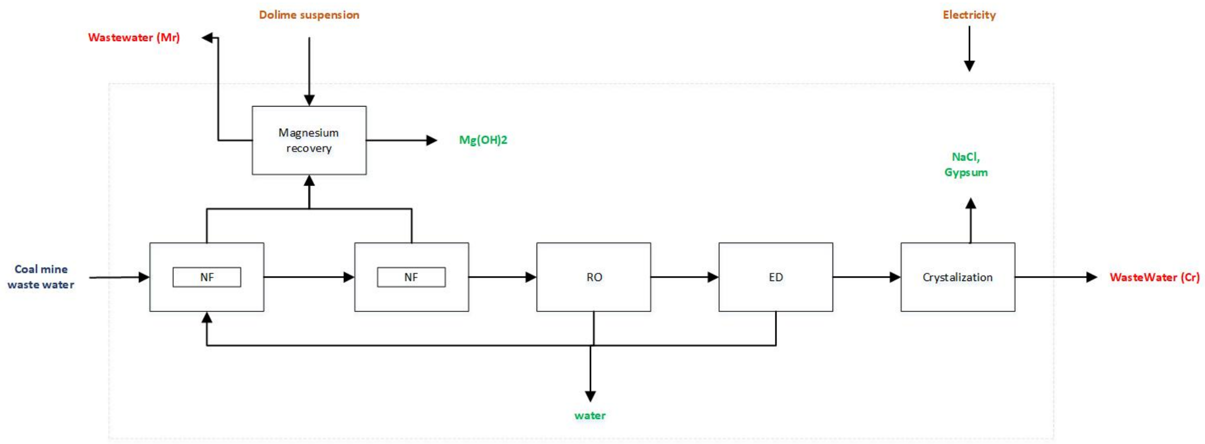

Figure 13: Configuration 1: two stage nanofiltration (NF), dilute from electrodialysis is recycled before the NF.

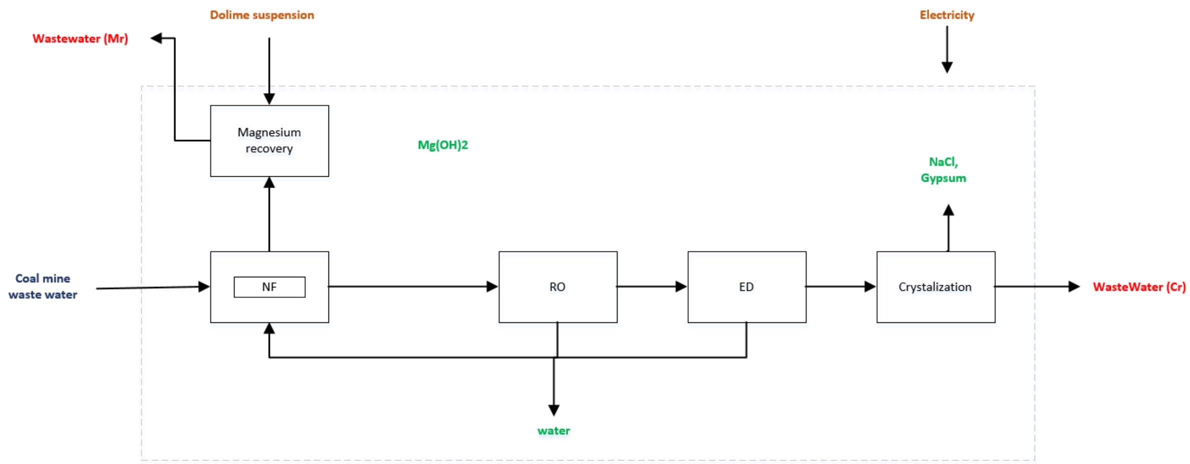

Figure 14: Configuration 2:single-stage nanofiltration, ED diluate is recycled back to the nanofiltration

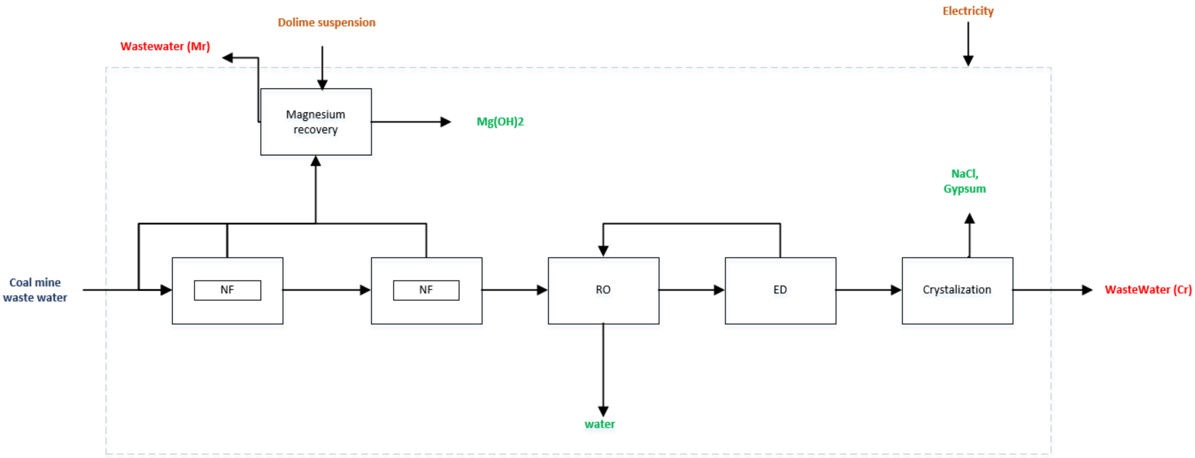

Figure 15: Configuration 3: two-stage nanofiltration, 75% of NF retentate is recycled, ED dilute is recycled back before the RO.

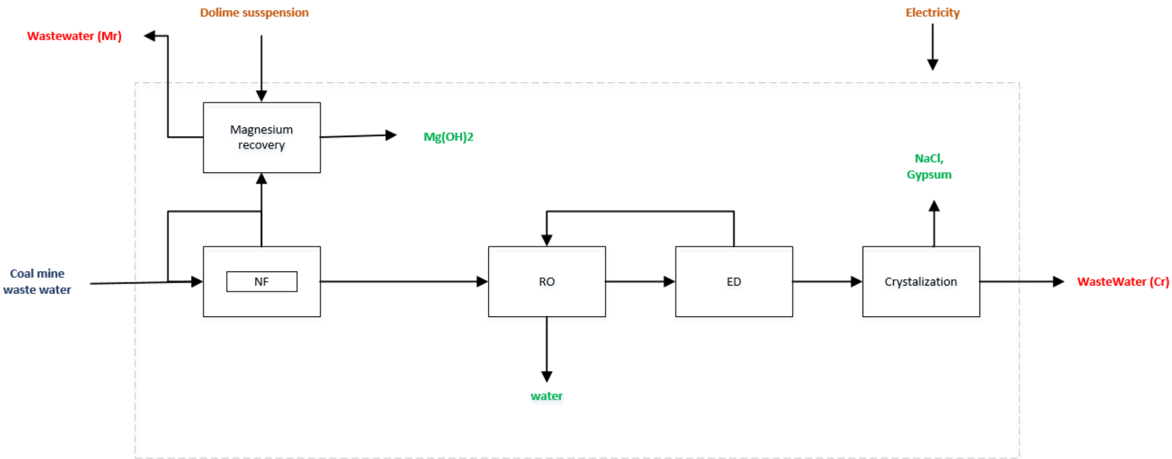

Figure 16: Configuration 4: single stage nanofiltration, 75% of NF retentate is recycled, ED diluate is recycled back before the RO.

5.4 LCIA

Life cycle impacts have been assessed with the use of the ILCD[8] method (EU 2013). Common and important impact categories for LCIA on wastewater include the toxicity related ones, eutrophication (marine and freshwater), global warming, acidification, ionizing radiation and in some cases water use, land use and stratospheric ozone depletion (Larsen,2018). IMPACT 2002+ has been also used as an additional impact assessment method, in order to obtain as robust results as possible (Larsen,2018).

Individual contributions of the different processes to the total environmental impact was assessed. However, the contribution of each process is not representative as reliable data is only for the energy consumption of the whole process. The avoided products are included in the LCIA. The results have been obtained with the use of SimaPro v9 Software and Ecoinvent v3.5 database and are presented in Figure 17 and Figure 18 (impact categories with zero values are not displayed in the figures). Figure 18 illustrates the contribution of each process stage (based on the inputs and outputs of each stage), including the electricity (which was currently only available for the whole system) and the positive impacts of the avoided products (deionised water, magnesium hydroxide, gypsum and sodium chloride).

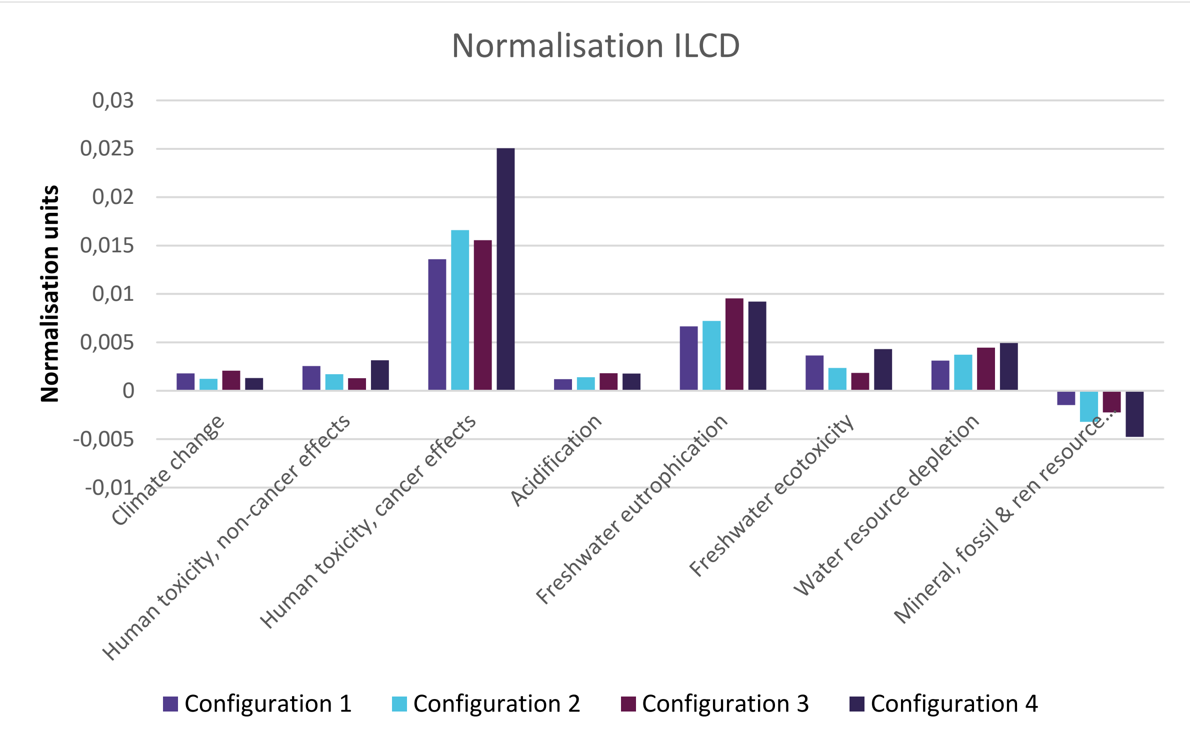

Figure 17: ZB coal mine pilot, LCA results. Comparison of the 4 configurations

8 ILCD 2011 Midpoint+ V1.10 / EC-JRC Global, equal weighting

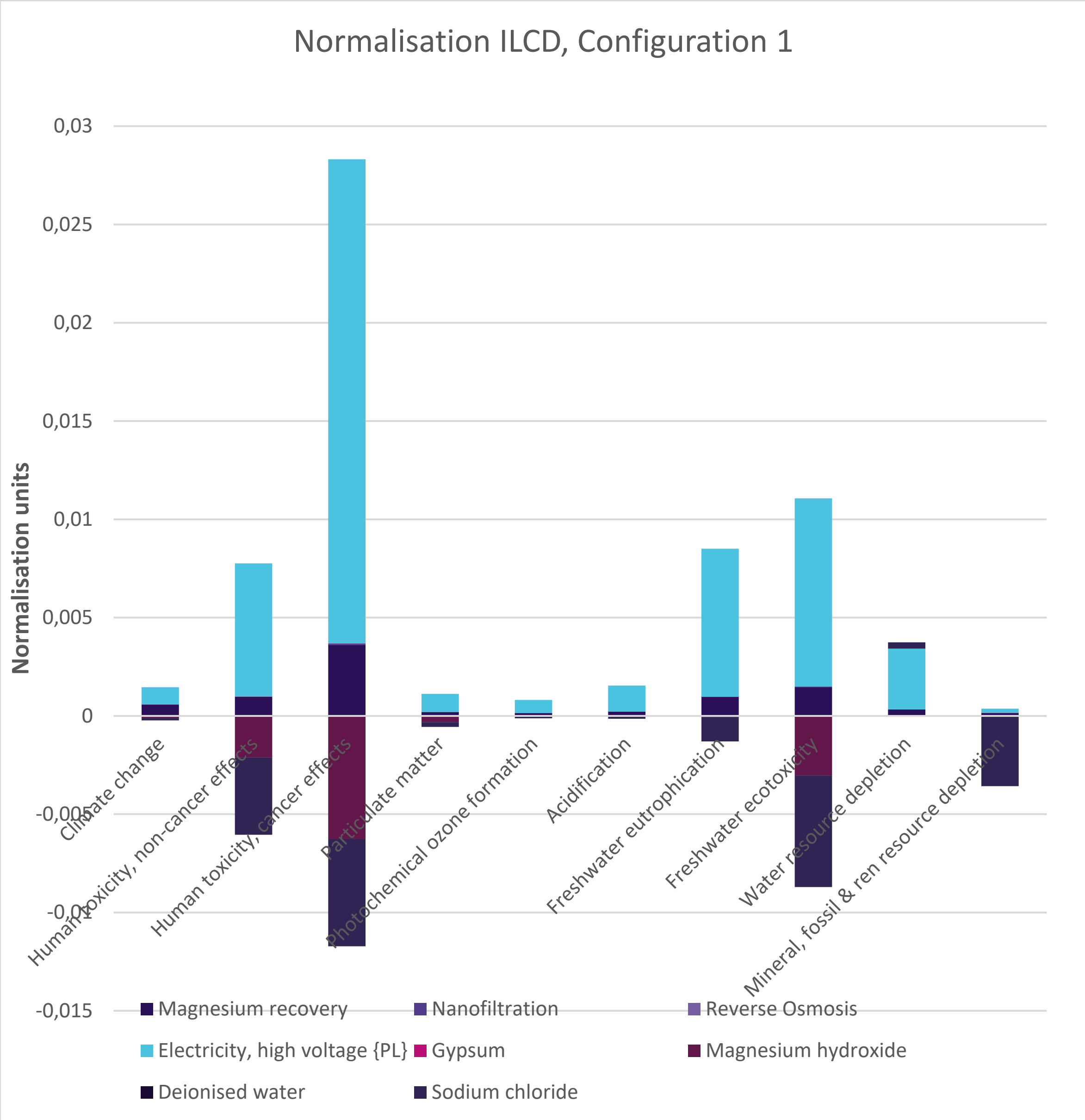

Figure 18: ZB coal mine pilot, LCA Normalisation results of configuration 1

5.5 LCC

Life Cycle Costing Analysis is a process of evaluating the economic feasibility of a technology. Comparing the life cycle costs of various options, the most – effective option for a given use should be identified, exploring trade-offs between low initial costs and long-term cost savings.

The functional unit of the system is “the treatment of 1 m^3 of coal mine wastewater”. Specifically, this wastewater refers to a typical composition of the wastewater stream of “Bolesław Śmiały” coal mine. System boundaries in LCC are based on the scheme proposed in Figure 12 . The considered phases are the same than those considered in the LCA study. The current system boundaries cover the operation units of the examined system (nanofiltration, reverse osmosis, electrodialysis and crystallization), the needed electricity, the auxiliary materials and the produced products. The emissions to the environment will be implemented during the next steps of the project. Moreover, the pretreatment process of wastewater and the construction of the individual units are not included as no sufficient data was available.

Following the approach of the LCA, four configurations for the treatment of 1 m^3 of wastewater are examined. During the LCC analysis, the requested prices for the auxiliary materials and recovered products were collected from online specialized chemical shops and are presented in Table 9 and Table 10 respectively.

Table 9: Price data for auxiliary materials

Auxiliary material	Stage	Unit	Unit Cost	Source
Dolomite	Magnesium Recovery	€/kg	3,0	https://www.growit.gr/%CF%80%CF%81%CE%BF%CE%B9%CE%BF%CE%BD/%CE%B4%CE%BF%CE%BB%CE%BF%CE%BC%CE%B9%CF%84%CE%B7%CF%82-%CF%83%CE%BA%CE%BF%CE%BD%CE%B7-1kg/
			12,0	https://www.growmarket.gr/edafoveltiotika/dolomite-500-gr-detail
Sodium Tripolyphosphate , >85%	NF	€/kg	292,0	https://www.sigmaaldrich.com/catalog/search?term=sodium+tripolyphosphate&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
			140,8	https://shop-lab-honeywell.com/sodium-tripolyphosphate-238503/
			102,7	https://shop-lab-honeywell.com/sodium-tripolyphosphate-238503/
EDTA, ≥98%	NF	€/kg	173,0	https://www.sigmaaldrich.com/catalog/search?term=EDTA&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
			66,6	https://www.sigmaaldrich.com/catalog/search?term=EDTA&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
			199,0	https://www.sigmaaldrich.com/catalog/search?term=EDTA&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
			117,3	https://shop-lab-honeywell.com/catalogsearch/result/?q=EDTA+
Sodium Hydroxide, ≥98%	RO	€/kg	116,0	https://www.sigmaaldrich.com/catalog/search?term=NaOH&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
			29,8	https://shop-lab-honeywell.com/catalogsearch/result/?q=Sodium+Hydroxide&query_within=NaOH
			23,7	https://shop-lab-honeywell.com/catalogsearch/result/?q=Sodium+Hydroxide&query_within=NaOH
Hydrochloric acid, 30-32% w/w	RO	€/kg	80,5	https://www.sigmaaldrich.com/catalog/search?term=HCl&interface=All&N=0&mode=partialmax&lang=en&region=GR&focus=product
			37,8	https://www.sigmaaldrich.com/catalog/search?term=HCl&interface=All&N=0&mode=partialmax&lang=en&region=NL&focus=product
EDTA	RO	€/kg	*as EDTA (NF)	

Table 10: Price data for recovered products

Recovered product	Unit	Unit Cost	Source
Magnesium hydroxide	€/kg	48,7	https://shop-lab-honeywell.com/products/chemicals/magnesium-hydroxide
		158	https://www.sigmaaldrich.com/catalog/search?term=Mg%28OH%292&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
Sodium chloride	€/kg	29,04	https://shop-lab-honeywell.com/products/chemicals/sodium-chloride
		54,4	https://www.sigmaaldrich.com/catalog/search?term=Sodium+chloride&interface=Product%20Name&N=0+&mode=mode%20matchpartialmax&lang=en&region=GR&focus=productN=0%20220003048%20219853286%20219853132
Gypsum	€/kg	0,40	https://www.bricoman.se/en/building-materials/cement-mortars-gypsums-plasters/gypsum-and-gypsum-mortars
		2,	https://sklep.jasam.eu/product-pol-10370-Dolina-Nidy-Gips-Szpachlowy-2kg.html
		0,498	https://www.leroymerlin.gr/gr/domika-ulika/gupsosanides/axesouar-gupsosanidas/gupsos-kallitehnias-5kg-62055980/
		0,17	https://www.baufox.com/%CE%B3%CF%8D%CF%88%CE%BF%CF%82-%CE%BA%CE%B1%CE%BB%CE%BB%CE%B9%CF%84%CE%B5%CF%87%CE%BD%CE%AF%CE%B1%CF%82-%CE%B6%CE%B1%CE%BA%CF%8D%CE%BD%CE%B8%CE%BF%CF%85-40kg%CF%83%CE%B1%CE%BA%CE%AF
		0,44	https://www.leroymerlin.gr/gr/search-results/?q=%CE%B3%CF%8D%CF%88%CE%BF%CF%82&type=products
Deionised water	€/L	13,0	https://shop-lab-honeywell.com/catalogsearch/result/?q=water
		0,75	https://www.stelpet.gr/Proion/19475/146/Apionismeno-nero-4Lt-Wurth/
		2,56	https://www.chemicals.co.uk/cart

As observed in Table 9 and Table 10, there are price divergences in many cases based on the quality characteristics of the product. To ensure a representative LCC analysis, an average market price for each material and product was selected. It is worth mentioning that in the case of deionised water, there are various market prices depending on its quality and usage. Assuming a medium quality of deionised water, an average market price equal to 0,75 €/L was selected. The electricity price in Poland is 0,141 €/kWh including the taxes (Eurostat, 2018).

In Table 11 the LCC results for each possible configuration are presented according to the aforementioned assumptions. The total cost per function unit is estimated by deducting the expenditures by the revenues.

Table 11: Life Cycle Costing results

	Cost / functional unit (treatment of 1m^3 of coal mine wastewater)			
	Conf. 1	**Conf. 2**	**Conf. 3**	**Conf. 4**
Auxiliary materials				
Dolomite	(-) 162 €	(-) 126 €	(-) 330€	(-) 69 €
Sodium chloride	(-) 0,14 €	(-) 0,07 €	(-) 0,14 €	(-) 0,07 €
EDTA	(-) 1,39 €	(-) 0,69 €	(-) 1,39 €	(-) 0,69 €
Sodium Hydroxide	(-) 0,03 €	(-) 0,03 €	(-) 0,03 €	(-) 0,03 €
Hydrochloric acid	(-) 0,004 €	(-) 0,004 €	(-) 0,004 €	(-) 0,004 €

	Cost / functional unit (treatment of 1m^3 of coal mine wastewater)			
EDTA	(-) 0,83 €	(-) 0,83 €	(-) 0,83 €	(-) 0,83 €
Wastewater emissions				
Wastewater (Mr)	-	-	-	-
Wastewater (Cr)	-	-	-	-
Recovered products				
Deionised water	424,69 €	506,44 €	521,81 €	641,25 €
Sodium chloride	142,9 €	272,2 €	213,8 €	393,2 €
Gypsum	0,01 €	0,02 €	0,71 €	0,57 €
Magnesium hydroxide	140, 8 €	110,4 €	286,9 €	59,7 €
Energy consumption				
Dolime production	(-) 0,15 €	(-) 0,12 €	(-) 0,31 €	(-) 0,06 €
Processes stages	(-) 0,90 €	(-) 11,6 €	(-) 1,25 €	(-) 1,61 €
TOTAL	**542,84 €**	**748,91 €**	**688,74 €**	**1.022,75 €**

5.6 Discussion

5.6.1 LCA Results

Similar results were obtained from both used impact assessment methods (ILCD and IMPACT 2002+). The comparison of the four possible configurations revealed that the configurations 1 and 2 have the best environmental performance (1: Two stage NF, electrodialysis diluate recycled to NF; 2: Single-stage NF, ED diluate recycled to NF). The LCA results for these configurations were similar. On the other hand, configuration 4 (Single stage NF, 75% of NF retentate recycled, ED diluate recycled to RO) has the worst environmental performance.

In all configurations, the energy consumption and use of dolime suspension at the magnesium recovery process contribute most to the negative environmental impact of the process.

On the other hand, the recovery of materials, most notably magnesium hydroxide, provides a significant positive contribution to the environmental performance of the process. This relies on the assumption that the materials recovered from the ZB coal mine system meet the industry requirements for their final use.

The use of the auxiliary materials for cleaning and regeneration purposes do not have a significant impact on the overall environmental performance of the process.

5.6.2 LCC Results

Concerning the LCC, all of the examined configurations have positive results and in contrast with its environmental performance, the fourth configuration (single stage nanofiltration, 75% of NF retentate is recycled, ED diluent is recycled back before the RO) is the most cost-effective one, making 1.022,75 €/ m^3 wastewater input profit, not taking into account any externalities.

5.6.3 Design recommendations

Currently, the pilot plant is still in the design process and data on the scaling up of the individual processes are not yet available. Data used in the present study are based on projections for the operation of pilot scale unit. However, the current analysis allows a first screening of the potential environmental impacts and design recommendations based on environmental impact considerations. The analysis suggests that the main aspect to be optimized is the energy consumption of the system, as well as the corresponding energy source (i.e. renewable energy could replace the current energy mix). The optimisation of magnesium hydroxide recovery stage in all configurations will contribute to a better environmental performance of the pilot unit.

Concerning the recovered materials, it is of high importance to perform various tests in order to achieve a high quality that will meet the end-users' requirements. The reuse of these materials contributes a lot to the positive environmental impact of the process.

5.6.4 Further work

The pilot plant will be constructed during the next phase of the ZB project. Consistent and accurate data collection will take place from the start-up of the pilot plant in accordance with the database for data collection framework of Work Package 3. It is important to collect a representative set of data under various operation conditions. Data concerning the inputs and outputs of each stage, together with the energy consumption, the cleaning and regeneration cycles, the spare parts and the quality of the recovered materials will be collected. The implementation in the LCA study of the new data set will provide a more accurate picture of the brine wastewater treatment. This will enable a more robust evaluation of the ZB system. Moreover, externalities and CAPEX will be included in the LCC study. Finally, the collection of data from the pilot plant and the update of the LCA and LCC models could provide useful input for a possible industrial application.

6. Case Study 3: Textile Industry, Turkey

6.1 Intro

The main environmental concern in the textile industry is the discharge of untreated process effluents mainly due to their high organic content, colour, toxicity and salinity. Salts are used in the dyeing processes and water softening, whereas, the use of acids for the caustic neutralization in the mercerization process as well as the regeneration of water softening discharges also cause salt generation. Salts are estimated to be in the most intense pollutants in textile wastewater in terms of weight.

The ZB pilot plant in Turkey aims at recovering the brine solution from the reverse osmosis concentrate originating from existing advanced treatment system of textile wastewater. The system will be tested in ZORLU textile industry.

In Figure 19, the current design of the process outline of the pilot plant is presented. The ZB pilot plant in Turkey will consist of three stages: (i) Ion Exchange, (ii) Ozonation and (iii) Reverse Osmosis.

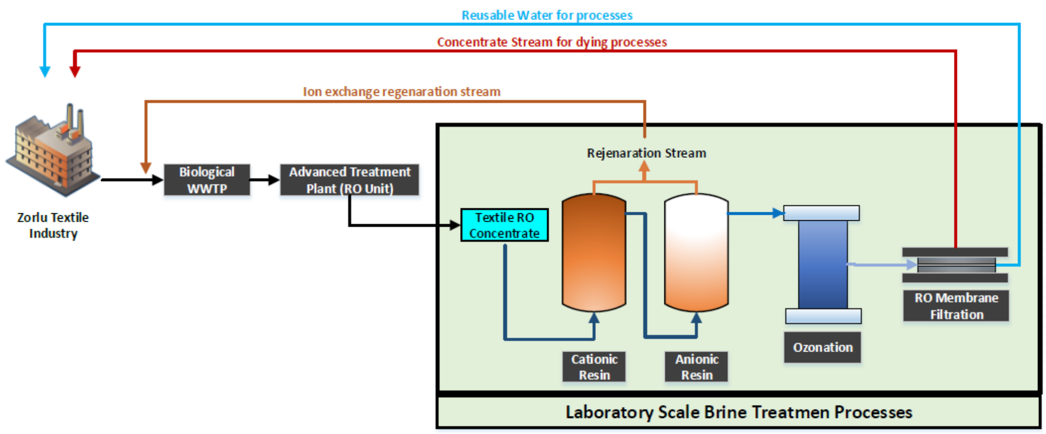

Figure 19: Textile case study: laboratory brine treatment process

After its startup, the pilot system will be evaluated against the following objectives:

- Demonstration of circular economy solutions in textile sector at a pilot scale through innovative brine treatment.
- Utilization of the recovered concentrated salt solution for the dyeing process baths.
- Utilization of recovered materials and water (internal or external valorization).
- Minimization of solid by-product and subsequent needs of landfilling.

- Increase recovery of resources and lost products through advanced selective separation technologies.

A LCA and LCC study has been carried out for the ZB textile case study and is presented in the following sections.

6.2 Goal and Scope

The **goal** of the preliminary LCA study is to assess the performance of the ZB pilot textile system by comparing possible configurations of the process units. The results will be primarily used to help the design procedure by providing initial environmental and sustainability input to the plant design and operation. It will be examined which stages in the life cycle of the wastewater treatment contribute most to the total impact of the process and what can be done to improve the process performance. The results will be used by the technology providers and practitioners involved in the textile case study of the ZB project as input to the design and operation procedure.

The **scope** of the present LCA study is described by the following:

- The functional unit of the study will be 1 m^3 of RO textile wastewater (see also Figure 19). The functional unit is described by the composition presented in Table 12.

Allocation

- Based on the recommendations of ISO 14044, allocation was avoided in the present study by expanding the product system to include the additional functions.
- The treatment of the ZORLU textile RO wastewater with the ZB pilot plant is a multifunctional process resulting in the recovery of valuable products. The pilot plant is evaluated with a focus on the treatment of the wastewater. In the LCA analysis, a system expansion has been performed to include the production the avoided products: water for processes and brine solution

The system boundaries are presented in Figure 20. The system boundaries start with the input of the RO brine wastewater to the treatment train and will entail all the technologies involved in the treatment of the RO wastewater. The steps included in the system boundaries are the operation units (namely: ion exchange, ozonation and reverse osmosis), the needed electricity and auxiliary materials, the cleaning and regeneration cycles as well as the produced products and the emissions to the environment. The recovered products of the process are: (i) the brine solution that will be used in the dyeing process and (ii) process water. For the analysis, these products are considered to be avoided products.

Table 12: Textile RO wastewater composition

Parameter	Unit	Value
Salinity, NaCl	%	6,22
pH	-	8,2
Total Phosphorus	mg/L	18,5
CO_3	mg/L	34,9
Zn	(ppb)	40,15
NH_4-N	mg/L	48,8
SiO_2	mg/L	49,9
Total Nitrogen	mg/L	59,8
Color Pt-Co	Pt-Co	71,8
Li	(ppb)	173,6
Total Hardness	mg $CaCO_3$/L	202,2
Al	(ppb)	282,9
COD	mg/L	290,9
B	(ppb)	371,5
Sr	(ppb)	461,15
Fe	(ppb)	731,6
Cl	mg/L	1598,7
SO_4	mg/L	1987,8
HCO_3	mg/L	2298,5
Conductivity	µs/cm	10629,2
Mg	(ppb)	11832,3
Ca	(ppb)	61477
K	(ppb)	127759
Na	(ppb)	2392000

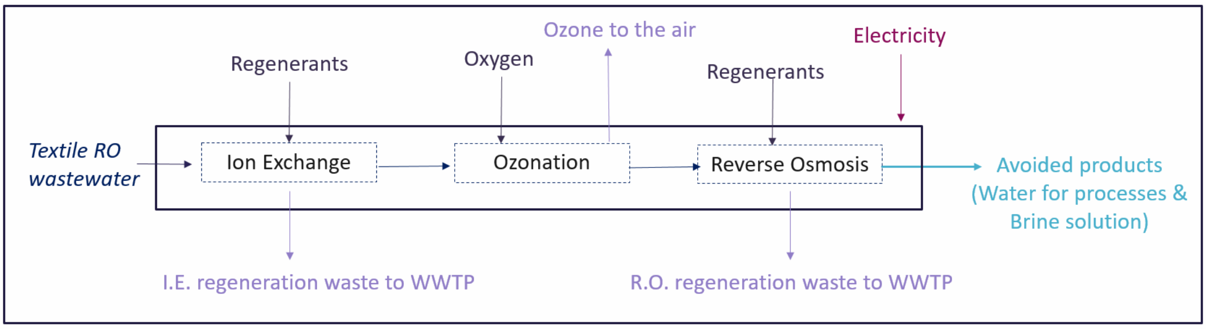

Figure 20: Textile case study: system boundaries

Data quality requirements

The pilot plant is designed by Scientific and Technological Research Council of Turkey (TUBITAK). Foreground data are collected with the purpose to address the goal of the study. Foreground data are mainly laboratory data from bench scale tests. Primary data providers were TUBITAK partners and published data of WP3. Projections for the pilot scale treatment of the ZORLU RO wastewater treatment were made with the use of the bench scale tests results and literature data. Data gaps and uncertainty of information were overcome with the use of literature data (mainly Ecoinvent database). The background data used was selected to be recent and representative for Turkey. Specifically, data for energy consumption were retrieved from Ecoinvent v.3 database for Turkey.

Assumptions and limitations

- The present study is conducted with the use of experimental (bench scale) and simulation data resulting to some limitations that will affect the results of the study.
- Construction of the individual units is not taken into account.

The LCA study is conducted with the use of SimaPro v.9 software and Ecoinvent v.3 database

6.3 LCI

The LCI of the textile case study has been built for the pilot scale treatment of 1m^3 of ZORLU industry wastewater (RO wastewater) with an estimated plant capacity of 3m^3/day.

The data consisting the LCI involves the energy consumption of the individual units, chemical reagents for operational and cleaning purposes, spare parts (anionic and cationic resins and membrane module) and recovered products. More information is provided in Table 13, to Table 16.

Table 13: Chemical reagents needs of the ZB pilot plant (for the treatment of 1m^3 of ZORLU RO wastewater).

Chemical reagent	Stage	dose	details
Sodium Hydroxide (NaOH)	Ion Exchange	0,145 kg	NaOH-regenerant, 3,2%
Hydrochloric acid (HCl)		0,208 kg	HCl-regenerant, 4,6%
Salt (Sodium Chloride)		0,486 kg	NaCl, 10%
0xygen	ozonation	O,02 kg	Amount of ozone applied: 300 mg/L of solution to be treated
Sodium Hydroxide (NaOH)	Reverse Osmosis	0,0012	48% NaOH solution
Hydrochloric acid (HCl)		0,0006 L	0,1% HCl solution
Citric acid		0,012 kg	as solid (powdered)
EDTA		0,006 kg	2% EDTA

Table 14: Spare parts needs of the ZB pilot plant (for the treatment of 1m³ of ZORLU RO wastewater).

Component	Stage	Amount	details
Anionic resin	Ion Exchange	375 kg	Replaced every 10 year
Cationic		498 kg	
Flat sheet membrane module	Reverse Osmosis	140 cm^2	Replaced every 3 years

Table 15: Energy needs of the ZB pilot plant (for the treatment of 1m³ of ZORLU RO wastewater).

Stage	Energy Use (Electricity) kWh	details
Ion Exchange	0,48	*Peristaltic pump power consumption: 0,03 kw. (For Operation & Regeneration time)*
Ozonation	0,23	*Generator power consumption: ~0,18 kw.*
Reverse Osmosis	18,4	Electric motor for high pressure. Power: hp=3,2 kW

Table 16: Recovered products after the treatment of 1 m³ of ZORLU RO wastewater

Avoided product	Value
Water for processes	0,6 m^3
Brine Solution	0,4 m^3

6.4 LCIA

Life cycle impacts have been assessed with the use of ILCD[9] method as recommended by EU 2013. Relevant impact categories for LCIA of wastewater include the toxicity related ones, eutrophication (marine and freshwater), global warming, acidification, ionizing radiation and in some cases water use, land use and stratospheric ozone depletion (Larsen, 2018). IMPACT 2002+ has also been used as an additional impact assessment method to obtain robust results (Larsen, 2018).

The individual contribution of the unit processes to the total environmental impact were assessed and the avoided products (water for processes and brine solution) were included in the LCIA. The results are presented in Figure 21 and Figure 22 (impact categories with zero values are not displayed in the figures).

9 ILCD 2011 Midpoint+ V1.10 / EC-JRC Global, equal weighting

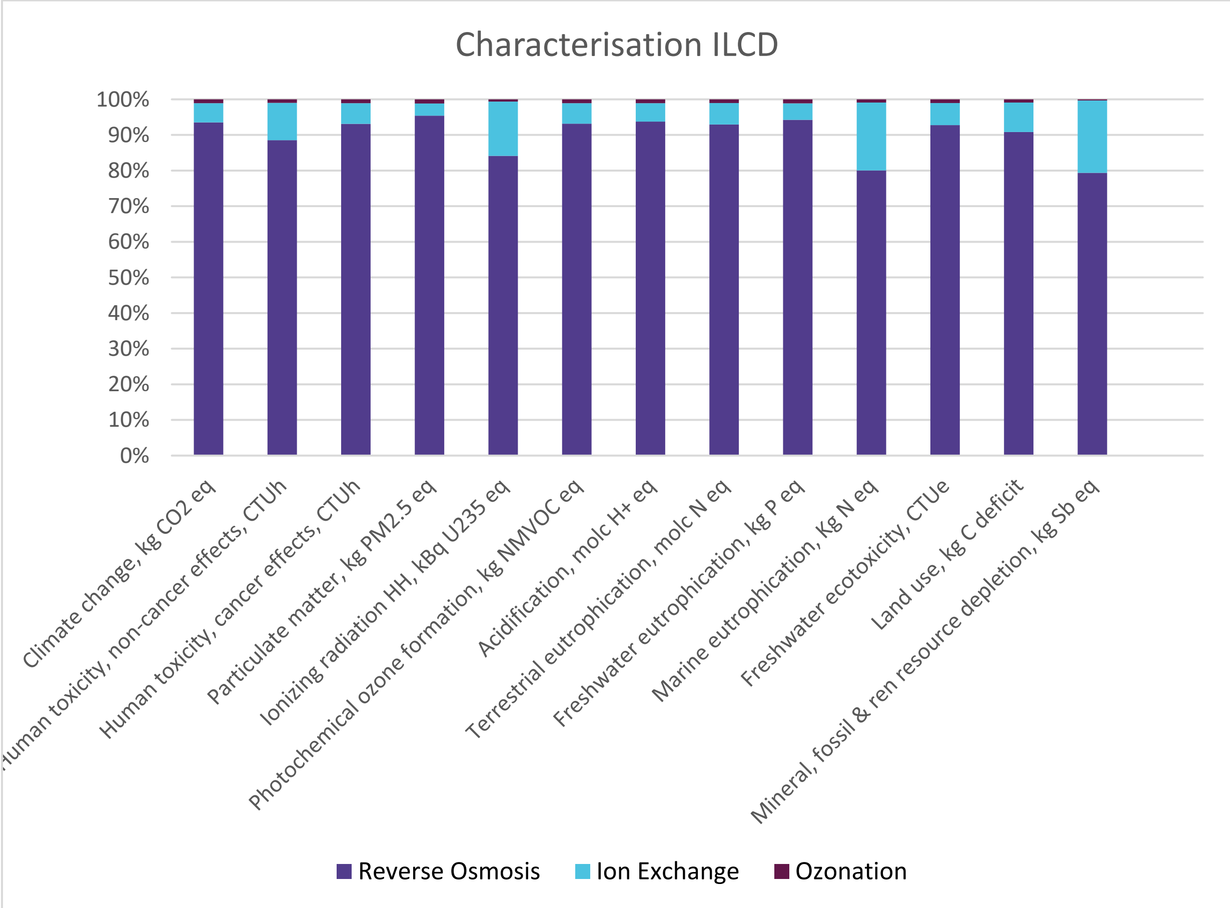

Figure 21: LCIA midpoint characterisation results (ILCD) of the proposed ZB treatment of the ZORLU textile RO wastewater. Avoided products are not displayed in the figure.

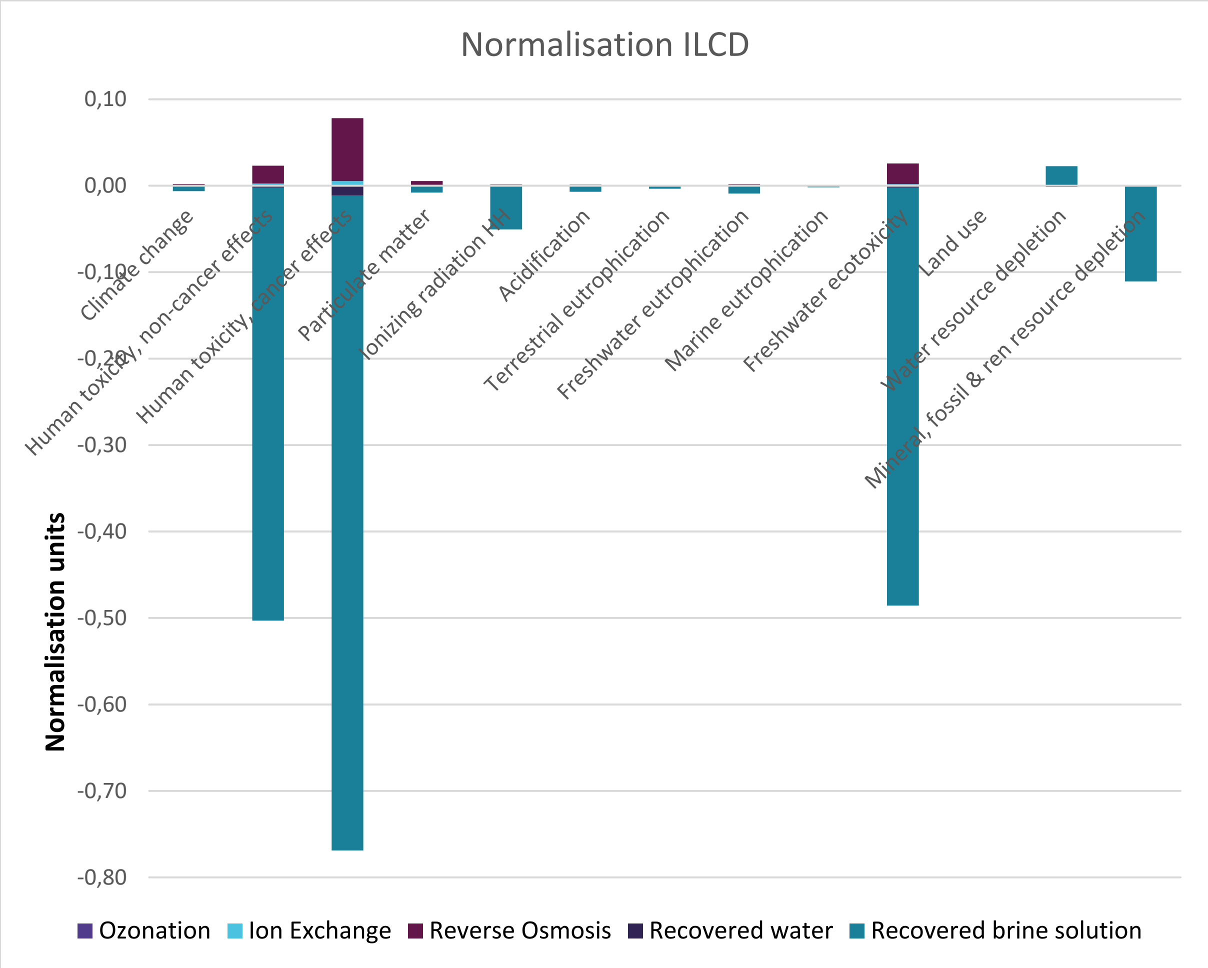

Figure 22: LCIA mid point normalisation results (ILCD) of the proposed ZB treatment of the ZORLU textile RO wastewater. (avoided products included)

6.5 LCC

The functional unit of the system is "the treatment of 1 m^3 of textile industry wastewater". Specifically, this wastewater refers to a typical composition of the wastewater stream of "ZORLU" textile industry. The system boundaries used in LCC are based on the scheme proposed in Figure 20. The considered phases are the same than those considered in the LCA study. The current system boundaries cover the operation units of the examined system (ion exchange, ozonation and reverse osmosis), the needed electricity, the auxiliary materials and the produced products. The emissions to the environment will be implemented during the next steps of the project. Moreover, the construction of the individual units is not included as adequate data was not available.

During the LCC analysis, the requested prices for the reagent chemicals and recovered products were collected from online specialized chemical shops as shown in the Table 17 and Table 18 respectively.

Table 17: Price data for reagent chemicals

Auxiliary material	Unit	Unit Cost	Source
Sodium Hydroxide, ≥95%	€/kg	116,0	https://www.sigmaaldrich.com/catalog/search?term=NaOH&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
		29,8	https://shop-lab-honeywell.com/catalogsearch/result/?q=Sodium+Hydroxide&query_within=NaOH
		23,7	https://shop-lab-honeywell.com/catalogsearch/result/?q=Sodium+Hydroxide&query_within=NaOH
Hydrochloric Acid, ≥95%	€/kg	80,5	https://www.sigmaaldrich.com/catalog/search?term=HCl&interface=All&N=0&mode=partialmax&lang=en&region=GR&focus=product
		37,8	https://www.sigmaaldrich.com/catalog/search?term=HCl&interface=All&N=0&mode=partialmax&lang=en&region=NL&focus=product
Sodium Chloride, ≥95%	€/kg	29,04	https://shop-lab-honeywell.com/products/chemicals/sodium-chloride
		54,4	https://www.sigmaaldrich.com/catalog/search?term=Sodium+chloride&interface=Product%20Name&N=0+&mode=mode%20matchpartialmax&lang=en&region=GR&focus=productN=0%20220003048%20219853286%20219853132
Oxygen, 9-11%	€/kg	114	https://shop-lab-honeywell.com/sodium-perborate-tetrahydrate-244120/
Sodium Hydroxide solution	€/L	129	https://www.sigmaaldrich.com/catalog/search?term=NaOH+solution&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
		42	https://www.sigmaaldrich.com/catalog/search?term=NaOH+solution&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
Hydrochloric Acid solution	€/L	21	https://shop-lab-honeywell.com/catalogsearch/result/?q=hcl+solution+0.1
		15,5	https://shop-lab-honeywell.com/catalogsearch/result/?q=hcl+solution+0.1
		11,6	https://shop-lab-honeywell.com/catalogsearch/result/?q=hcl+solution+0.1
Citric Acid, ≥95%	€/kg	47,8	https://shop-lab-honeywell.com/catalogsearch/result/?q=citric+acid+
		39,6	https://shop-lab-honeywell.com/catalogsearch/result/?q=citric+acid+
		55,0	https://shop-lab-honeywell.com/catalogsearch/result/?q=citric+acid+
EDTA, ≥95%	€/kg	173,0	https://www.sigmaaldrich.com/catalog/search?term=EDTA&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
		66,6	https://www.sigmaaldrich.com/catalog/search?term=EDTA&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
		199,0	https://www.sigmaaldrich.com/catalog/search?term=EDTA&interface=All&N=0&mode=match%20partialmax&lang=en&region=GR&focus=product
		117,3	https://shop-lab-honeywell.com/catalogsearch/result/?q=EDTA+

Table 18: Price data for recovered products

Auxiliary material	Unit	Unit Cost	Source
Deionised water	€/m^3	13,04	https://shop-lab-honeywell.com/catalogsearch/result/?q=water
		0,75	https://www.stelpet.gr/Proion/19475/146/Apionismeno-nero-4Lt-Wurth/
		2,56	https://www.chemicals.co.uk/cart
Brine solution	€/ m^3	0	

From the above presented data, an average market price was estimated for each reagent chemical and recovered product. It is worth to mention that in the case of deionised water, there are various market prices depending on its quality and usage. Assuming a medium quality of deionised water, an average market price equal to 0,75 €/L was selected.

As for the electricity price, according to World Energy Council (2018), is estimated 0,09 €/kWh (0,59 Turkish cents/KWh).

Table 19 presents the LCC results based on the LCI data about energy consumption of the individual units, chemical reagents for operational and cleaning purposes and, recovered products and the average market prices as presented above.

Table 19: Life Cycle Costing Results

	Dose / Amount	Unit	Cost / Functional Unit
Chemical Reagent			
Sodium Hydroxide	0,145	kg	(-) **8,19 €**
Hydrochloric acid	0,208	kg	(-) **12,30 €**
Salt (Sodium Chloride)	0,486	kg	(-) **20,28 €**
Oxygen	0,02	kg	(-) **2,29 €**
Sodium Hydroxide solution	0,0012	L	(-) **0,10 €**
Hydrochloric acid solution	0,0006	L	(-) **0,01 €**
Citric acid	0,012	kg	(-) **0,57 €**
EDTA	0,006	kg	(-) **0,83 €**
Energy Consumption			
Ion Exchange	0,48	kWh	(-) **0,05 €**
Ozonation	0,23	kWh	(-) **0,02 €**
RO	18,4	kWh	(-) **1,74 €**
Avoided product			
Deionised water	0,6	m^3	**450,00 €**
Brine Solution	0,4	m^3	**0,00 €**
TOTAL			**403,62 €**

Based on Table 17, the LCC result is positive at **403,62 €/m³** wastewater input, not taking into account any externalities.

6.6 Discussion

6.6.1 Results

Similar results were obtained from both used impact assessment methods (ILCD and IMPACT 2002+). Specifically, the results revealed that Reverse Osmosis contributes more at the negative environmental impact of the process. Further analysis of the Reverse Osmosis process showed that this is due to the energy consumption requirements of the plant. As it is shown in Figure 21 and Figure 22 Reverse Osmosis stage contributes most at all the impact categories, with a factor of higher than 80%, except ozone layer depletion.

On the other hand, the recovery of materials, most notably the brine solution, provides a significant positive contribution to the environmental performance of the process.

Moreover, it was assumed that the materials recovered from the ZB textile system meet the industry requirements for their final use. The Reverse Osmosis concentrate is aimed to be used for the dyeing process of the ZORLU textile industry, where a brine solution (mainly NaCl) is currently used. Recovered water is aimed to be used also at ZORLU industry for process water. It is worth mentioning that transport of the recovered materials is not included in the present study.

The use of auxiliary materials (mainly cleaning and operational chemicals) do not have a significant impact on the overall environmental performance of the process.

6.6.2 Design recommendations

The design of the pilot plant as well as the bench scale tests are still at an early stage and data for the scaling up of different stages are currently not available. Data used in the present study is based on projections for the pilot scale unit. However, this kind of data only allows a first screening of the possible environmental impacts to provide initial design recommendations. To this end, the main aspect of the ZB pilot plant design that needs to be optimized is the energy consumption of the Reverse Osmosis unit.

With regard to the recovered materials, it is important to perform tests to ensure that the recovered water and brine solution will meet the quality required for use in the company’s processes. The reuse of these materials will contribute significantly to the positive environmental impact of the process.

6.6.3 Further work

During the next phase of the ZB project the pilot plant will be constructed. Consistent and accurate data collection will take place, from the start-up of the pilot plant in accordance to the database for data collection built in the framework of Work Package 3.

As the characteristics of the ZORLU textile Reverse Osmosis wastewater that is going to be treated are variable due to textile operations, it is important to collect a representative set of data from various operation conditions. Data concerning the inputs and outputs of each stage, together with the energy consumption, the cleaning and regeneration cycles, the spare parts and the quality of the recovered materials will be collected. Moreover, it is foreseen to collect accurate data for the existing wastewater treatment plant at ZORLU textile industry where is currently discharged the brine wastewater.

The implementation in the LCA study of the new data set will allow to obtain a more complete picture of the brine wastewater treatment and evaluate the ZB pilot system against the objectives of the project. Moreover, the externalised will also be included in the LCC analysis at a later stage. Finally, the collection of data from the pilot plant and the update of the LCA and LCC models could provide useful input for a possible industrial application.

7. Case Study 4: Silica Industry, Spain

7.1 Intro

This section assesses the demonstration site located at Industrias Químicas del Ebro S.A. (IQE) in Spain. IQE is a chemical manufacturing company focused primarily on silicate products. Its operation is an important economic activity in the Zaragoza area. It generates job opportunities and has high influence in the economy of the region. However, due to IQE productive activity, high amounts of waste streams with high salinity are produced. Figure 23 presents the water cycle at IQE.

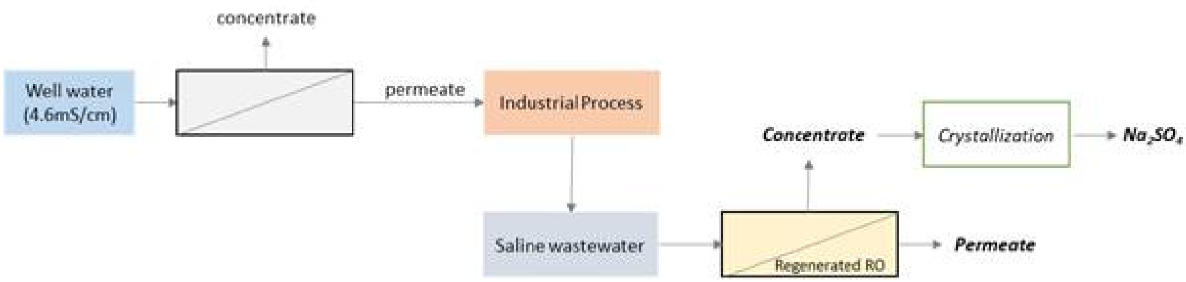

Figure 23 Water cycle in the production process at IQE.

Firstly, groundwater is extracted and pre-treated to be brought into a reverse osmosis (RO) system. Osmotic water produced is then used into the production process where saline wastewater streams are generated. Unfortunately, the management of these streams has a high environmental impact and an elevated cost is associated to it. This cost is related to the discharge of these streams that must be treated in a wastewater treatment plant.

The implementation of the new treatment process should enable a reduction of costs derived from water consumption and wastewater management. These strategies must demonstrate new configurations to recover sodium sulphate, ultrapure water and heat could bring tangible benefits from both an environmental and economic perspectives. As a whole, technology development is required to tackle the associated problems caused by streams from silica production.

In this preliminary report, a simplified version of the solution is assessed. Hence, the system entails part of the treatment of wastewater from silica production in IQE facilities. This simplification is carried out because of the early stage of the project and the current lack of relevant data for the complete system. Some of the technical actions of the project are still ongoing or still at bench scale.

Hence, the present report is focused on the ZB proposed solution. For that, an industrial plant based on membrane technology has been designed in order to have solid data for the preliminary study. Data from this design has been entered into SimaPro LCA software in order to show results more according to a real environment under industrial conditions.

7.2 Goal and Scope

The main goal of the LCA is to evaluate the environmental benefits of the innovative ZB technology to treat IQE's brine generated compared to the existing situation, where brine is released and treated in a municipal wastewater treatment plant (WWTP). Coupled to this main objective, LCA has the aim to achieve two secondary objectives:

- To demonstrate that the implementation of regenerated membranes is a successful strategy for decreasing environmental impact of the technology.
- To determine the relevance of the ZB technology into the whole silica production. In other words, how the impact generated by ZB could affect the whole environmental impact of IQE's activity.

The preliminary environmental assessment will be continuously updated with new system data as it is produced from bench scale and pilot scale test. Hence, the present study is focused on assessing the ZB technology at full scale but due to the lack of relevant data, it does not yet include all stages that will be considered in the final LCA.

7.2.1 Function and functional unit

The function of the system under study is to treat the silica production wastewater and recover by-products resource from the brines. Heat recovery systems and regenerated membranes are utilised in this system. The aim is to counterbalance the impact added by the ZB solution and generate an added value for the company. Hence, ZB technology is divided into the different sub-systems which compose the treatment following a modular scheme. Further details regarding the complete scheme and the different modules can be found in system boundaries chapter (7.2.3) and LCI chapter (7.3).

Consequently, the functional unit (FU) of the study is: "the treatment of 1 m^3 of effluent from silica production at IQE facilities and the implementation of circular economy strategies derived from its management". In the final analysis report of the project it is foreseen to study the system from a Na_2SO_4 perspective also. This is to determine the significance of salt production as a by-product. Hence, a secondary FU will be deployed: "the production of 1 kg of Na_2SO_4 coming from the treated effluent of IQE operation and recovered by ZB technology".

Hence, a dual FU approach will enable assessment of the environmental performance from two different approximations: based on the treatment of a brine flow, which is an input of the ZB technology and by the other hand, by the procurement of a by-product at the exit of the plant as main output.

7.2.2 Allocation

Following the recommendations of ISO 14040 (2006) and 14044 (2006), allocation is avoided in this study through system expansion. In this regard, all by-products will be included in the system boundaries, considering its further destination and usage. Nevertheless, this approach is fully dependant on the evolution of the project. Consequently, future decisions could modify the approach currently adopted.

7.2.3 System boundaries

This report is focused on the stages, which currently have full scale data. Hence, the considered steps are brine treatment and silica production (represented in Figure 24 with the green dotted line).

Membrane regeneration is also considered within the system boundaries of this study. However, different laboratory tests are currently running to find the optimum operation parameters. Therefore, this preliminary assessment focuses on a comparison of the environmental impacts of the using a conventional R.O. membrane with a regenerated membrane. This aspect mainly entails a comparison of capital goods production, setting the basis for future comparisons. When further test data on the membrane characteristics is available, the operation phase of the membranes will be included. The current assessment of the regenerated membranes utilises conventional R.O. operational data, therefore adopting a conservative approach. The system boundaries of the final study will include the whole ZB scheme listed below when upscaling will be ready, as well is represented in Figure 24.

- *Silica production*: The IQE scheme will be included in the system to provide a complete picture of the process. Its inclusion is aimed at finding out what the importance of the ZB is in reference to the silica productive scheme.
- *Brine treatment:* This module receives the effluents from IQE and obtains ultrapure water and concentrated brines. It is based on physico-chemical and membranes technologies.
- *Membrane regeneration:* The inclusion of this stage is aimed at providing RO membranes that have been given a second life and are a critical component of the ZB process.
- *Brine concentration:* Current strategies for brine concentration rely on brine crystallization and EFC (Eutectic Freeze crystallization). At the end, the goal of this step is to concentrate the brines and recover water and salts.
- *Heat recovery:* Different processes during silica production in IQE have heat surplus which are not recovered. In this way, the heat recovery stage aims to utilise the waste heat for use mainly in crystallization step.

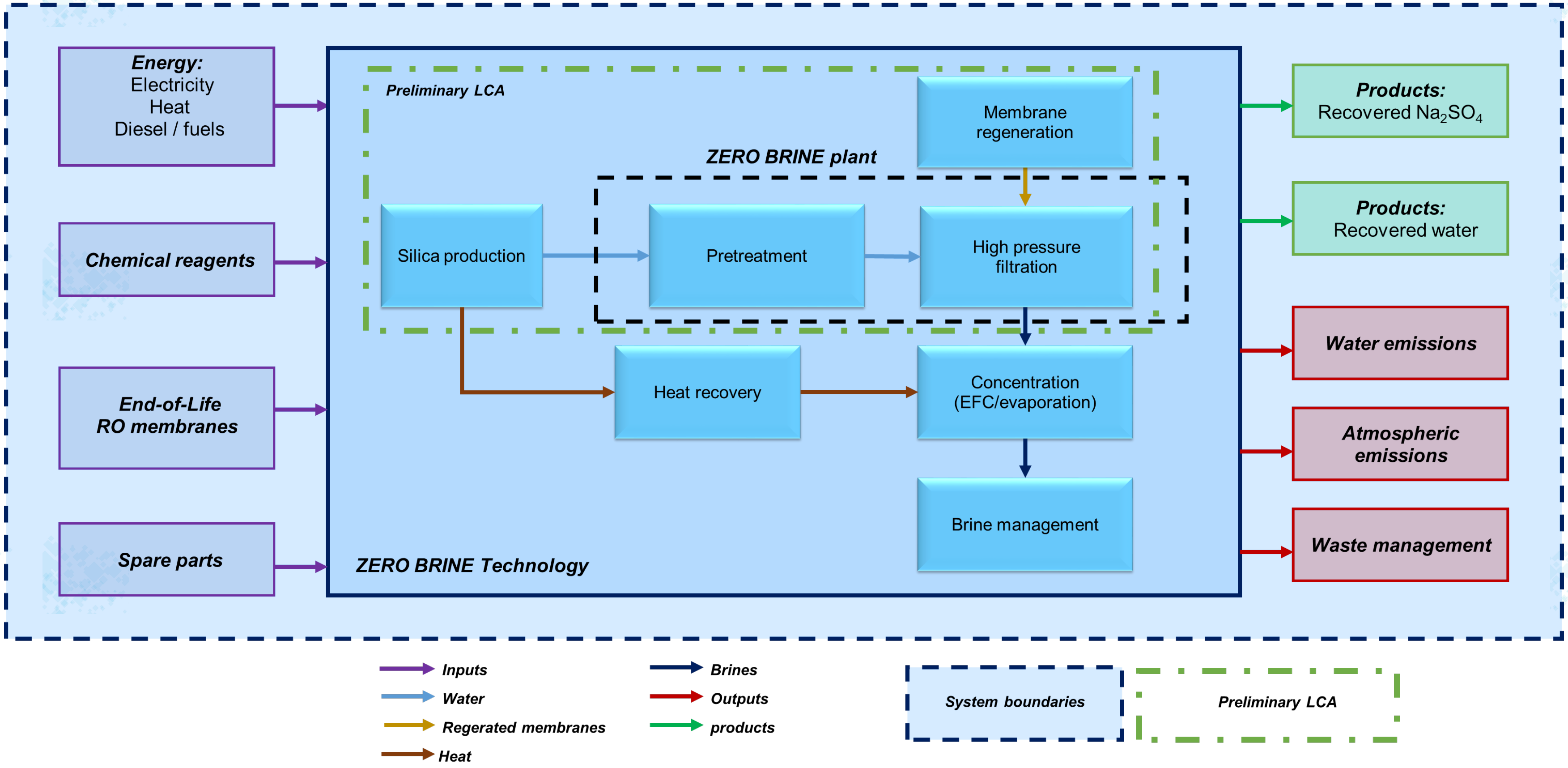

Figure 24: System boundaries of both preliminary and final LCA studies

The ZB brine treatment plant can be subdivided into 5 sections, as listed below and shown in Figure 25:

- *Physico-chemical treatment:* brines coming from IQE's production process enter the plant. Different chemical reagents are added (limestone, coagulants and flocculants). After settling, sludge and clarified water are separated.
- *Physico-chemical sludge treatment*: Sludge from pre-treatment is thickened and flocculants are added. After that, a centrifugal screw for reducing its water content mashes the sludge.
- *Sand filtering:* clarified water from the pre-treatment gets into the sand filters at high pressure. The aim of this step is to remove solids before membrane filtration.
- *Ultrafiltration step:* Sodium hypochlorite, sodium hydroxide and hydrochloric acid are added to the water in the filtration stage. The next step is ultrafiltration.
- *Reverse osmosis:* Permeate from the UF stage is fed into the RO filtration step. Hydrochloric acid, sodium hydroxide and antifouling reagent are added to the stream. Permeate after this step is ready to be reintroduced in IQE's silica production scheme.

For each part of the process, for both capital goods and operation all factors are considered. The operation phase consists of inputs and outputs, energy consumption, chemicals involved, wastes and products. For stages to be included in the next steps of the project, both capital goods and operation will be implemented.

Regenerated membranes are considered as "zero environmental burdens" regarding its production. The impact of these devices is allocated to the regeneration process and its transportation from the place where have been used. In this case, end-of-life membranes are conveyed from "El Prat" desalination plant, located 300 km away from IQE facilities. At this time, this stage is limited to operational data. Nevertheless, the final study will include data for the capital goods.

Silica production is considered within the system boundaries in all assessed scenarios (further information can be found on chapter 7.2.4).

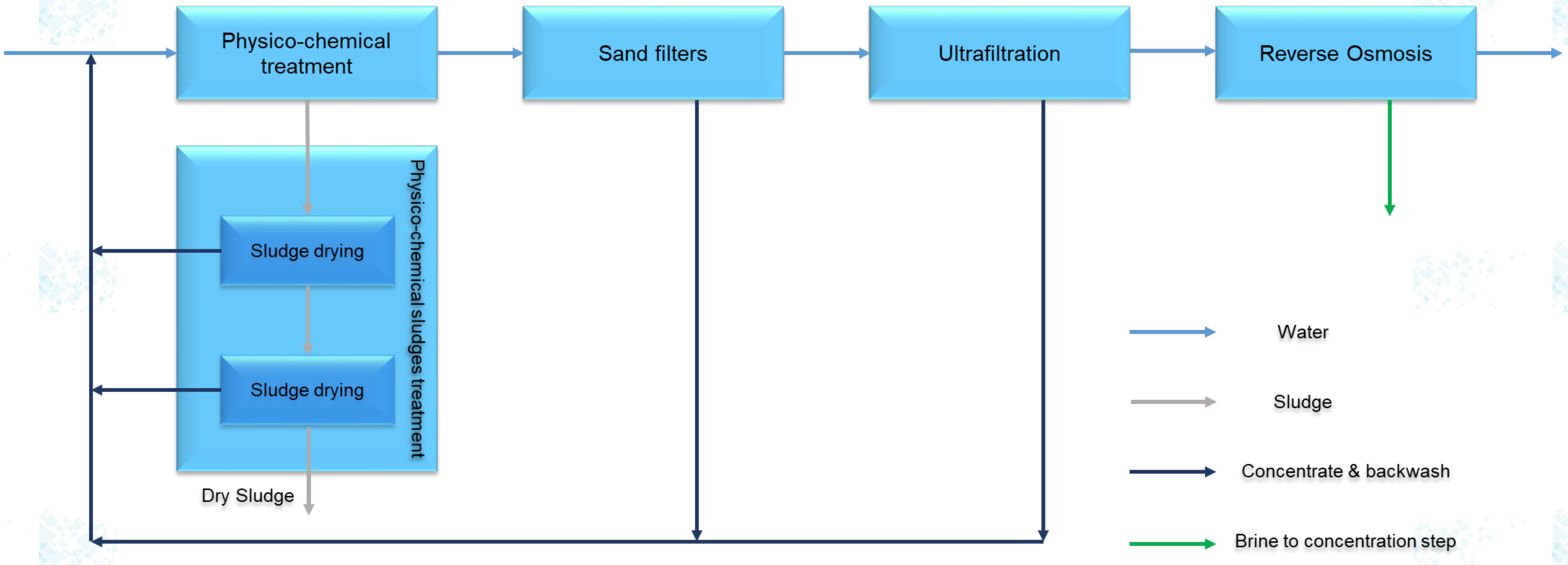

Figure 25 Diagram of ZB plant

7.2.4 Scenarios /process configurations

As a preliminary assessment this LCA covers a single situation based on the technology assessment of ZB brine filtration technology. In the updated versions of the LCA, the complete environmental assessment of the ZB strategy will assess the following scenarios:

- *Standard scenario (reference system)*: Based on the current situation: Treatment of IQE's brine in the municipal WWTP "La Cartuja". No recovery of salts nor energy and water is performed in this scenario.
- *ZB basis scenario.* ZB technology implementation for the treatment of wastewater from silica production. This scenario will also include the membrane regeneration step to account their environmental gains derived.
  - *Sub-Scenario 1*: ZB + Recovery of Na_2SO_4 is included.
  - *Sub-Scenario 2*: ZB + EFC technology in the concentration step.
  - *Sub-Scenario 3*: ZB + Evaporation technology included in the concentration step.

Each scenario will show their results within and without silica production and will be compared against the reference system. This approach is aimed at finding out the relevance of ZB system in relation to silica production scheme as stated in the goal and scope of the study.

7.2.5 Data quality

The inventory for the current report has been built mainly from primary data. It has been implemented from a technical report of the industrial scale up of membrane step provided by TYPSA. It entails both operation (energy and chemicals consumption) and capital goods. Primary data from membrane regeneration has been gathered from TYPSA and operation tests. Despite the very good data quality, it is anticipated that this will be updated and be refined during the data collection of the pilot stage of the project.

IQE provided silica and wastewaters production amount (primary data). Secondary data for building up the inventory has been taken from IQE's Environmental Operation License (publicly available) (PRTR, 2019). Furthermore, "Large Volume Inorganic Chemicals - Solids and Others industry" BREF document (EC, 2007) has been also considered.

The main limitations of this study are strongly related to its preliminary concept. Concentration technology is still under development (EFC and evaporation), as well as heat recovery. Therefore, no representative inventory can be built for these stages.

7.3 LCI

The LCI has been built based on an industrial plant design for treating IQE wastewater, with a capacity of 20 m^3/h (480 m^3/day). This scheme entails both pre-treatment and high-pressure stages.

Table 20 shows the chemical quantities required by the process. Table 21 shows the replacement period of different devices, like UF and RO membranes, and filtering devices. Since energy is one the main aspects of filtration devices, Table 22 provides a breakdown of energy needs of the whole plant, divided by its main stages.

Table 20 Chemical reagent dosage during ZB plant operation

Chemical reagents	Stage	Pure chemical (g/m3)	Daily dose (kg/d)	Annual dose (Tn/y)
Alumina sulphate	Physico-chemical treatment	10	26,67	9,73
Calcium hydroxide		100	48	17,52
Anionic polyelectrolyte		1	0,48	0,18
Cationic polyelectrolyte	Sludge treatment	5,03	1,93	0,705
Sodic hydroxide	UF	1,33	2,00	0,73
Hydrochloric acid		0,8	1,20	0,44
sodium hypochlorite		0,006	0,03	0,01
Basic cleaning chemical		8,68	3,33	1,22
Acid cleaning chemical		8,68	3,33	1,22
Hydrochloric acid	RO	20,00	29,09	10,62
Antifouling		4,00	2,00	0,73
Basic cleaning chemical		4,34	1,67	0,61
Acid cleaning chemical		4,34	1,67	0,61

Table 21 Spare parts for ZB plant operation

Element	Stage	Installed elements (unts)	Reposition percentage (annual %)	Reposed elements (annual units)
UF membranes	UF	4	20	0,8
RO membranes	RO	28	20	5,6
Cartridge filters (process)		12	1reposition/month	144
Cartridge filters (cleaning)		12	1 reposition month	144

Table 22 Energy needs of the ZB plant

Stage	Daily consumption (kwh/d)	Specific consumption (kwh/m3)
Physico-chemical treatment	192	0,5
Sludge treatment	67	0,8
Sand filtration	50	0,12
UF	91	0,24
RO	1.450	3,8
Auxiliary systems	23	0,1
Total	1.872	4,9

Capital goods have also been considered in the inventory, primarily major equipment such as tanks, filters and membranes. At this stage of the project, secondary devices like valves and sensors are not considered into the inventory. Table 23 sums up the capital goods information.

Table 23 Capital goods considered in the ZB plant

ITEM	Material	Capacity	Mass (kg)
Tank	HDPE	1 m^3	50
Coagulation chamber	GFRP	2 m^3	90
Dosing hopper	GFRP	1m^3	60
Rectangular flocculation chamber	GFRP	5m^3	150
Settler	GFRP	5,4m^2	300
Drying sludge tank	GFRP	20m^3	450
Accumulation tank	HDPE	500 l	35
Centrifugal settler	Stainless steel	2,5 m3/h	650
Sludge accumulator	Stainless steel	5m^3	590
Sand filter	GFRP	2m^3	120
Dosing tank	HDPE	125 l	15
Piping	PVC	100	meters

Table 24 summaries the operational data for the membrane regeneration stage, normalised to the regeneration of one membrane. Transport of the regenerated membranes is included in the system, considering 300 km from "El Prat" desalination plant.

Table 24 Operational data for membrane regeneration

Item	*Category*	*value*	*units*
RO Membrane		1	Unit
Deionised water	Flow	667	l
Sodium chloride	Flow	1	kg
Electricity	Energy	8	kWh
Deionised water	Flow	167	l
Sodium hipochlorite	Flow	10	l
Wastewater	Flow	167	l
Electricity	Energy	0,33	kWh
Deionised water	Flow	667	l
Sodium chloride	Flow	1	kg
Electricity	Energy	8	kWh

Silica production inventory is shown in Table 25. It is based on operational data, assuming capital goods of industrial facilities are negligible. Since IQE produces other chemical products, mass allocation has been applied to build up the inventory of this step.

Table 25 Operational data for Silica production

General information		
Silica production	25.000	Tn/y
Effluent production	438.000	m^3/y
Products	***tn/y***	***%***
Silica	25.000	0,625
Al silicate	10.000	0,25
Al Hydroxide	5.000	0,125
Raw materials	***Total (tn/year)***	***Alloc. to silica (tn/tn silica)***
Sulphuric acid	11.750	0,29
Sodic silicate (30%)	120.750	3,02
NaOH	200	0,01
Sodic aluminate	5.500	0,14
Aluminium sulfate	25.000	0,63
Sodic carbonate (soda ash)	2.500	0,06
Water consumption	***Total (m3/year)***	***Alloc. to silica (m3/tn silica)***
Public network	3.5	0,1
Osmotic water	473	11,8
Energy	***Total (MWh/year)***	***Alloc. to silica (MWh/tn silica)***
Electricity	6.4	5,56
Wastewaters	***Total (m3/year)***	***Alloc. to silica (m3/tn silica)***
Wastewaters	236.000	147.500
Atmospheric emissions (4 sources)	***Total (mg/m^3)***	***Alloc. to silica (kg/tn silica)***
PM	50	0,30
NOx	200	0,10
Cl2		0,05
HCl		0,10
VOC		0,30
CO2		640,00
Wastes		***Alloc. to silica (kg/tn silica)***
Hazardous waste		2,00
Non-hazardous waste		10,00

Source: PRTR, 2019 and EC, 2007.

7.4 LCIA

Environmental impacts have been assessed with a set of seven impact categories, representing different areas of environmental concern. After an overview of all indicators, selected impact categories are discussed in more detail to reveal individual contributions of different processes and aggregates to the total environmental impact.

The selection of these environmental categories followed the recommendation set on Waste water collection and treatment services PCR rule: System boundaries, impact categories and general guidelines (UN CPC 9411 & 9423). The obtained results have been obtained using SimaPro Developer v8.5.2.0 Software and Ecoinvent database.

Different results have been obtained according to the objectives of the study:

- Environmental assessment of the ZB technology. Shown in Figure 26 and Table 26
- Assessment of regenerated membranes against conventional RO membranes. Shown in Figure 27
- Environmental significance of ZB technology integrated into silica production scheme. Shown in Figure 28

Table 26 Results for technology assessment of the ZB filtration plant for IQE brines management per m³ of brine

Impact category	Unit	Total	B.1.1. Physico-chemical treatment.	B.1.2. Physico-chemical sludge treatment.	B.1.3. Sand filtering.	B.1.4. UF.	B.1.5. RO.	B.1.6. Others.	Membrane regen.
Global warming	kg CO_2 eq	2,38	0,25	0,02	0,08	0,12	1,88	0,03	4,2E-04
Ozone formation, Human health	kg NOx eq	0,01	6,6E-04	4,1E-05	2,05E-04	3,03E-04	4,8E-03	7,5E-05	9,5E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	0,01	6,60E-04	4,2E-05	2,06E-04	3,06E-04	4,8E-03	7,6E-05	9,7E-07
Terrestrial acidification	kg SO_2 eq	0,01	1,43E-03	1,0E-04	4,42E-04	6,5E-04	0,01	1,6E-04	2,0 E-06
Freshwater eutrophication	kg P eq	7,4E-04	8,01E-05	4,6E-06	2,45E-05	3,7E-05	5,9E-04	9,0E-06	1,4E-07
Freshwater ecotoxicity	kg 1,4-DCB e	0,06	0,01	4,0E-04	1,9E-03	2,9E-03	0,05	7,2E-04	1,1E-05
Land use	m2a crop eq	0,07	0,01	3,71E-04	2,4E-03	3,6E-03	0,06	8,9E-04	1,3E-05

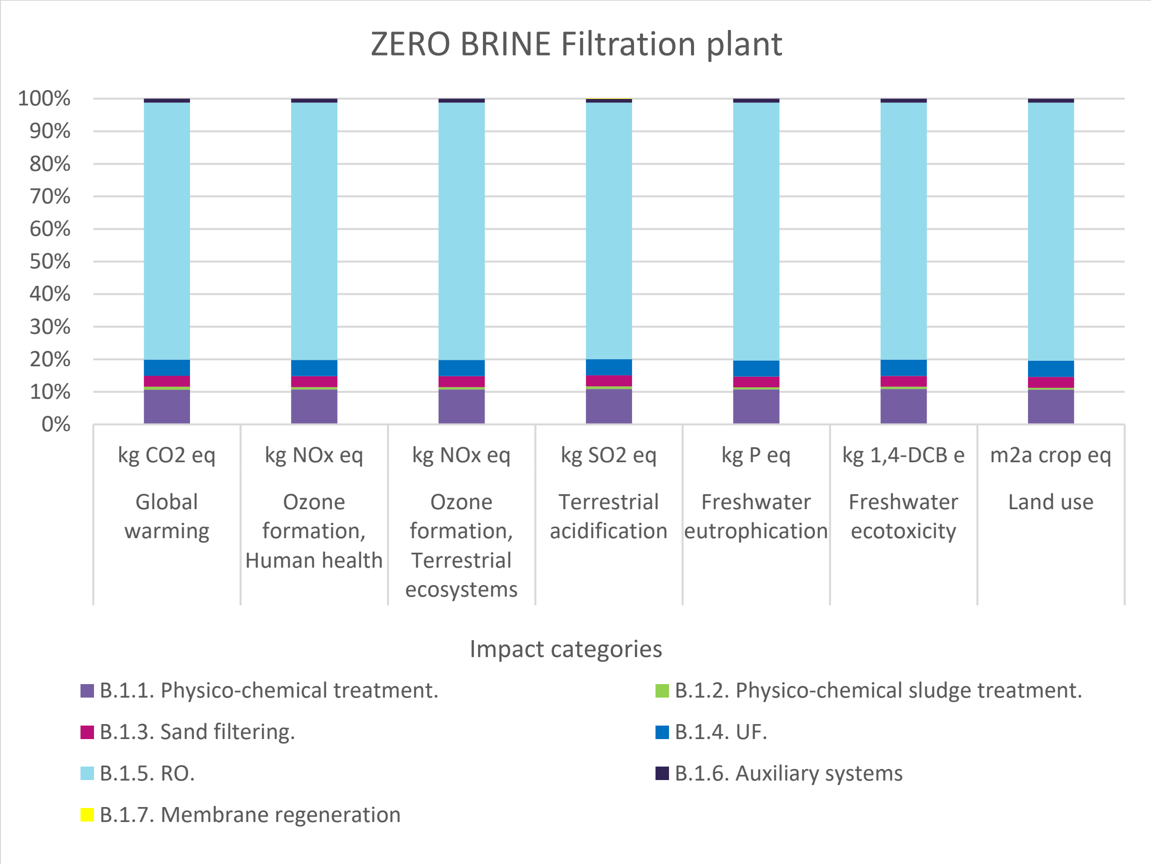

Figure 26 Results for technology assessment of the filtration plant for IQE brines management

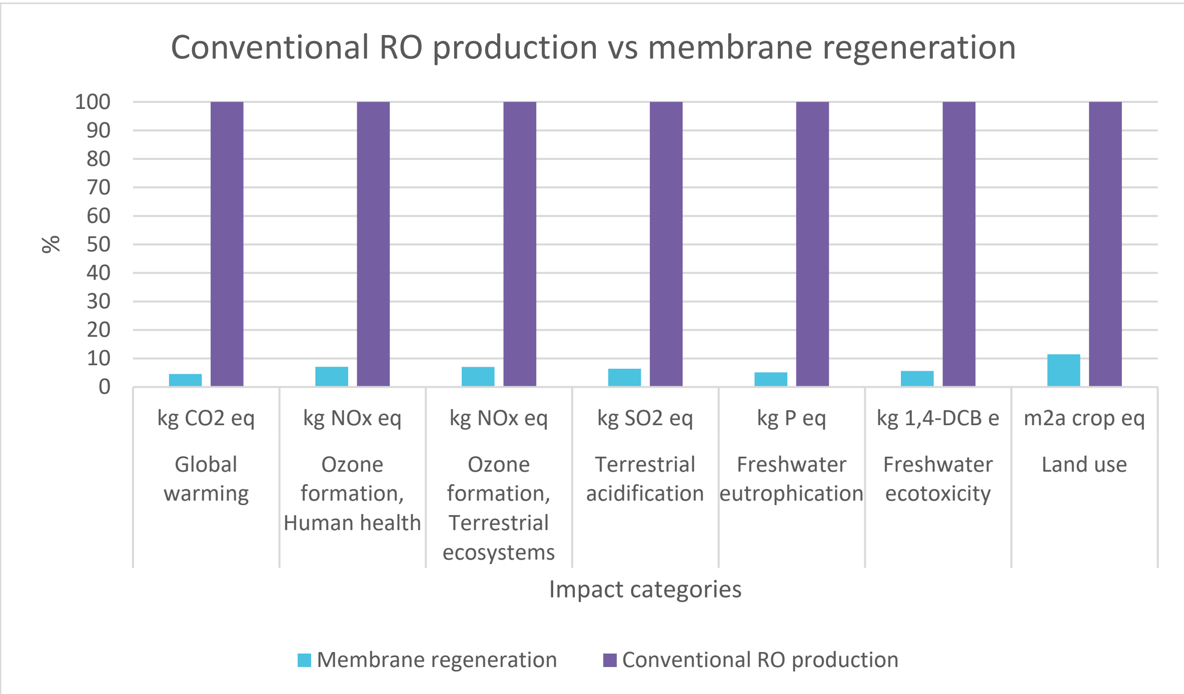

Figure 27 Environmental performance comparison between conventional RO production and membrane regeneration process.

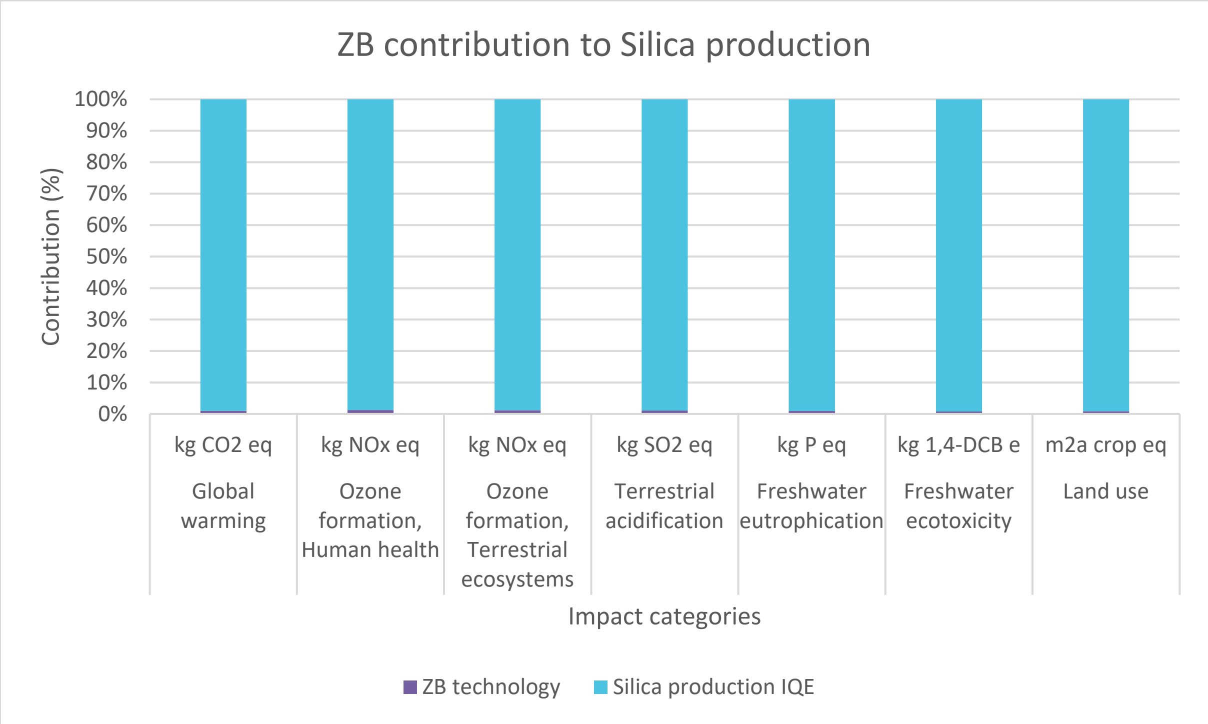

Figure 28 Contribution of ZB technology to overall system, considering silica production

7.5 LCC

This chapter aims to determine the techno-economic feasibility of ZB technology. For that, the Life Cycle Costing (LCC) assessment methodology has been applied. The system has been developed according to the recommendations of SETAC (Swarr et al. 2011b) and ISO 15663-1, 15663-2 and 15663-3. To ensure consistency of the results, the LCA standards ISO 14040 and 14044 have also been followed. Consequently, a consistent and common approach is followed across the LCA and LCC analysis. The same functional unit is therefore used in both studies: “the treatment of 1 m^3 of effluent from silica production at IQE facilities, and the implementation of circular economy principles derived from its management”. This procedure is applied also to the allocation procedures.

System boundaries in LCC are based on the scheme proposed in Figure 25. The considered phases are the same than those considered in the LCA study. The current system boundaries cover both capital goods and operation of membrane plant of the project. Furthermore, operation stage from membrane regeneration is also implemented. Hence, the other stages of the system will be implemented during next steps of the project. For the LCC study, the same lifespan of 25 years is considered.

The foreseen scenarios for the definitive LCC study match those proposed in section 7.2.4. At this point, the present study is based on the current technology development level. Hence, the report establishes a single scenario in which the technology is assessed.

The implemented data in this study entails monetarisation of the LCA inventory (for further details of the LCI, see section 7.3). Data regarding capital goods (plant cost) and device replacement (spare parts) has been provided by TYPSA. Therefore, it is primary data. Costs from chemical reagents, staff and electricity are secondary data. Regarding staff cost and work time, different assumptions has been taken based on technician's expertise.

The inventory is divided into different categories. The main division entails CAPEX and OPEX. The first category includes costs from initial investments: infrastructures (capital goods), research activities (technology development) and other expenses. OPEX category considers operational costs: staff, consumables (chemical reagents), energy, spare parts, and revenues from products.

At this point, the inventory is under development because of the early stage of the project. Table 27 shows a detailed inventory of the status of the system. Monetary units are kept from the bibliographic sources.

Table 27 Life Cycle Costing inventory

	Category	Sub Category	Cost		Unit cost	Unit
CAPEX COSTS	R+D	R+D/m³	0,37	€/m³		
CAPEX COSTS	Capital Goods	Total plant cost	680.000	€	680.000	€
CAPEX COSTS	Other expenses		0	€	0	€/kg
OPEX COSTS	Staff	Operator	542	€	22,60	€/h
OPEX COSTS	Staff	Foreman	88	€	29,36	€/h
OPEX COSTS	Consumables	Aluminium sulphate	7.009	€	152	$/tn
OPEX COSTS	Consumables	$Ca(OH)_2$	88.082	€	191	$/tn
OPEX COSTS	Consumables	Anionic polyelectrolyte	9.499	€	2060	€/kg
OPEX COSTS	Consumables	Cationic polyelectrolyte	46.830	€	2060	€/tn
OPEX COSTS	Consumables	NaClO	0,01	€	0,3	$/kg
OPEX COSTS	Consumables	NaOH	11.670	€	258	$/tn
OPEX COSTS	Consumables	HCl	544	€	12,7	$/kg
OPEX COSTS	Consumables	HCl	918	€	12,7	$/kg
OPEX COSTS	Consumables	NaOH	4.047	€	258	$/tn
OPEX COSTS	Consumables	Antifouling	11.972	€	828	$/tn
OPEX COSTS	Consumables	NaCl	0,01	€	42	$/tn
OPEX COSTS	Consumables	Deionised water	0,18	€	2,02755	$/l
OPEX COSTS	Consumables	Deionised water	0,05	€	2,02755	$/tn
OPEX COSTS	Consumables	NaClO	0,00	€	0,3	$/kg
OPEX COSTS	Consumables	NaCl	0,01	€	42	$/tn
OPEX COSTS	Consumables	Deionised water	0,18	€	2,02755	$/tn
OPEX COSTS	Energy	Physico-chemical	224.040	€	0,11	€/kWh
OPEX COSTS	Energy	Physico-chemical sludge treatment	77.777	€	0,11	€/kWh
OPEX COSTS	Energy	Sand filtration	57.984	€	0,11	€/kWh
OPEX COSTS	Energy	Ultrafiltration	106.634	€	0,11	€/kWh
OPEX COSTS	Energy	Reverse osmosis	1.694.668	€	0,11	€/kWh
OPEX COSTS	Energy	Membrane regeneration	269	€	0,11	€/kWh
OPEX COSTS	Device replacement	PAD tank 1m³	10.500	€	750	€/ud
OPEX COSTS	Device replacement	PAD tank 0,5 m³	1.000	€	500	€/ud
OPEX COSTS	Device replacement	PAD tank 0,125 m³	500	€	250	€/ud
OPEX COSTS	Device replacement	PRFV settler 5,4 m²	110.000	€	55.000	€/ud
OPEX COSTS	Device replacement	Dosing hopper	6.800	€	850	€/ud
OPEX COSTS	Device replacement	Coagulation chamber 2 m³	22.000	€	1.100	€/ud
OPEX COSTS	Device replacement	PRFV flocculation chamber 5 m³	8.000	€	4.000	€/ud
OPEX COSTS	Device replacement	PRFV sludge thickener 20 m³	15.000	€	7.500	€/ud
OPEX COSTS	Device replacement	STEEL centrifuge settler 2,5 m³	135.000	€	45.000	€/ud
OPEX COSTS	Device replacement	STEEL sludge collector 5m³	8.000	€	4.000	€/ud
OPEX COSTS	Device replacement	Sand filter	10.000	€	10.000	€/ud
OPEX COSTS	Device replacement	Cartridge filter	3.600	€	1	€/ud
OPEX COSTS	Device replacement	RO membranes	0	€	0	€/ud
OPEX COSTS	Device replacement	Piping	20.000	€	10000	€/ud
OPEX COSTS	Device replacement	Centrifuge pump 20 m³/h	52.500	€	3.500	€/ud
OPEX COSTS	Device replacement	Dosing membrane pump	8.250	€	550	€/ud
OPEX COSTS	Device replacement	Dosing piston pump	2.550	€	850	€/ud
OPEX COSTS	Device replacement	Dosing piston pump	1.650	€	550	€/ud
OPEX COSTS	Device replacement	Stirrer	4.500	€	750	€/ud
OPEX COSTS	Device replacement	Stirrer	2.300	€	1.150	€/ud
OPEX COSTS	Device replacement	Peristaltic pump	2.250	€	750	€/ud
OPEX COSTS	Device replacement	Screw pump	5.700	€	1.900	€/ud
OPEX COSTS	Device replacement	Transporting screw	5.000	€	2.500	€/ud
OPEX COSTS	Device replacement	Blower	16.200	€	5.400	€/ud
OPEX COSTS	Device replacement	Piston pump	195.000	€	65.000	€/ud
OPEX COSTS	Device replacement	encapsulated pump	45.000	€	15.000	€/ud
OPEX COSTS	Device replacement	Plastic pump	25.500	€	8.500	€/ud
OPEX COSTS	Device replacement	Phmmeter	3.750	€	750	€/ud
OPEX COSTS	Device replacement	Level sensor	3.750	€	1.250	€/ud
OPEX COSTS	Device replacement	Pressure sensor	4.500	€	1.500	€/ud
	Products	Products	0,00	€	0	€/m³

Table 28 breakdowns the overall cost and contributions to costs. The results are divided into Overall costs (€) and Contribution to costs (%). "Total costs" depicts all costs during the whole lifespan of the project. "Cost/m^3" shows the cost per treated cubic meter by ZB technology. "% by category" determines the contribution of each category to CAPEX or OPEX, depending on which one belongs. "% of total" shows the contribution of each item to total costs. Figure 29 and Figure 30 represent he graphical depict of the obtained results.

Table 28 Life Cycle Costing results

		OVERALL COSTS		**CONTRIBUTION TO COSTS**	
		Total cost	Cost/m^3	% by category	% of total
CAPEX	Technology development	1.491.000	0,37	0,69	0,14
	Capital goods	680.000	0,17	0,31	0,06
	Overheads	0,00	0,00	0,00	0,00
		2.171.000	***0,53***	***1,00***	***0,20***
OPEX	Staff	5.359.080	1,31	0,63	0,51
	Consumables	180.600	0,04	0,02	0,02
	Energy	2.161.400	0,53	0,26	0,20
	Devices replacement	728.800	0,18	0,09	0,07
	Products	0,00	0,00	0,00	0,00
		8.429.800	***2,07***	***1,00***	***0,80***
	TOTAL	10.600.800	2,60		

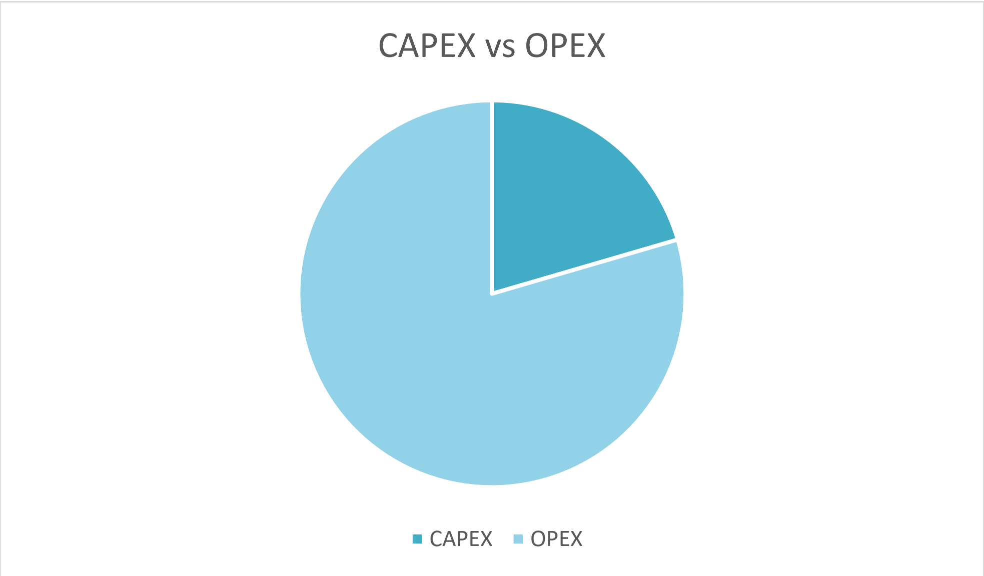

Figure 29 Costs distribution between CAPEX and OPEX

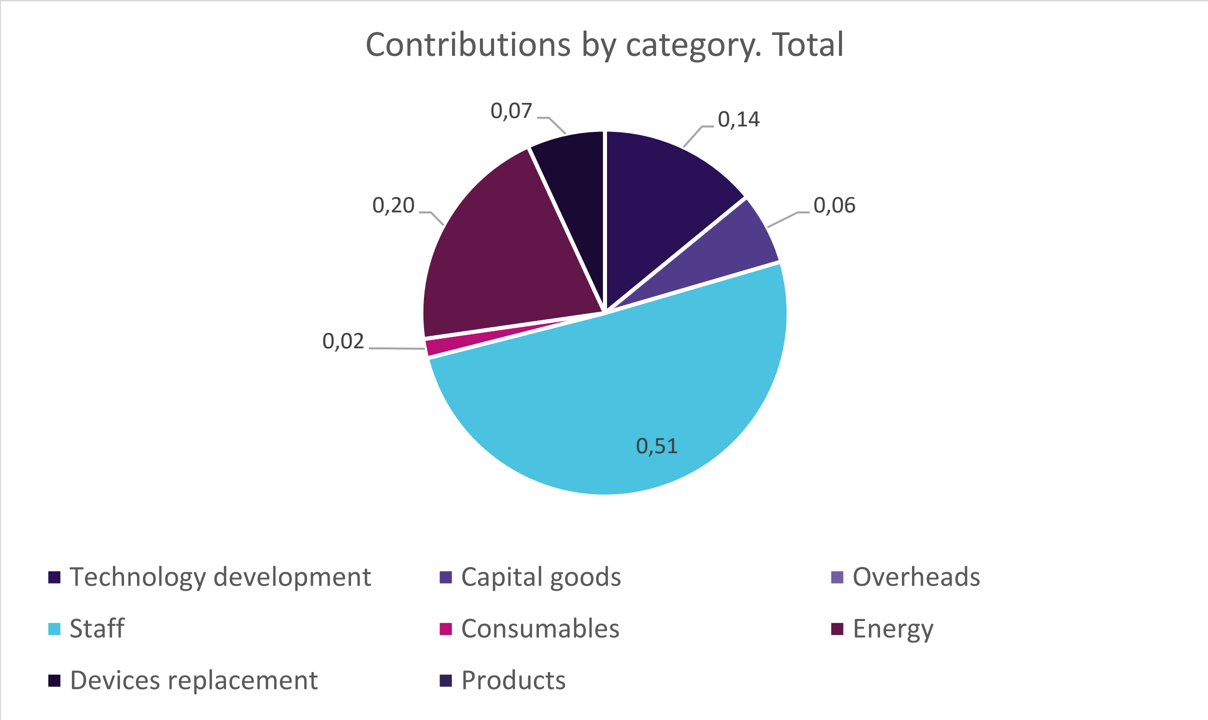

Figure 30 Costs distribution among all the assessed categories

7.6 Discussion

7.6.1 Results

Environmental assessment of ZB technology is represented in Figure 26. It can clearly be seen that reverse osmosis is the stage with higher contributions during all the considered impact categories, with circa 80% of contribution. After it, physico-chemical treatment is responsible for circa 20% of the impacts, and UF 15%.

These contributions are mainly caused by the operation step. Energy consumption is the main contributor to the environmental impact. Table 20 confirms this trend where energy required per stage is detailed, and the energy consumption ranking is similar to the overall contribution of the environmental impacts.

Concerning the impact of regenerated membranes, it is worth mentioning that membrane regeneration has negligible impacts in relation to the overall system impacts, as shown in Table 24 and Figure 26. Results from Figure 27 show that the regeneration process decreases the environmental impact of membrane production by circa 90% for all environmental impact categories assessed. The next steps of the project will provide data to assess the environmental performance of the operation of regenerated membrane in the system.

Finally, when considering ZB impact in the whole production system, Figure 28 includes silica production before IQE's brine treatment. Results show that less than 1% of the impacts are related to ZB plant. The rest of the impacts are allocated to Silica production. Hence, it suggests that the ZB system will have a negligible impact when implemented in the whole system. In addition, the current wastewater treatment has not yet been included for a comparison. It is worth mentioning that the inclusion of recovered products in the next assessment stage should further decrease the overall contribution of ZB technology.

The LCC showed that the main costs are derived from the OPEX (80%) and 20% from CAPEX (Table 26). Regarding the CAPEX stage, the highest contribution comes from technology development stage (R+D costs associated to the project) (70% of the CAPEX, 14% of the total costs). Capital goods normally tend to have a discrete contribution in both environmental and economic assessments. In this case, this category causes 30% of the CAPEX costs, which means 6% of the total costs.

As previously stated, OPEX accounts for 80% of the costs of the plant. The main category is "staff", which accounts for over 60% of the OPEX, and more than 50% of the total cost. Energy is the second highest contribution to the costs of the system, with 20% of the plant costs. Consumables and device replacement have residual contribution to OPEX, and consequently to total costs.

7.6.2 Design recommendations

Different aspects of the ZB scheme will be implemented and improved during the project. The scaling up of different stages that are currently under development will help to give inputs to LCA and LCC.

It has been shown that energy consumption is one of the main contributions to environmental impacts. Consequently, a more efficient operation is the major way for improving environmental performance of the system. To counterbalance that effect, steps such as heat recovery will help to improve the environmental profile. Furthermore, the implementation of regenerated membranes operation is expected decrease the energy consumption of the plant, due to their technical characteristics.

Crystallization, EFC and heat recovery will be the most important process steps relevant to the environmental and economic viability of the ZB system. The inclusion of further test data into the LCA will allow the identification of the main hotspots of the complete system. These findings will enable further environmental based recommendations that will be communicated to the ZB design team to improve system performance.

7.6.3 Further work

Further work regarding the LCA and LCC of the ZB project includes:

- Inclusion of steps which are currently under technical development. Coupled to that, its subsequent inputs, outputs and products will be included. Implementation of EFC, crystallization and heat recovery will allow also to find out the environmental benefits of the recovered products.
- Implementation of regenerated membrane operation. Technical information from tests will provide operational data mainly on the electricity consumption.
- Inclusion of conventional wastewater treatment plant for comparative analysis. When this WWTP is included in the system of analysis, a comparative assessment will be developed. This aspect also includes the impacts on local water bodies through the implementation of water treatment performance.
- Data refinement of the implemented systems. Technical development of the already included steps will lead to a high-quality inventory. Hence, more solid results will be obtained.
- In terms of LCC, the inclusion of revenues from by-products will help to develop a stronger system. In this sense, refining data will also help to improve the system. Especially data referred to staff, which is the main contribution to economic impact.

7.6.4 Conclusions

Different conclusions can be extracted from this preliminary ZB LCA:

- ZB technology has a negligible impact when implemented in the silica production scheme.
- Membrane regeneration is a successful circular economy strategy, due to it allows dramatically reducing environmental impacts of membranes.
- Energy consumption is the main contribution to ZB environmental impacts. For improving its environmental performance, this aspect should be tackled. Useful strategies for that are increasing efficiency of the system and/or utilisation of low carbon/renewable energy sources.

8. Discussion and conclusion

8.1 Discussion

This section provides a summary of the LCA and LCC's for the case studies based on the preliminary analysis. It should be noted that these are primarily based on experimental data at the bench scale and are therefore currently assessing sub-optimal systems. It is expected that the full scale ZB systems will operate with greater efficiency and lower overall environmental impact.

Demineralised Water Plant in the Netherlands

For the DWP the current analysis suggests that the ZB system has a greater environmental impact than the current system for the impact categories covered. In particular, the GHG emissions of the ZB system are double those of the current plant with 262 and 130 kgCO2eq per $1m^3$ of generated brine, respectively. Abiotic depletion is also double in the ZB system.

The increase in environmental impacts is mainly due to the use of chemicals sulphuric acid and sodium hydroxide used in the TOC removal process. These impacts were not compensated by the recovery of the salt, calcium hydroxide and magnesium. In addition, if waste heat is not utilised in the evaporation phase, there will be a slight decrease in the environmental performance…

This suggest several potential considerations in the next phase of the design and implementation process. Reducing the use of the chemicals in the TOC removal or utilising lower impact chemicals should therefore be considered.

The LCC illustrated that the recovery of the products from the brine will produce a strong positive economic outcome if a market is identified and a high product quality is attained.

Coal Mine Effluent in Poland

The comparison of four different configurations showed that the best environmental performance is obtained from two of the configurations: 1) Two stage NF, with electrodialysis diluate recycled to NF; and 2) Single-stage NF, with ED diluate recycled to NF.

Most of the environmental impact of the system configurations resulted from the system energy consumption and the use of dolime in the magnesium recovery process. However, the recovery of magnesium hydroxide and sodium chloride would counteract a large proportion of the impact for five of the impact categories (human toxicity, freshwater toxicity and resource depletion, the latter of which results in an overall positive environmental impact).

The LCC considered only the operating costs but suggests a large positive economic outcome for each of the system configurations. In fact, the recovered products could generate between 500-1000 Euros per m3 (based only on market price and not a packaged and distributed product) if markets were found for the products and high quality was attained.

The main design recommendations relate to the energy consumption from electricity. Due to the energy mix in Poland, which is largely produced from coal the electricity has a high carbon intensity. Therefore, to lower GHG emissions, consideration should be given to the installation or switching to renewable sources. Since the use of dolime in the magnesium recovery process is another cause of environmental impact (for toxicity impact categories), the optimisation of this process (and reduction of the quantity of dolime used) should reduce these impacts.

For the present analysis energy consumption was only available for the whole system and not for the individual processes. When more disaggregated data becomes available this will allow identification of the main energy intensive processes and possible process improvements.

Turkey Textile Plant

For the Turkey textile case study, the main impacts were shown to derive from the RO and its energy use. The recovery of materials has large benefits, particularly brine, which has potential to be used in the dyeing process. Transport of recovered materials was currently not included in the assessment however.

Therefore, the main design recommendation at this stage is to focus on reducing the energy consumption of the RO process and investigating options for using renewable energy.

The LCC showed positive results from the recovery of deionised water with a potential value of €450 per m3 of treated wastewater. This relies on the assumption that a market can be identified and at this stage piping costs are not included. In addition, the generated brine solution can be reused in the dyeing process, but the value has not yet been calculated.

Spain Silica Plant

In the Spanish case study, the RO stage was the cause of the main environmental impact (80%) of the treatment system for all considered impact categories. Next is the physico-chemical treatment with 20% and UF with 15% of impacts. These are primarily caused during the operation, as opposed to the raw material or production stage. This is closely related to the energy consumption.

The production and use of regenerated membranes clearly has lower environmental impacts than using new RO membranes. When including the silica production into the system boundaries, the results suggest that the ZB system would contribute only 1% to the overall impact.

The LCC included both CAPEX and OPEX, with operating costs representing 80% of the costs. The R&D costs associated with the project contributed 70% of the CAPEX. The cost of staff is the main operating expenditure representing 60%, with energy being responsible for 20%.

As energy use is the main concern, design improvements include consideration of potential heat recovery for the crystallisation step and the use of renewable energy sources.

8.2 Conclusion and next steps

The initial LCA and LCC results have been mainly positive for the ZB system. In addition, since the assessments are currently made using bench scale data, the full-scale plant would be expected to have lower environmental impacts.

The Netherlands DWP case study suggests that the ZB system has higher environmental impacts, but this has to be considered cautiously as the impact of the current discharge of brine into the sea. This impact will be integrated into the next stages of assessments.

The Turkey textile and Spanish silica case studies both identified the RO process as the main concern, due to its energy consumption. However, we expect the energy consumption of the full-scale plant to be significantly less. Nonetheless, this should be considered in the on-going design of the pilot and eventual full-scale plants. The environmental performance would benefit from a closer examination of the energy supply, and consideration of the potential to utilise renewable energy sources such as wind and solar. This should also be a consideration to include in the subsequent LCC analysis of ZB WP7. Hence the next phase of LCC should assess the economic implications of installing renewable energy sources for the operation.

In the next stage the major improvements in the analysis include:

- A better comparison to the reference systems
- Improved representation and robustness of analysis through a combination of increased data points from the pilot plants and subsequent use of this data to model the full-scale plants.
- Standardised way to handle data uncertainties.

8.2.1 Next steps

The primary goal during the next phase of the LCA and LCC work is to bolster the analysis with improved operational datasets that will be supplied through the operation of the pilot plants. Where possible, the pilot plant operational data will be input into modelling software to model the performance of a full-scale plant. The modelled parameters from this will then be used in the final LCA and LCC analysis to provide a robust and representative assessment.

The Unified Approach will be fully developed and implemented across the case study analysis. Importantly, this will include a standard way to handle lack of data. We intend to communicate this challenge and necessity to the relevant stakeholders so that they have sufficient time to supply the data and confirmed deadlines to do so. Where data cannot be obtained a standard way to model and obtain proxy data, e.g. from literature will be applied. In addition, a full sensitivity analysis will be performed for each case study to account for any data uncertainties.

The aim of the final LCA and LCC's is also to provide a comparison of the ZB systems with the existing/reference systems. A cross comparison can then also be made between the different case studies which will allow further insight to why some systems may or may not be performing in certain areas. The LCA and LCC will be combined with a Social LCA to provide a full sustainability assessment. Furthermore, the LCC will include a consideration of the environmental externalities that will add a further dimension.

The final results will be reported in D7.7: "Report on LCA and LCC results of case studies and technologies involved in the ZERO BRINE project". This will be complemented with D7.2 that provides an evaluation of the results from the demonstration activities with a more techno-economic focus.

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10. Appendix 1: Demineralised Water Plant, The Netherlands

Table 29 and Table 30 present the expected quantities of consumables needed per hour of operation in the pilot plant, the price and source of the price that was used for the LCC modelling.

Table 29. Consumption and price data of chemicals in the ZB system for the DWP Netherlands plant

Technology provider	**Chemical product**	**Quantity within pilot** (kg/h)[a]	**Price** (€/kg)	**Source**
Site 01				
Lenntech	Antiscalant (Vitec 3000)	0.5	136	https://www.sigmaaldrich.com/catalog/product/sial/398101?lang=en&region=NL
UNIPA	NaOH	6.6	0.16	Brinkmann et al., 2014
UNIPA	HCL 30-32% w/w	0.8	37.8	https://www.sigmaaldrich.com/catalog/search?term=HCl&interface=All&N=0&mode=partialmax&lang=en&region=NL&focus=product
Site 02				
Lenntech	Antiscalant (Vitec 4000)	0.62	136	https://www.sigmaaldrich.com/catalog/product/sial/398101?lang=en&region=NL
ARVIA	35% H_2SO_4	36.1	0.5	https://www.alibaba.com/product-detail/Sulfamic-acid-is-produced-industrially-by_60263809067.html?spm=a2700.7724838.2017115.26.162669e026I5ce
ARVIA	25% NaOH	24.37	0.16	Brinkmann et al., 2014
TU Delft	HCL 30-32% w/w	0.5	37.8	https://www.sigmaaldrich.com/catalog/search?term=HCl&interface=All&N=0&mode=partialmax&lang=en&region=NL&focus=product

[a] it was assumed that the pilot system will operate for 8 hours per day

Table 30. Prices for recovered products in the ZB system for the DWP Netherlands plant

Recovered product		
Magnesium Oxide >97%	924	https://www.sigmaaldrich.com/catalog/search?term=Magnesium+Oxide&interface=All&N=0&mode=match%20partialmax&lang=en&region=NL&focus=product
Soda ash	73.3	https://www.sigmaaldrich.com/catalog/search?term=soda+sh&interface=All&N=0&mode=match%20partialmax&lang=en&region=NL&focus=product
Calcium hydroxide	86.9	https://www.sigmaaldrich.com/catalog/product/sigald/239232?lang=en&region=NL

11. Appendix 2: Polish Coal Mine

Table 31: Coal mine LCI, functional unit: 1m^3 of wastewater

		Unit	Conf. 1	Conf.2	Conf. 3	Conf. 4
Energy consumption						
dolime production		kWh	1.1	0.8	2.2	0.4
Processes stages		kWh	6.4	8.2	8.9	11.4
Auxiliary materials						
material	**stage**					
Dolomite	Magnesium recovery	kg	21.6	16.9	44.1	9.2
Sodium Tripolyphosphate	NF	kg	0.0008	0.0004	0.0008	0.0004
EDTA		kg	0.01	0.005	0.01	0.005
Sodium Hydroxide	RO	kg	0.00058	0.00058	0.00058	0.00058
Hydrochloric acid		kg	0.00006	0.00006	0.00006	0.00006
EDTA		kg	0.006	0.006	0.006	0.006
Wastewater emissions						
Wastewater (Mr)		m^3	0.4	0.3	0.3	0.1
Wastewater (Cr)		m^3	0.0004	0.005	0.002	0.01
Recover Products						
Deionised water		m^3	0.6	0.7	0.7	0.9
Sodium Chloride (NaCl)		kg	3.4	6.525	5.125	9.4
Gypsum		kg	<0.03	0.03	1.03	0.8
Magnesium Hydroxide ($Mg(OH)_2$)		kg	1.4	1.1	2.8	0.6

Table 32: Wastewater (Mr) composition of different configurations

Ions conc. (g/m^3)	Conf. 1	Conf. 2	Conf. 3	Conf.4
Cl^-	23370	19900	15470	16600
SO_4^{2-}	1912	2736	1370	3990
Mg^{2+}	0	0	0	0
Ca^{2+}	1897	2102	5404	1850
Ca^{2+}	23370	19900	15470	16600

Table 33: Wastewater (Cr) composition of different configurations

Ions conc. (g/m^3)	Conf. 1	Conf. 2	Conf. 3	Conf.4
Cl^-	200000	200000	200000	200000
SO_4^{2-}	376	455	291	1608
Mg^{2+}	7545	11700	4477	12890
Ca^{2+}	22210	17390	27700	15490
Ca^{2+}	200000	200000	200000	200000