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A case in Poland

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Assessing the environmental performance of a novel coal mine brine treatment technique: A case in Poland

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ABSTRACT

Although the energy transition results in decreased use of coal for power production, hard coal extraction will continue due to its importance in steel production and coal mine wastewater will continue generating after mines closure. The coal mining sector produces wastewater which results in environmental burdens and often contains valuable materials that can be treated to eliminate effluent discharge and recover contained materials. The aim of this study is to determine whether the implementation of a novel wastewater treatment technique in an existing coal wastewater treatment plant (WWTP) can improve both environmental performance and resource recovery potential. Our study assesses for the first time the environmental performance of the WWTP of Dębieńsko at the Upper Silesian Coal Basin, in Poland because coal mine effluents need to be treated to eliminate current environmental impacts on surface water bodies (rivers). The existing wastewater treatment system comprises reverse osmosis, evaporation and crystallization technologies. In the case of the novel ZERO BRINE technique, lab performance data is scaled-up and used for nanofiltration, reverse osmosis, electrodialysis and crystallization technologies. The environmental impacts analysis is performed with life cycle assessment (LCA) by considering mid-point impact categories (climate change, terrestrial acidification and fossil resource scarcity) and end-point damages (human health, ecosystems and resources). The functional unit is 1 m^3 of coal mine wastewater input and a scenario is developed where the plant functionality concerns salt production. Results show that the implementation of the ZERO BRINE technique can improve the environmental performance of the WWTP for all considered impact categories due to a reduction in electricity consumption by 13% in the entire plant. Climate change, acidification, fossil resources scarcity, human health, ecosystems, and resources were improved by 16%, 13%, 12%, 25%, 21% and 13%, respectively. A sensitivity analysis is performed on the electricity consumption of electrodialysis which shows an additional improvement by 7% on all impacts. The ZERO BRINE technique produces both water and different types of salts. In this case, the multi-functionality of the system is addressed through substitution, while sensitivity analyses are carried out using mass and economic allocation methods.

1. Introduction

Coal has different uses, according to its quality and type, with bituminous coal being used as coking material by the metallurgy industry. Mining of coking coal is expected to remain an important activity in the future (Joint Research Centre, 2018) because it is considered a critical raw material by the EC (European Commission, 2020). Underground coal mining results in salty wastewater effluents which pollute the local aquatic environment (Krzemień et al., 2016). Therefore, it is crucial to (re)design the treatment trains of such salty wastewater effluents in the coking coal mining sector.

Coal is produced in 11 EU countries, and contributes significantly to energy security in approximately half of the member countries (Xevgenos et al., 2020). Coking coal was identified as one of the 30 critical raw materials by the European Commission (European Commission, 2020) due to its high supply risk and economic importance for the metallurgy

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industry (European Commission, 2017). As such, coking coal mining will remain an important sector in the future (Joint Research Centre, 2018). Bituminous coal is a type of hard coal that is used for producing metallurgical coke (Kato and Matsueda, 2018). The European metallurgy industry relies on domestic coking to meet 37% of its needs and accounts for 95% of coke usage (Joint Research Centre, 2018). Poland produces 95% of hard coal in the EU (Eurostat, 2020) and in the Upper Silesian Coal Basin many coal mines pump and discharge wastewater that is extremely saline, i.e. brine. In 2018, approximately 155 Mm^3 of brine were drained directly to rivers causing substantial damage to Polish water resources (Central Statistical Office of Poland, 2018). For instance, more than 4 Mt of salt are released to Vistula river which results in 100–250 M$/y losses in industry, agriculture and water transport (Jasinski and Lawton-Smith, 2018).

During coal mining, saline groundwater is pumped out to decrease the upper level of underground water and allow mine exploitation (Gombert et al., 2019). The deeper a mine operates, the more saline coal mine water is. The direct drainage of this saline groundwater stream to freshwater bodies results in their salination and poisoning, which harms the ecosystems and river life, and freshwater shortages that affect the environment and society (Krzemień et al., 2016). An underground coal mine generates approximately 3 m^3 of brine/t of produced coal (Gombert et al., 2019). Coal mines will continue generating saline water even after closure which needs to be removed to protect neighboring coal mines from water hazard and land surface from flooding. According to Gzyl et al. (2017), an environmentally safe disposal method for management of mine brine is its direct transportation to sea via pipeline when coal mines are close to the sea. On the other hand, Xevgenos et al. (2021a) presented a novel technique for a Zero Liquid Discharge system based on circular economy practices based on previous work done on sustainable brine treatment management practices (Xevgenos et al., 2015a, 2015b, 2015a), and more recent work on the environmental impacts of desalination brines (Xevgenos et al., 2021b).

Although environmental impacts of coal mining within Life Cycle Assessment (LCA) are typically embedded as background information in several systems, such as power supply and distribution, some authors have reported dedicated studies to the coal mine sector. A recent review paper from Farjana et al. (2019) identified four LCA studies of coal mining. These studies followed a cradle-to-coal mine gate approach for cases in Poland (Burchart-Korol et al., 2016), Brazil (Guimarães da Silva et al., 2018), Australia (Adiansyah et al., 2017) and China (Zhang et al., 2018), and quantified acidification, global warming and resources used indicators. Among these studies, only Adiansyah et al. (2017) considered brine within the life cycle boundaries due to coal mine tailings management, while Burchart-Korol et al. (2016) investigated global warming categories and Recipe endpoint damages of Polish coal mining. Literature regarding environmental performance assessment with LCA focusing on brine generation due to coal mining is very scarce, does not consider circularity and waste water input (in m^3) is the functional unit, except for Kim et al. (2018). Kim et al. investigated a closed forward osmosis loop to treat coal mine brine and recover clean water with respect to global warming and energy use (Kim et al., 2018). Masindi et al. assessed the sustainability of acid coal mine drainage in South Africa based on a system comprising a mixer-clarifier, a holding tank and a sludge tank which used various chemicals, such as limestone, magnesite, soda ash and CO_2 bubbling treatment (Masindi et al., 2018). These authors also modelled a scenario of a simplified sludge valorization stage with a laboratory oven to explore environmental benefits and suggest future research. Bajdur et al. assessed the environmental performance of treating pit water from a Polish coal mine with a new synthetic polyelectrolyte (Bajdur et al., 2016). Last, Xevgenos et al. (2021a) proposed an innovative design for coal mine brine treatment at the Dębieńsko's wastewater treatment plant (WWTP) in Poland primarily focused on the power consumption as a proxy performance indicator to reduce environmental burden.

In Poland a technology of coal mine water desalination is crucial for reaching goals set by National and EU regulations, such as the Water Framework Directive, and good regional water quality before and after coal mines closure. To our knowledge there is no study that assesses the environmental performance of coal mine brine treatment while focusing on critical raw materials recovery with nanofiltration (NF) and electrodialysis (ED) technologies. The aim of this study is to build on the work by Xevgenos et al. (2021a) and evaluate the environmental performance of the current design and an innovative design of Dębieńsko WWTP for brine treatment and critical raw materials recovery with LCA. With our work we aim to contribute, inter alia, in providing evidence to policy makers with view to enable a just transition in the Silesian region.

2. Methodology

This paper applies the LCA framework standardized through the ISO14040 (ISO, 2006). Simapro LCA software (Pre Consultants, 2018) and Ecoinvent LCI database (Wernet et al., 2016) were used to conduct the LCA of the current design and an innovative design of Dębieńsko WWTP. This section describes the case-study and presents the "Goal and Scope" and "Life Cycle Inventory" stages.

2.1. *Case study*

The Dębieńsko case study regards a WWTP which treats the brine of the active Budryk coal mine (see Fig. 1) at the Upper Silesian Coal Basin (USCB). This basin is characterized by the greatest number of developed and undeveloped coal deposits and large quantity of reserves of coking coal (Smakowski et al., 2011). Budryk coal mine is an underground mine that has an annual coal production of approximately 5 Mt and is located far away from the sea (see Fig. 1), as a result it is impossible to transport brine with a pipeline to the sea. The only current option is to treat brine and dispose it safely to Vistula river close by. The Dębieńsko WWTP was the first plant globally to apply a Zero Liquid Discharge system to treat coal mine brine effluents and recover clean water and saleable sodium salt. The WWTP produces up to 100 kt of salt/y (Turek et al., 2005). However, brine management and salt recovery yield can be improved from current best practice of 69% to more than 80%. Especially if such an improvement involves recovery of magnesium salt, a critical raw material for the EU (European Commission, 2020).

2.2. *Life cycle assessment*

The following section presents the "Goal and Scope" and "Life Cycle Inventory" stages.

2.2.1. *Goal and scope definition*

This LCA study aims to determine whether the implementation of novel wastewater treatment design (Xevgenos et al., 2021a) for coal mine brine can lead to lower environmental impacts than the existing treatment process design of Dębieńsko WWTP. Both designs aim to primarily treat brine and secondarily produce clean water at different stages and salt (see Fig. 2). The novel brine treatment design also produces magnesium hydroxide. The latter case leads to multifunctionality which is specifically addressed in section 2.2.3. Both designs are compared in terms of three mid-point environmental impact categories and three end-point categories. Last, recovered salt from redesigned Dębieńsko WWTP is compared with salt production with solution mining, and both systems are compared assuming their main function is to produce clean water.

2.2.1.1. Functional unit. The objective of the WWTP is to treat brine. Thus, the functional unit of the system is 1 m^3 of brine input at the plant. Having a functional unit of wastewater inputs is also reported by Brancoli and Bolton (2019) as the most typical functional unit as waste treatment systems in LCA studies. However, in order to compare

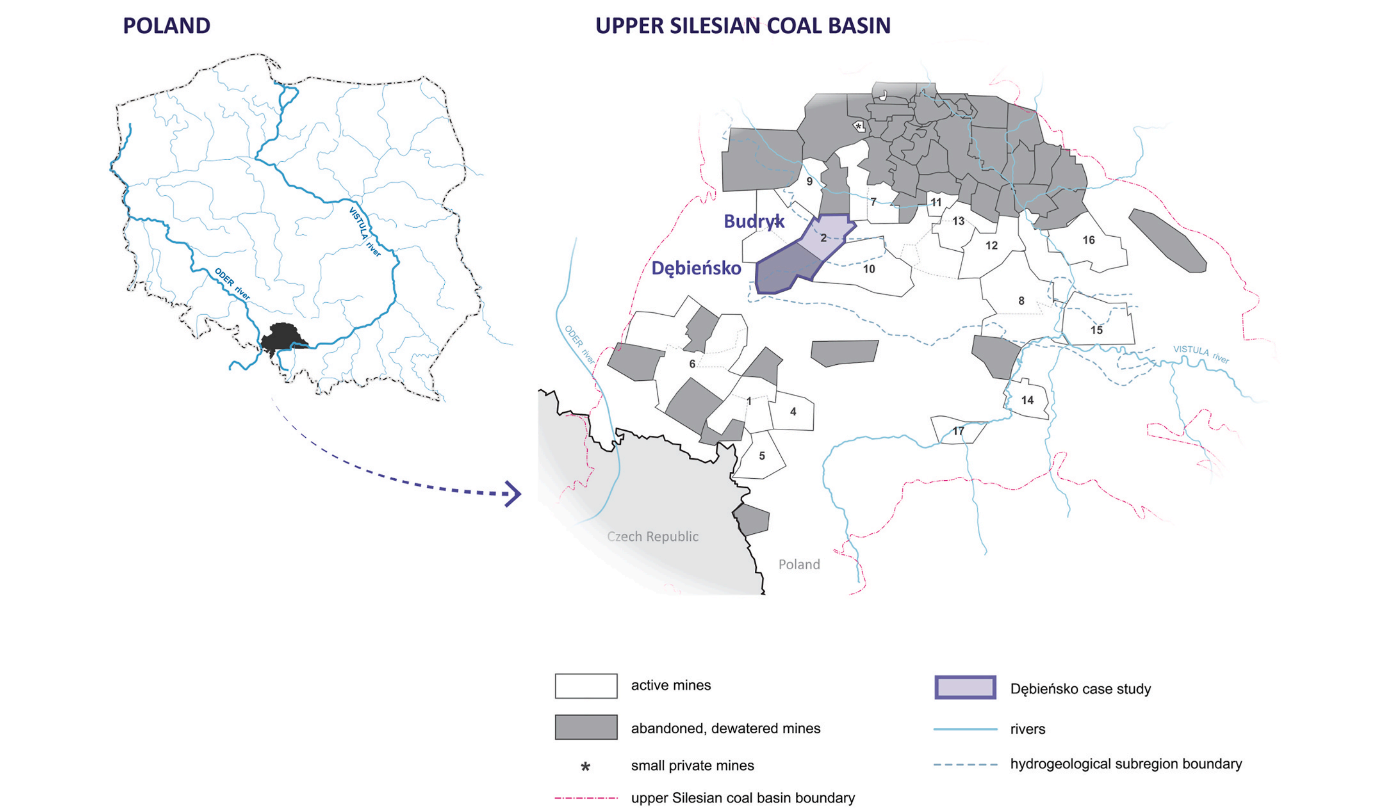

Fig. 1. Location of JSW KWK Budryk coal mine in Poland and in relation to Vistula river (Adapted from: Xevgenos et al., 2020).

secondary salt production with conventional salt production with solution mining, the discussion section will be expanded to compare the redesigned Dębieńsko WWTP with respect to 1 t of NaCl produced at the plant. Last, 1 m^3 of clean generated water was considered as an additional functional unit. In this case, generated water was the main products and co-products were treated as avoided impacts. These results can be found in the Appendix Table S3.

2.2.1.2. Allocation. Multifunctional processes exist in the redesigned WWTP because more than one product is generated. In this case, substitution method was selected to handle co-products and all environmental impacts and damages are attributed to the function of wastewater treatment. The effects of the allocation method on the LCA results was also investigated when mass and economic allocations are applied instead of substitution. Table 1 presents the allocation factors and prices of co-products which were used to calculate economic allocation factors. Output flow in mass in Tables 2 and 3 were used to calculate mass allocation factors. For mass and economic allocations, salt and magnesium hydroxide were the most desired products in comparison to water and gypsum, respectively.

2.2.1.3. System boundaries. Fig. 2 illustrates gate-to-gate system boundaries of considered systems. System boundaries comprise of upstream processes for utilities generation and chemicals production, core processes, such as WWTP stages and downstream processes, such as water discharge in Vistula river. The current (Fig. 2A) and innovative (Fig. 2B) designs of Dębieńsko WWTP are focal parts of the system boundaries which exclude coal mine operation. In the current WWTP design (see Fig. 2A), brine from the upper part of Budryk coal mine (Budryk miernie) is firstly treated with reverse osmosis (RO) to increase the content of monovalent ions in the RO retentate and produce clean water. The RO retentate is then mixed with brine from the same coal mine but from larger depth (Budryk), sodium salt is added and concentrated via evaporation. Due to evaporation, the bivalent ions content is increased in the saturated brine, as well as potential scaling threats. Thirdly, the saturated brine is treated via crystallization to produce salt, lye and gypsum. Gypsum is re-used in the coal mine as fire preventing material and lye replaces road salt in winter. Water produced from both concentration and crystallization is mixed with clean water generated in RO and disposed to Vistula river.

The innovative design (Fig. 2B) (Xevgenos et al., 2021a) will treat both types of Budryk coal mines brine simultaneously. The design is supplied by a network of innovative water technology suppliers established within the ZERO BRINE project for commercializing the project results. It employs a two-stage nanofiltration (NF) as the first step where brine is separated to permeate and a stream rich in magnesium. The objective of the first step is the largest possible reduction of bivalent ions content in the permeate by the second-stage NF. To achieve this, the applied feed pressure and recovery are 57 bar and 65% in the first stage, respectively, and 62 bar and 80% in the second stage, respectively. The NF1 retentate is treated with precipitation and crystallization for recovering gypsum, de-icing liquid and magnesium hydroxide. Precipitation is employed to mainly remove calcium in the form of gypsum and crystallization aims at removing magnesium. The crystallizer employs a water solution of dolime as alkaline reactant. Dolime is produced via calcination of dolomite, i.e. dolomite is heated at high temperatures to produce MgO, CaO and CO_2 (Jakić et al., 2016). The NF2 retentate is recirculated as feed to the first-stage NF to increase the total NF efficiency to the largest possible extent. The NF2 permeate is then processed via RO to produce RO retentate and clean water with a recovery of approximately 37%. The objective of RO is the increase of salt (NaCl) content in the RO retentate while reducing its volume. Similar to the current design, recovered water from RO is disposed safely to Vistula river. The RO retentate is treated via electrodialysis (ED) to produce ED dilute and ED concentrate. The ED dilute is recirculated to the RO to increase the recovery of clean water. The objective of ED is to concentrate the NaCl content in ED concentrate and reduce operational costs of the crystallization stage. ED concentrate is mixed with salt to produce

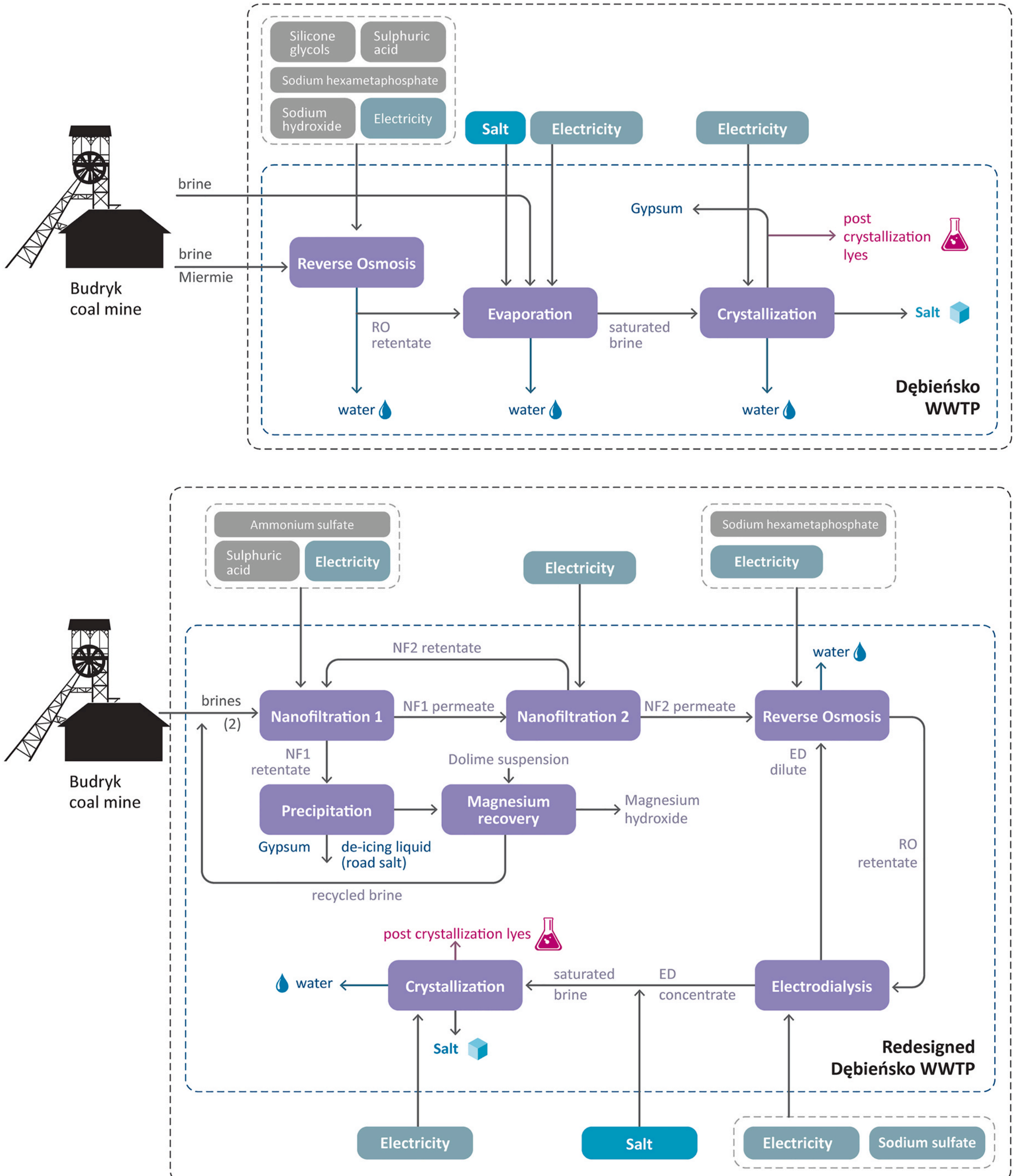

Fig. 2. System boundaries of current Dębieńsko WWTP (A) and redesigned Dębieńsko WWTP (B). Blue colored products denote background processes.

saturated brine which is fed to a crystallizer to produce high purity salt, clean water and post crystallization lyes (Turek et al., 2018). In both designs, processes consume electricity, but chemicals are also employed.

2.2.1.4. Environmental impacts. Based on literature we focused on midpoint environmental impacts of terrestrial acidification, fossil resource scarcity and climate change; and also on endpoints damages to human health, ecosystems, and consumption of resources with ReCiPe 2016 V1.02 (Huijbregts et al., 2017) which is focused on European geographic continent (Farjana et al., 2019). The goal of the ReCiPe method is to convert the long list of environmental releases to endpoint indicators of damage.

2.2.1.5. Assumptions. The following assumptions have been considered:

- The goal is to understand the relative differences between the two WWTP designs. Therefore, the cut-off rule was used for coal mine extraction. This means that no environmental footprint due to coal extraction is allocated to generated brine because it is considered a waste of mine extraction process and holds a zero financial value.
- Electricity consumption due to water pumping is considered for NF and RO (operating at high pressure) and crystallization stages (for recirculation purposes), but not for precipitation and ED processes. Pumping for precipitation is not expected because the NF1 retentate comes out under pressure. Pumping is needed for ED, however, the

Table 1
Allocation factors based on mass and economic allocations.

	Mass allocation factor	Economic allocation factor	Price (€/kg)
Magnesium recovery			
Magnesium hydroxide	0.764	0.977	1.58
Gypsum	0.236	0.023	0.12
Reverse osmosis			
RO retentate	0.63	074	0.06[a]
Water	0.37	0.26	0.0005
Crystallization			
Salt	0.221	0.97	0.057
Gypsum	0	0	0.12
Water	0.779	0.003	0.0005

[a] Based on t of NaCl in the brine.

energy consumption due to pumping is negligible in relation to the large energy consumption of ED.

- Dolime was produced via dolomite calcination in the chemical lab and energy consumption data was not possible to be collected. All products of the calcination process were calculated based on the stoichiometry of the reaction, including the generated CO_2. Dolomite production data was collected from Ecoinvent database.
- It was not clear what products the de-icing liquid and crystallization lyes can substitute and to what extent. Therefore, they were assumed to be waste without the need for treatment before disposal.
- Due to the fact that solution mining is a well-established technique and the fact that we could not find explicit data on Polish solution mining, data from solution mining by NOBIAN in the Netherlands was used (Scherpbier, 2018) in 3.3. Section.
- The environmental impact due to infrastructure construction and demolition is neglected (Herrero-Gonzalez et al., 2020).
- It was assumed that for mass and economic allocations, salt and magnesium hydroxide were the most desired products in comparison to gypsum and water. For economic allocation factors, the price of RO retentate was calculated based on its content of sodium chloride.

2.2.2. *Life Cycle Inventory*

Data collection was performed with the Ecoinvent database (Wernet et al., 2016) for secondary processes, such as utilities generation and chemicals production. The inventory of primary data was collected via scientific international literature (Turek et al., 2005; Xevgenos et al., 2021) and personal communication with the Dębieńsko plant authorities

Table 2
Life Cycle Inventory of System A - primary core processes (Based on Xevgenos et al., 2021).

Technology	Input **(units)**	Amount	Data type	Output **(units)**	Amount	Data type
Reverse osmosis	Brine miernie (m^3)	3,800	Primary	RO retentate (m^3)	2,083	Primary
	Electricity (kWh)[a]	4,410	Primary	Clean water (m^3)	1,717	Primary
	Sulphuric acid (96%) (kg)	2,478.9	Secondary			
	Sodium Hydroxide (50%) (kg)	9.3	Secondary			
	Sodium hexametaphosphate (kg)	28.3	Secondary			
	Silicone glycols (kg)	17.0	Secondary			
Evaporation	RO retentate (m^3)	2,083	Primary	Saturated brine (m^3)	874	Primary
	Budryk brine (m^3)	750	Primary	Clean water (kg)	1,959	Primary
	Electricity (kWh)[b]	86,172	Primary			
	Table salt	82,192	Primary			
Crystallization	Saturated brine (m^3)	874	Primary	Table salt (kg)	190,328	Primary
	Electricity (kWh)	45,044	Primary	Gypsum (kg)	3,710	Primary
				Water (m^3)	4,358	Primary
Total electricity consumption **(kWh/m^3 brine)**		29.8				

[a] 44 kWh per 1 m^3 of distillate 1 (Turek et al., 2005).
[b] 66 kWh per 1 m^3 of distillate 2 (Turek et al., 2005).

Table 3
Life Cycle Inventory of System B - primary core processes (Based on Xevgenos et al., 2021).

Technology	Input (units)	Amount	Data type	Output (units)	Amount	Data type
Nanofiltration 1	Budryk brine (m^3)	750	Primary	NF1 permeate (m^3)	5,535	Secondary
	Brine miernie (m^3)	3,800	Primary	NF1 retentate (m^3)	2,372	Secondary
	NF2 retentate (m^3)	1,107	Secondary			
	Recycled brine (m^3)	2,250	Secondary			
	Electricity (kWh)	10,410	Secondary			
	Sulphuric acid (96%) (kg)	1,001	Secondary			
	Ammonium sulphate (kg)	341	Secondary			
Nanofiltration 2	NF1 permeate (m^3)	5,535	Secondary	NF2 permeate (m^3)	4,428	Secondary
	Electricity (kWh)	9,821	Secondary	NF2 retentate (m^3)	1,107	Secondary
Magnesium hydroxide recovery	NF1 retentate (m^3)	2,372	Secondary	Magnesium hydroxide (kg)	11,409	Secondary
	Dolime (kg)	6,007	Secondary	Gypsum (kg)	3,530	Secondary
				De-icing liquid (m^3)	118	Secondary
				Recycled brine (m^3)	2,250	Secondary
Reverse osmosis	NF2 permeate (m^3)	4,428	Secondary	RO retentate (m^3)	6,090	Secondary
	ED dilute (m^3)	5,238	Secondary	Water (m^3)	3,576	Secondary
	Electricity (kWh)	10,207	Secondary			
	Sodium hexametaphosphate (kg)	96.7	Secondary			
Electrodialysis	RO retentate (m^3)	6,090	Secondary	ED dilute (m^3)	5,238	Secondary
	Electricity (kWh)	37,578	Secondary	ED concentrate (m^3)	852	Secondary
	Sodium sulphate (kg)	1,528	Secondary			Secondary
Crystallization	ED concentrate (m^3)	852	Secondary	Table salt (kg)	239,757	Secondary
	Electricity (kWh)	49,646	Secondary	Clean water (m^3)	846.4	Secondary
	Table salt (kg)	82,192	Secondary	Post crystallization lyes (m^3)	5.6	Secondary
Total electricity consumption (kWh/m^3 brine)		25.8				

for the current design of WWTP and process modelling for the innovative design of WWTP. Tables 2 and 3 present the Life Cycle inventories of reference system A and original system B. The inventories of background processes and co-products can be found in Supplementary Material Tables S3 and S4.

3. Results and discussion

3.1. Case study results

Fig. 3 presents midpoint and endpoint environmental impact results and how much each process stage contributes. All midpoint impact categories results can be found in Table S2 in Supplementary Material. The innovative design results in better environmental performance with respect to all impact categories than current design. It is noteworthy that all processes have proportional contributions to each impact and damage indicators, showing a strong dependence among selected categories. Two hotspots are identified, the ED and crystallization stages. Both stages consume almost 72% of the total electricity and ED employs sodium sulphate as input. Environmental benefits are expected if the Dębieńsko WWTP will be redesigned due to the reduced electricity consumption of the innovative design and (to a lesser extent) due to the recovery of secondary materials, e.g., magnesium hydroxide, salt and gypsum. Electricity is the main input of all technologies at the redesigned Dębieńsko WWTP system, especially for ED and crystallization. ED and crystallization consume approximately 31.6% and 41.8% of total electricity, respectively. Due to the fact that most of Polish electricity is generated via lignite and hard coal combustion, all environmental impact categories are dominated by electricity generation. Environmental credits due to by-products generation, such as salt, magnesium hydroxide and gypsum, are shown. Last, water use is significantly improved from -0.04 m^3 to -0.18 m^3 water for the reference and original systems, respectively. This result shows that both designs result in producing water in the life cycle, but due to original system B (novel Zero Brine technique) water production is improved by 400%. Last, changing the functional unit to 1 m^3 of generated water, and considering all other recovered materials as co-products resulted also in environmental benefits because the system boundaries and the involved processes did not change. Table S7 shows these results with the alternative functional unit.

Our results for climate change are in agreement with Masindi et al. (2018), Bajdur et al. (2016) and Kim et al. (2018). Masindi et al. (2018) presented a carbon footprint of 29.6 kg CO_2 eq. which is close to the 25.1 kg CO_2 eq. for the current design of Dębieńsko WWTP and both studies identified electricity as the main contributor to climate change. Electricity consumption is almost double our study (29.8 kWh/m^3 brine) than the 12.9 kWh/m^3 brine of South African electricity mix which is consumed by primary processes for pumping and propelling. Bajdur et al. (2016) presented only relative contribution of inputs to the total environmental impact, and concluded that Polish electricity has the largest negative environmental impact on treatment of coal mine pit water. Kim et al. (2018) concluded that electricity use was the main contributor to carbon footprint, but forward osmosis membrane material was contributing significantly. Last, Adiansyah et al. investigated coal mine tailings management strategies and concluded that the largest contributor of climate change is electricity and black coal (Adiansyah et al., 2017).

To put our results in perspective for the coal mining sector, it is important to show the carbon footprint of 1 t of coal production with 3 m^3 of brine generated and treated with the novel ZERO BINE technique. Burchart-Korol et al. (2016), Zhang et al. (2018) and Guimarães da Silva et al. (Guimarães da Silva et al., 2018) calculated a carbon footprint of 185 kg CO_2 eq. per t of coal in an underground Polish mine, 73.3 kg CO_2 eq. per t of coal in an opencast Chinese mine, 32.9 kg CO_2 eq. per t of coal in an surface Brazilian mine, respectively. 3 m^3 of treated brine result in 63.6 kg CO_2 eq., which means that avoiding environmental pollution and recovering materials with the novel ZERO BINE technique can increase the carbon footprint of coal mining by 34–193%.

3.2. Sensitivity analysis of uncertain parameters

3.2.1. Effect of upscaling technologies

A sensitivity analysis is performed with respect to ED and crystallization stages because electricity consumption at electrodialysis was decreased by 20% in lab scale experiments (but this was not considered in our study) and crystallization stage is an environmental hotspot. Fig. 4 shows that sensitivity analysis results in a maximum relative decrease of 14–16%. A lower ED power consumption results in

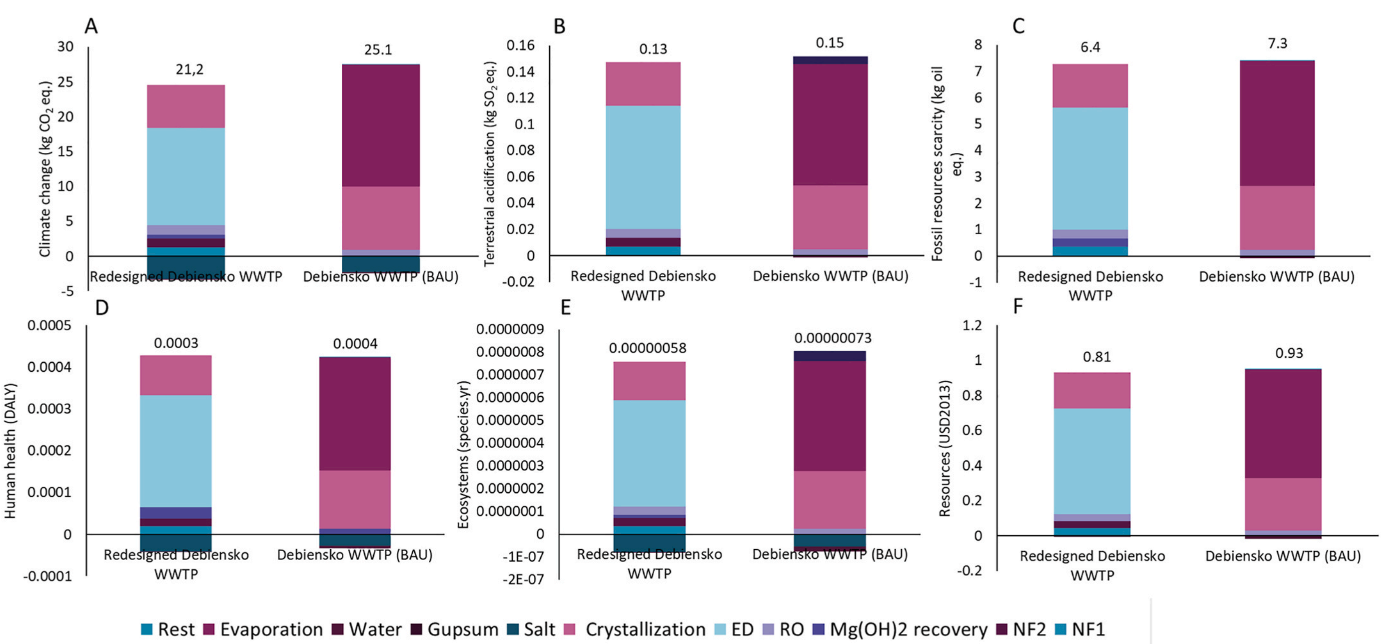

Fig. 3. Midpoint (upper side) and endpoint (lower side) LCA results of considered systems of System A and B, A: Climate change, B: terrestrial acidification, C: Fossil resources scarcity, D: Human health, E: Ecosystems and F: Resources.

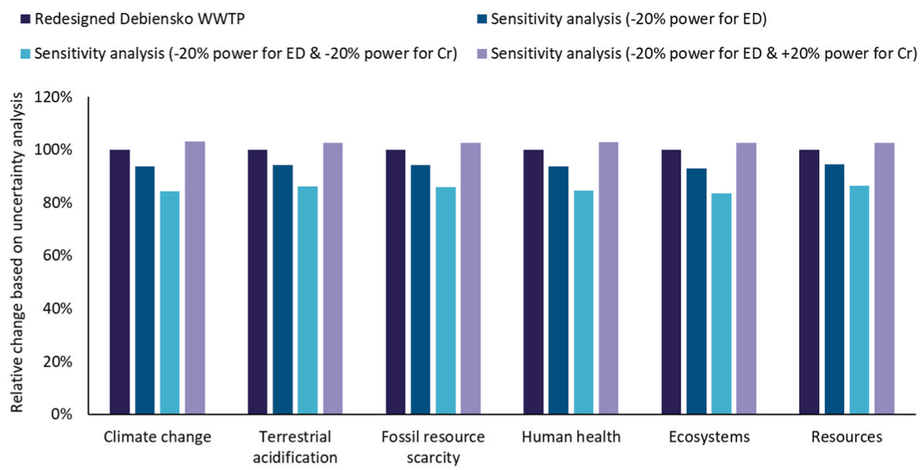

Fig. 4. Sensitivity analysis for electrodialysis and crystallization stages.

decreasing all environmental and damage indicators by approximately 7%. Even though the power reduction is 20%, other parameters are contributing to the results, such as consumption of sodium sulphate at the ED stage. Furthermore, a combined electricity decrease of ED and crystallization results in decreasing further environmental burdens but an increase in crystallization stage would counter the lower ED electricity decrease and result in increasing all environmental burdens and damages by 2.5–3.2%.

3.2.2. Effect of allocation type

Fig. 5 shows the effect of allocation types. The redesigned Dębieńsko WWTP system was modelled with substitution, and mass and economic allocations were compared with it. Mass allocation results in very low environmental impacts and damages because the amount of recovered water is disproportionally larger than recovered solid products. In contrast, when economic allocation is applied, the price of magnesium hydroxide and salt is much larger than water price resulting in larger Climate change, Human health and Ecosystems scores. This happens mainly because the absence of the avoided emissions (credits due to substitution) for magnesium hydroxide and salt. On the other hand, terrestrial acidification, fossil resources scarcity and resources scores are smaller than Redesigned Dębieńsko WWTP system due to the allocation factors at the RO stage (see Table 1). These allocation factors result in reducing the considered impacts by half.

3.3. Recovered salt and comparison with virgin salt extraction

Fig. 6 shows the comparison between salt production from underground solution mining and salt recovery at the redesigned Dębieńsko WWTP. Conventional salt production results in lower environmental burdens, except for Human health damage indicator. The latter happens due to the contribution of barium carbonate that is used for the production of barium chloride to all endpoint indicators (see Fig. S1 in Supplementary Material). Barium chloride is used during the brine purification stage of conventional salt production. Barium carbonate is contributing to all indicators that contribute to Human health, and especially to human non-carcinogenic toxicity indicator which is the largest contributor to Human health. All midpoint impact categories can be found in Table S3 in Supplementary Material.

It should be stressed that coal mine brine is more diluted than the brine treated through solution mining to produce salt. To produce the same amount of salt, more energy is consumed when a more diluted brine is employed. However, one should consider that the coal mine effluent needs to be properly treated to eliminate its environmental impacts on the receiving water bodies (Vistula and Oder rivers). The recovery of salts should then be seen as an additional environmental benefit which so far had not been quantified in the literature. With our work, we quantified the environmental impacts of the (linear) salt production technique. We argue that these should be considered as indirect environmental savings, when coal mine effluent treatment is required.

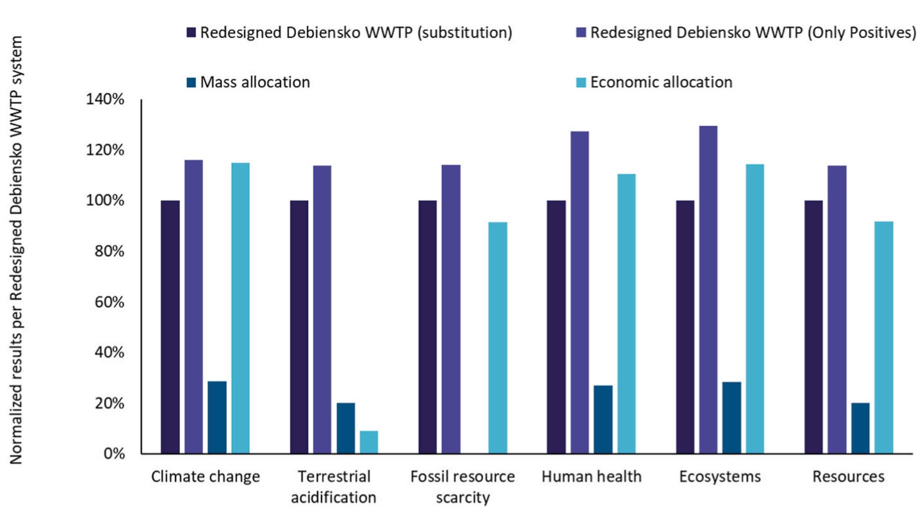

Fig. 5. Sensitivity analysis due to allocation method.

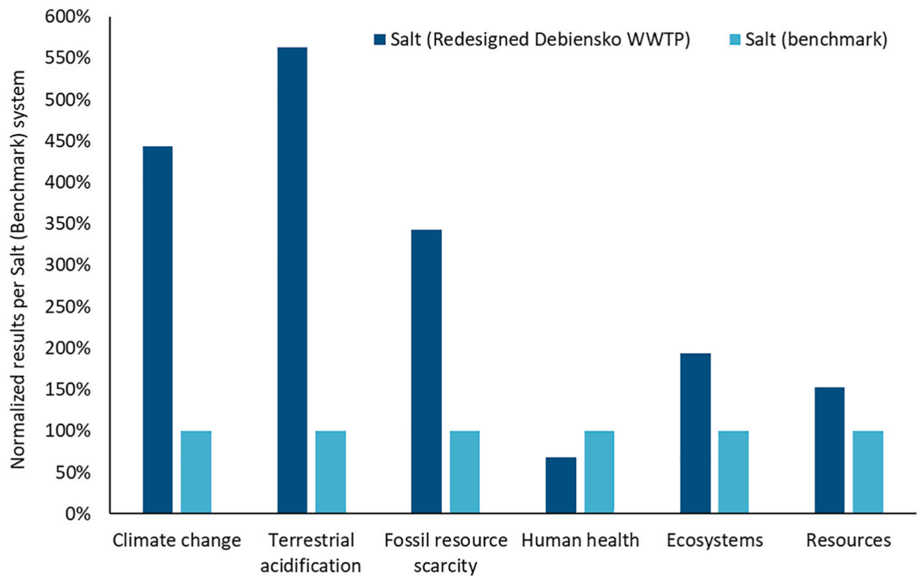

Fig. 6. Comparison between Salt (benchmark) and Salt (redesigned Dębieńsko WWTP) with 1 t of salt as functional unit.

Last, depletion of scarce materials, such as magnesium, is not covered by abiotic depletion potential category of impact models (Berger et al., 2020) and this is one of the drivers for redesigning the Dębieńsko WWTP.

4. Limitations

A major limitation of our study is the source of foreground data for the redesigned Dębieńsko WWTP system. This data derived from a model based on a pilot consisting of the same technologies (NF, ED, etc.) but with another Polish coal mine brine. This can result in a slightly different process efficiency due to the brine source but higher process energy efficiency is expected on industrial scale. We aimed to address the process energy efficiency variability with the uncertainty analysis for the ED stage. Another limitation is the lack of electricity consumption data for dolime production. Such data would contribute to the redesigned Dębieńsko WWTP system and result in increasing terrestrial acidification, fossil resource scarcity, ecosystems and resources. Especially, if dolime is produced in countries with fossil-based electricity production, such as Poland. Last, we did not consider in our study the replacement of membranes in NF and RO stages. Typically, infrastructure contributes to a small extent in LCA results of process industry systems, but it is still uncertain how much replacing membranes every 10–15 years would affect the LCA results.

5. Conclusions

The aim of this study was to evaluate the environmental performance of the current design and an innovative design of Dębieńsko WWTP for recovering clean water, critical raw materials and reducing electricity consumption with LCA. The results of this study are useful to operating and closed underground coal mines because they produce saline wastewater results in salination and poisoning of ecosystems and river life, and freshwater shortages that affect the environment and society.

Redesigning Dębieńsko WWTP resulted in environmental benefits for all considered impacts and damages mainly due to the reduction in electricity consumption per brine input and, to a lesser extent, due to improving brine management, and salt recovery yield from 69% to more than 80%. Furthermore, the new design can be further improved if one focuses on reducing electricity consumption of ED and crystallization stages, and sodium sulphate consumption of ED stage. Secondary salt, clean water, and a critical raw material (magnesium) were recovered and did not leak out from economy. The recovered solid products provide a circular perspective of treating Polish coal mine wastewater but future steps need to include either a substantial electricity consumption reduction or "greening" the Polish electricity mix in order to become environmentally competitive with conventional salt production.

CRediT authorship contribution statement

G.A. Tsalidis: Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **K. Panteleaki Tourkodimitri:** Writing – review & editing. **K. Mitko:** Writing – review & editing, Resources. **G. Gzyl:** Writing – original draft, Writing – review & editing. **A. Skalny:** Writing – review & editing. **J.A. Posada:** Methodology, Writing – review & editing. **D. Xevgenos:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.131973.

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