ZERO BRINE

D7.4 Report containing the economic assessment of full-scale implementation

February 2022

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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

The ZERO BRINE project demonstrates new configurations to recover resources from saline impaired effluents (brines) generated by various process industries, while minimising environmental impact of industries by minimizing saline wastewater discharge. The water treatment systems consists of both commercially available technologies, and recently developed technologies. In several deliverable reports of the ZERO BRINE project, the environmental, economic, and social impacts of its technologies are presented and discussed.

The aim of this Deliverable 7.4 is to provide an overview of the feasibility studies that the demonstration locations have made for full scale implementation. After the economic assessments, a discussion and reflection is provided. All locations show that a treatment configuration consisting of various technologies can deal with several types of brine water. The differences in outcomes also show that for each new wastewater type, process designs need to be made and optimization is necessary to adapt ZERO BRINE systems to other industrial contexts.

In the Dutch case, it is clear that it is impossible to find a positive business case with the ZERO BRINE system alone, there it is needed to find alternative solutions to make the system affordable. Work package 8 of ZERO BRINE discusses these opportunities. In the other three cases, the LCC results already show that is possible to find a positive economic balances based on OPEX, CAPEX, and revenues. These results are not yet optimized and further research is needed to see the find the optimal business opportunity in these cases.

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1 Introduction

This Deliverable 7.4 follows directly Deliverable 7.2 of ZEROBRINE, the reports should be read together. In the original project plan, the two deliverables were formulated separately, but in the course of the project, it became more and more clear that the same structure is applicable to both the evaluation of the results of the demonstration locations (Deliverable 7.2) and the evaluation of the cost structure of the demonstration locations (this Deliverable 7.4). This implies that some parts of the Deliverable reports overlap.

The ZERO BRINE project focuses 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 recover high quality end products with high purity to provide optimum market value and clean water. 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 to develop and demonstrate the ZERO BRINE systems under different industrial circumstances:

a. Demineralized water effluent in The Netherlands.
b. Coal mine effluent in Poland.
c. Textile industry effluent in Turkey.
d. Silica industry effluent in Spain.

In Deliverable 7.3, an initial analysis is presented to LCA and LCC of the demonstration projects of ZEROBRINE. The final analysis is presented in Deliverable 7.7. We have chosen to present all sources for the data and results in these two reports, in Deliverables 7.3 and 7.7 the results of the case studies are presented in detail. Further on, the underlying Deliverable 7.4 report takes the results of the following work packages:

- Deliverable 2.6: Report on the operation and optimization process of the pilot plants at Botlek.
- Deliverable 3.5: Report on the operation and optimization of the pilot system for treatment of coal mine water.
- Deliverable 3.8: Report on the operation & optimization of the pilot systems for the treatment of textile effluents.
- Deliverable 4.5: Innovative circular economy process in the precipitated silica industry: design and performance.

In order to avoid too much overlap between the deliverable reports, in this Deliverable 7.4 the results are given and the reader is referred to the other reports to find the experimental results, background data and calculation methods.

The rest of this report consists of a short description of the demonstration activities and their main outcomes, based on the documents mentioned above. This description is used to create an overview. From that a reflection is given on the common elements within the case studies and the transfer of that insight to the other deliverables of Work Package 7..

The objectives of this report are:

1. to collect the numbers on life cycle costs for the demonstration plants,
2. to conclude on the economic assessment of full scale implementation of the demonstration plants.

2 Methodology and approach

In line with the Unified Approach of ZEROBRINE's work package 7 and following the methods of the initial analysis of Deliverable 7.3, the following definition will be used for CAPEX and OPEX in this Deliverable 7.4 and Deliverable 7.7.

Life cycle costing (LCC) is an accounting technique that compiles all costs that an owner or producer of an asset will incur over its lifespan (Swarr, Hunkeler, & Klöpffer, Environmental life cycle costing: a code of practice, 2011a). It therefore considers both of capital expenditure and operating expenditure throughout the life cycle. LCC is defined in the International Organization for Standardization standard, Buildings and Constructed Assets, Service-life Planning, Part 5: Life-cycle Costing (International Organization for Standardization, 2017) as an "economic assessment considering all agreed projected significant and relevant cost flows over a period of analysis expressed in monetary value. The projected costs are those needed to achieve defined levels of performance, including reliability, safety and availability."

The approach adopted in ZEROBRINE is to include two components in line with (Swarr, et al., Environmental Life Cycle Costing: A code of practice, 2011b)

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

For the inclusion of costs in the LCC, the following definitions are made:

- CAPEX represent costs which are included at the beginning of the project, generally just a single time (price of the plant, taxes, fees, permits). These costs traditionally represent low contributions to the functional unit, due to the investment is repaid during the whole lifespan of the system (although may be more significant for innovative zero or circular technologies). Therefore, CAPEX costs are directly dependent on the lifespan, and its final value may vary through time.

- OPEX costs rely on continuous cash flows that the plant needs to operate. These costs have a fixed ratio per functional unit. 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. Lastly, in this report, maintenance is included in the OPEX costs.

To calculate the CAPEX we assume a lifetime of 20 years for the ZB systems, which is a reasonable approximation for wastewater treatment plants, an aligned with Deliverable 7.7.

This report compares the ZERO BRINE systems of four demonstration locations that require different configurations of technology that depend on the composition of the individual brines, as well as the elements targeted for recovery. This comparison should lead to insight on how ZERO BRINE technologies perform under different circumstances. In this ZEROBRINE Work Package 7 the environmental, social, and economic factors are taken into account. In the Work Packages 2, 3, and 4 all operating parameters are discussed in detail, as presented in the previous chapter. In this Deliverable 7.4, the focus is on costs of full scale implementation. In the remainder of this report, ‘Table 1 – Aggregated overview of full-scale’ will be filled in with the numbers from the feasibility studies of the demonstration locations. After which the results will be discussed shortly and it will be made clear how the results are taken over by the following Deliverables in this work package.

Table 1 – Aggregated overview of full-scale implementation

Location	Technologies	CAPEX	OPEX	Revenues
The Netherlands				
Poland				
Turkey				
Spain				

3 Results of the demonstration locations

First a short description of the ZERO BRINE demonstration locations is given, again here is referred to the other Deliverable reports that provide the necessary details for understanding the technologies and the underlying choices.

3.1 Demonstration location The Netherlands

In The Netherlands, the demonstration is performed in two locations, called Site 01 and Site 02. Site 01 pilot treats the regeneration effluent (spent regenerant) of the softening ion exchange unit of the Evides Demineralization Water Plant located in Botlek industrial area, see Figure 1. Site 02 pilot treats the reverse osmosis concentrate stream of the Evides Demineralization Water Plant located in Botlek industrial area, see Figure 2.

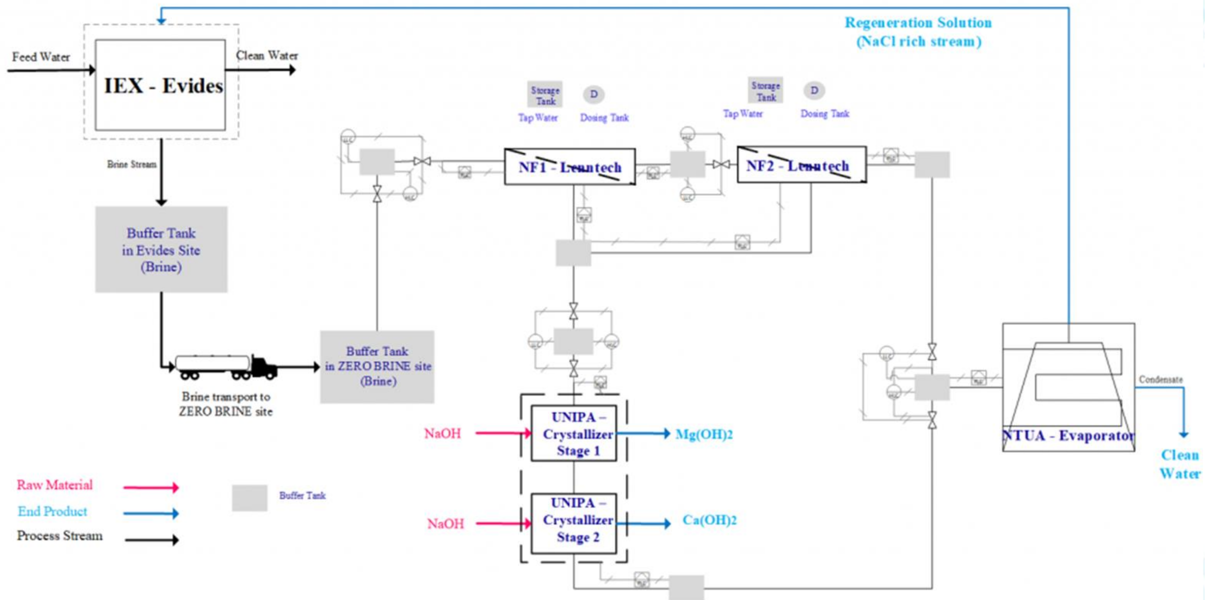

Figure 1 – Demonstration location The Netherlands – Site 01

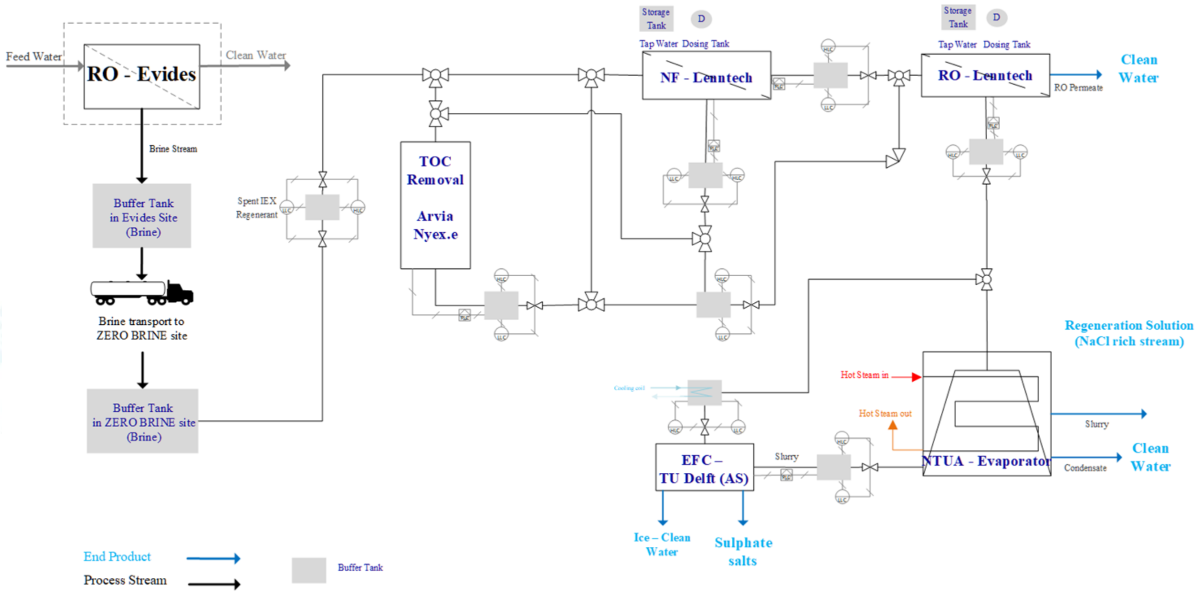

Figure 2 – Demonstration location The Netherlands – Site 02

The inventory data for LCC was collected after consulting technology suppliers. Table 2 shows the inventory of consumables and recovered materials per 1 m^3 of brine. In addition, maintenance is considered and is assumed to be 3% of the capital costs. Personnel cost is based on 3 employees with an average salary of 81,700 €/year spending 20% of their time at the ZB plant (calculated from average company values). Table 3 shows the capital costs per 1 m^3 of brine levelized on the entire life cycle of the plant, i.e. 35 years and a full scale plant capable of 290m^3/hr.

Table 2 – Operational costs and revenues for the demineralized water plant per 1 m³ brine

Material	Cost (€/1 m³ brine)
Operational Costs - Consumables	
Antiscalant (Vitec 3000) (Site 1)	0,00041725
HCL (Site 1)	0,00752
NaOH (Site 1)	0,02304
Clean water (Site 1)	0,006656
H2SO4 (Site 2)	1,476428335
NaOH (Site 2)	0,0887895
Antiscalant (Vitec 3000) (Site 2)	0,033153851
Clean water (Site 2)	0,409344
Electricity (Site 1)	0,002638873
Electricity (Site 2)	0,556802038
Operational costs – Maintenance and Personnel	
Maintenance	0,009258963
Personnel	0,116185136
Total Operational Costs	**€ 2,73 per 1 m³ of brine**
Recovered materials	
Recovered water	0,726146
Recovered deionized water	0,182823
Magnesium hydroxide	0,037162
Calcium hydroxide	0,025992
NaCl	0,045383
Na_2SO_4	0,293724
Total Revenues	**€ 1,31 per 1 m³ of brine**

Table 3 – Capital costs per 1 m³ brine levelized in the demineralized water plant location

Equipment	Cost (€/1 m³ brine)
Nanofiltration	0,012640842
Membrane Crystallization	0,002383702
Evaporator	0,07584505
Reverse osmosis	0,215506011
TOC removal	0,001625251
EFC	0,000631246
Total cost of Equipment	**€ 0,31 per 1 m³ of brine**

In Table 4, the consolidated results are given for the ZERO BRINE system of the Demineralized Water Plant in Rotterdam.

Table 4 – Consolidated results of the demineralized water plant in The Netherlands

Technologies	CAPEX	OPEX	Revenue
	per 1 m^3 of brine		
Nano filtration Crystallizer Eutectic Freeze Crystallizer Evaporator Multi effect distillation evaporator Reverse Osmosis	€ 0,31	€ 2,73	- € 1,31

3.2 Demonstration location Poland

In Poland a pilot plant in the "Bolesław Śmiały" coal mine in Łaziska Górne, has been operated. The tested system consisted of pretreatment, ultrafiltration, decarbonization, nanofiltration, reverse osmosis, and electrodialysis, see Figure 3. Recovery of magnesium hydroxide was tested in both conventional precipitation with slaked dolime suspension and crystallization with ion-exchange membrane. The recovery of sodium chloride using eutectic freeze crystallization has also been tested. The proposed setup is as follows: the brine pretreated with ultrafiltration is subjected to the first pass of nanofiltration (NF1); the permeate is subjected to a second pass of nanofiltration (NF2). The NF2 permeate is fed to the hybrid reverse osmosis (RO), from which the RO permeate is recovered, the ED concentrate is fed to a modern evaporator (MED), the ED dilute is recycled back to RO.

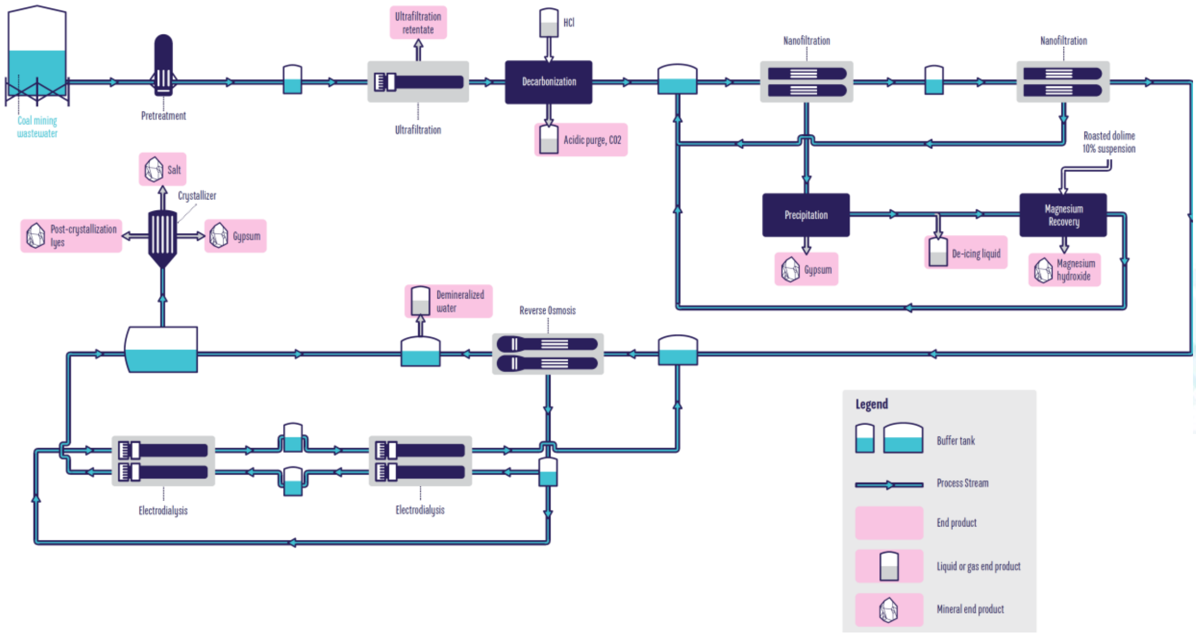

Figure 3 – Demonstration location Poland

The OPEX and CAPEX inventory values are provided in Table 5 and Table 6, respectively.

Table 5 – Operational costs and revenues for the coal mine per 1 m³ brine

Material	**Cost (€/1 m³ brine)**
Operational Costs - Consumables	
Electricity	1,221
Propylene glycol, liquid	0,000119
Lime	0,066785
Polypropylene	0,135708
Tap water	0,36296
Sodium sulfate, anhydrite	2,96E-05
Polystyrene	0,030805
Hydrochloric acid, in 30% solution state	1,41
Operational Costs - Waste disposal	
Inert material landfill	8,82E-06
Operational Costs – Maintenance and Personnel	
Maintenance	0,002
Personnel	0,176
Total Operational Costs	**€ 3,41 per 1 m³ of brine**
Recovered Products	
Deionised water	2,00
Sodium Chloride (NaCl)	0,9405
Gypsum	0,2856
Magnesium Hydroxide ($Mg(OH)_2$)	0,7189
Total revenue of recovered products	**€ 3,95 per 1 m³ of brine**

Table 6 – Capital costs per 1 m^3 brine levelized in the coal mine location

Equipment	Cost (€/1 m^3 brine)
Nanofiltration	0,040
Crystallizers	0,007
Ultrafiltration	0,026
Reverse Osmosis (RO)	0,039
Ion Exchange Membranes (Decarbonation)	0,009
Electrodialysis	0,009
Total cost of Equipment	**€ 0,13 per 1 m^3 of brine**

In Table 7, the consolidated results are given for the coal mine demonstration location in Poland.

Table 7 – Consolidated results of the coal mine in Poland

Technology	CAPEX	OPEX	Revenue
	per 1 m^3 of brine		
Nano filtration Reverse Osmosis Electro Dialysis	€ 0,13	€ 3,41	- € 3,95

3.3 Demonstration location Turkey

The developed ZERO BRINE system located at Zorlu Textile Industry, Turkey, was operated in the field of manufacturing polyester yarn and cotton home textile products. The system was designed for the treatment of reverse osmosis (RO) retentate of Zorlu Textile to recover recyclable salt as well as reusable water streams. The TPS comprised of a primary pre-treatment as well as a secondary concentration and softening stages, see Figure 4. The pretreatment was designed to remove impurities in the RO retentate, whereas, in the following stage the pretreated RO retentate was concentrated and further softened to conform to the textile dye processes prerequisites. Along these lines two different configurations were tested: 1) IEX softening the NF permeate, which then was concentrated by RO, 2) RO concentrating the NF permeate, followed by IEX softening the RO retentate.

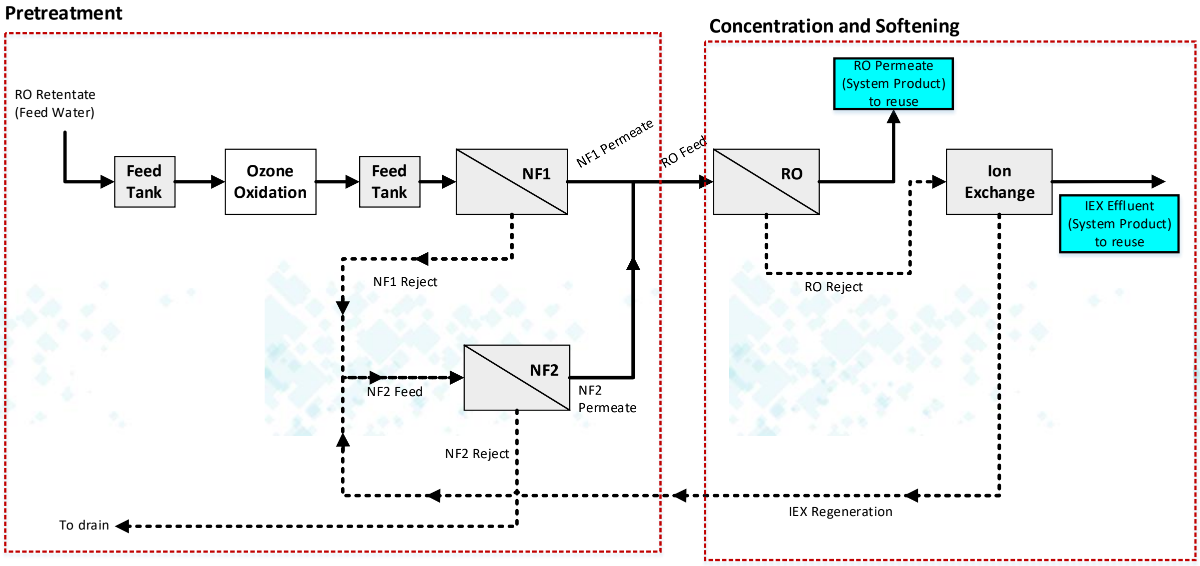

Figure 4 – Demonstration location Turkey

The OPEX and CAPEX inventory values are provided in Table 8.

Table 8 – Operational costs and revenues for the textile industry per 1 m³ brine

Material	Cost (€/1 m³ brine)
Operational Costs – Consumables	
Electricity	1,44
Operational Costs - Raw & Auxiliary materials	
Ammonia liquid	0,002198
Cyanoguanidine	0,09432
Polyacrylamide	0,0052
Polyaluminium chloride	0,224
Sodium hypochlorite	0,00949
Sulfuric acid	0,00583
Hydrochloric acid	0,001199
Cationic resin	0,285803
Operational Costs - Waste disposal	
Waste incineration	0,05195
Landfill	0,096682
Operational Costs – Maintenance and Personnel	
Maintenance	0,001
Personnel	0,256
Total Operational Costs	**€ 2,47 per 1 m³ of brine**
Recovered Products	
Deionised water	2,1525
Sodium chloride	0,11856
Total revenue of recovered products	**€ 2,27 per 1 m³ of brine**

Maintenance costs cover continuous maintenance as well as periodic maintenance and investments such as replacement of membranes. Investments are assumed to be depreciated linearly for a 35-year Life Cycle. Cost of staff covers the number of full-time employees (FTE) required to operate the plant and the cost reflects site and country specific conditions. Expected revenues from recovered products is included in the cost analysis and reflects primarily the market value of similar products in the market. The CAPEX inventory of the textile plant case is given in Table 9.

Table 9 – Capital costs per 1 m^3 brine levelized in the textile plant location

Equipment	Cost (€/1 m^3 brine)
Nanofiltration	0,030
Reverse Osmosis	0,029
Ion Exchange Membranes	0,007
Waste water treatment plant (upstream)	0,018
Ozonation	0,053
Total cost of Equipment	**€ 0,14 per 1 m^3 of brine**

In Table 1 – Aggregated overview of full-scale Table 10, the consolidated results are given for the ZERO BRINE system at the textile plant in Turkey

Table 10 – Consolidated results of the textile plant in Turkey

Technologies	CAPEX	OPEX	Revenue
	per 1 m^3 of brine		
Ozone oxidation Nano filtration Crystallizer Ion Exchange Reverse Osmosis	€ 0,14	€ 2,47	- €2,27

3.4 Demonstration location Spain

Industrias Químicas del Ebro (IQE) in Spain is the demonstration sites of ZERO BRINE in relation to the precipitated silica industry. Waste effluents containing high concentration of salts (saline wastewater) are treated by a concentration step with regenerated membranes followed by a crystallization step in which sodium sulphate is recovered, see Figure 5. Permeate had an adequate quality to be reused in the production process as process water and the concentrate was the one submitted to the crystallization step for the recovery of sodium sulphate. After a pre-treatment to remove Aluminium and Iron, the concentration step consisted in the use of regenerated membranes to obtain water at a suitable quality to be reused and a brine with Na_2SO_4 as concentrated as possible.

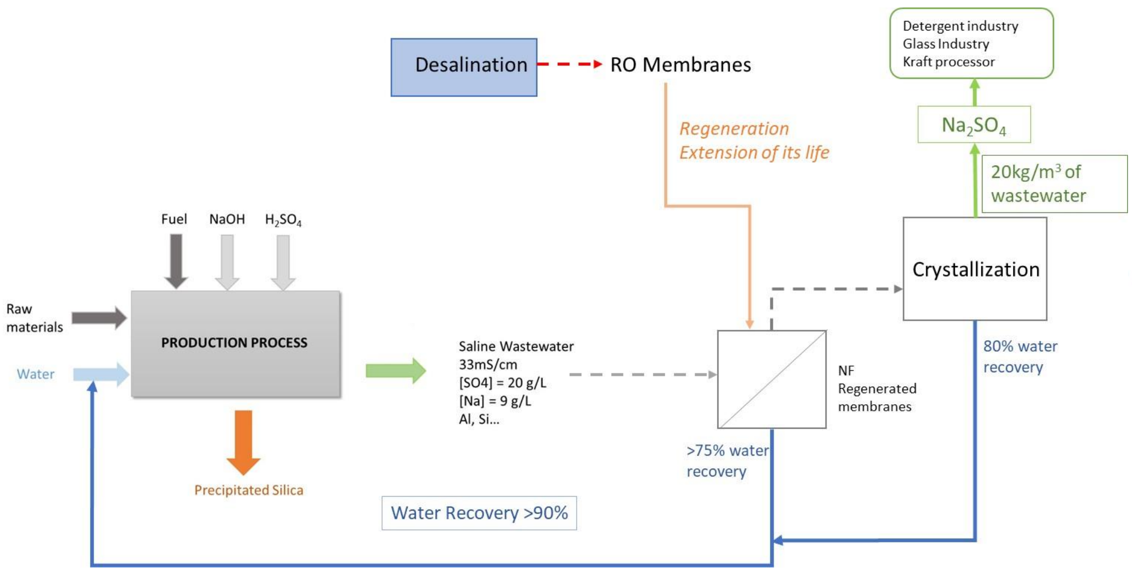

Figure 5 – Demonstration location Spain

The foreground inventory of the ZB technology has been built considering a full-scale industrial plant design to treat IQE wastewater, with a capacity of 150 m^3/h (3,600 m^3/day) and a lifespan of 35 years. This industrial plant design entails all the stages of the ZB technology explained above and in Figure 5.

Table 11 shows the chemical reagents and dosages required for the functioning of the ZEROBRINE process, as well as their costs.

Table 11 – Operational costs and revenues for the silica industry per 1 m^3 brine

Material	**Costs (€/m^3)**
Operational Costs - Consumables	
Alumina sulphate	0,00243
Calcium hydroxide	0,00889
Anionic polyelectrolyte	0,00636
Cationic polyelectrolyte	0,02629
Antifouling	0,02300
Hydrochloric acid	0,00199
NaCl/NaClO	0,00000
Deionized water	0,05518
RO membranes	0,13300
Electricity	0,83
Operational Costs – Maintenance and Personnel	
Maintenance*	0
Personnel	0,35
Total Operational Costs	**€ 1,44 per 1 m^3 of brine**
Recovered products	
Dried sludge for energy use	0,00225
Clean water	0,00000
Deionized water	0,03420
Sodium sulphate	0,98300
Total revenues of recovered products	**€ 1,02 per 1 m^3 of brine**

**The costs of performing the maintenance would fall within the personnel category, whereas the costs of replacing pieces and devices of the equipment was integrated in the capital.*

Table 12 includes a list of the capital goods (assets) and the related costs which have been considered in the inventory together with the costs of the spare parts.

Table 12 – Capital costs per 1 m^3 brine levelized in the silica industry location

Equipment	Cost (€/m^3 of brine)
Tank	0,33
Dosing hopper	
Flocculation chamber	
Settler	
Drying sludge tank	
Inert filter media	
Dosing tank	
Pipes	
Sand filter housing	
Total of cost of Equipment	**€ 0,33 per 1 m^3 of brine**

In Table 13, the consolidated results are presented of the silica plant in Spain.

Table 13 – Consolidated results of silica plant in Spain

Technologies	CAPEX	OPEX	Revenue
	per 1 m^3 of brine		
Nano filtration Crystallizer Reverse Osmosis Eutectic Freeze Crystallization Evaporator	€ 0,33	€ 1,44	- € 1,02

4 Economic assessment of the results

According to the reports on the experiments in the four demonstration locations, the following overview can be made in the overview table as presented in Chapter 2 'Methodology and approach', Table 1. The results are given in Table 14 after which the assessment is discussed.

4.1 Overview Table

In Table 14 on the next pages, economics of full-scale implementations are given, which are also discussed afterwards.

Table 14 – Economics of full scale implementation

Location	Technologies	CAPEX	OPEX *per 1 m³ of brine*	Revenue
Demineralized Water Plant – The Netherlands	1. Nano filtration 2. Crystallizer 3. Eutectic Freeze Crystallizer 4. Evaporator 5. Multi effect distillation evaporator 6. Reverse Osmosis	€ 0,31	€ 2,73	- € 1,31
Coal Mine – Poland	1. Nano filtration 2. Reverse Osmosis 3. Electro Dialysis	€ 0,13	€ 3,41	- € 3,95
Textile Factory – Turkey	1. Ozone oxidation 2. Nano filtration 3. Crystallizer 4. Ion Exchange 5. Reverse Osmosis	€ 0,14	€ 2,47	- €2,27
Silica Factory – Spain	1. Nano filtration 2. Crystallizer 3. Reverse Osmosis 4. Eutectic Freeze Crystallization 5. Evaporator	€ 0,33	€ 1,44	- € 1,02

4.2 Discussion of the overview table

In Table 14, the overview is provided for the four demonstration locations. Based on this table, the following observations can be given:

1. The ZEROBRINE systems are designed for and adapted to the specific circumstances of the demonstration locations. This shows that the approach is flexible and can be optimized for the quality requirements that are needed per location.
2. In the Dutch case, it is clear that it is impossible to find a positive business case with the ZERO BRINE system alone, there it is needed to find alternative solutions to make the system affordable.
3. In the other three cases, the LCC results already show that is possible to find a positive economic balance based on OPEX, CAPEX, and revenues. These results are not yet optimized and further research is needed the find the optimal business opportunity in these cases.
4. In the location in Turkey, the balance is almost at break even, so the recommendation is to also have a more specific look into the opportunities to find more opportunities in the nearby industry to see how the business case can be made more positive.

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5 Concluding remarks

The main objective of this report is to collect the outcomes of the four demonstration locations of ZEROBRINE, in order to do an economic assessment and to have a discussion about what the experiments have in common and how they contribute to circular economy. The main result to meet this objective is the assessment table in Chapter 4.

The technology assessment as presented in Chapter 4, shows overlaps and differences in the four demonstration locations. All locations show that a treatment configuration consisting of various technologies can deal with several types of brine water. This shows that ZERO BRINE systems have the potential to act as utility providers to different kinds of industry and also act as an intermediate between industries to make industrial symbiosis happen. The differences in outcomes also show that for each new waste water type, process designs need to be made and optimization is necessary to adapt ZERO BRINE systems to other industrial contexts. In the Dutch case, it is clear that it is impossible to find a positive business case with the ZERO BRINE system alone, there it is needed to find alternative solutions to make the system affordable. Work package 8 of ZERO BRINE discusses these opportunities. In the other three cases, the LCC results already show that is possible to find a positive economic balance based on OPEX, CAPEX, and revenues. These results are not yet optimized and further research is needed to see the find the optimal business opportunity in these cases.

In conclusion, we like to state that ZERO BRINE systems contribute to closing the cycles in chemical industry, silica industry, coal mine, and textile industry. Its system performance is dependent on the composition of the intake water and whether recovery balances increased resource use of the ZERO BRINE systems.

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