Redesigning the coal mine wastewater treatment to enable transition to circular economy practices: the ZERO BRINE and Dębieńsko case studies

D. Xevgenos[1, 3,*], G. Gzyl[2], K. Panteleaki Tourkodimitri[3], K. Mitko[4], G. A. Tsalidis[3], A. Skalny[2], M. Mortou[3], D. Sapoutzi[3], M. Turek[4]
[1]Faculty of Applied Sciences, Delft University of Technology, Delft, The Netherlands, [2]Central Mining Institute, Katowice, Poland, [3]SEALEAU, The Netherlands, [4]Silesian University of Technology, Poland

*Corresponding Author: e–mail: d.xevgenos@tudelft.nl / d.xevgenos@sealeau.com

ABSTRACT

Poland delivers high value to the EU as it is by far the largest coal producer. However, coal production comes with a high environmental cost at regional (or even national) level. The exploitation of hard coal mines leads to the generation of vast amounts of salty wastewater effluents (brines) which have severe environmental impacts. Currently, there are 18 hard coal mines in Poland, owned and operated by 5 coal mine companies, while several abandoned mines need still to be pumped to avoid flooding risks. The total mine water discharge in the Upper Silesian Coal Basin (USCB) is around 350,000 m^3/day, with the amount of chlorides and sulphates discharged to the rivers being approximately 4,000 tons/day. Brines from these mines are typically discharged into tributaries of the upper Wisła (Vistula) and upper Odra (Oder) rivers causing environmental and economic impacts.

The Dębieńsko wastewater treatment plant is treating brines from two coals mines leading to Zero Liquid Discharge (ZLD) as well as salt recovery since the '80s. However, its main drawback is the extremely high energy consumption (approx. 720 kWh/t of salt recovered), which has a high impact on the business viability and financial outcome. The aim of this work is to re-design the value proposition of the coal mine wastewater sector towards a Sustainable Business Model based on circular economy principles. To do so, we evaluate a novel coal mine brine treatment system that was demonstrated within the EU-funded project called ZERO BRINE, targeting higher salt recovery yields, improved energy efficiency, while achieving environmental and economic benefits. For this purpose, technologies such as ultrafiltration, nanofiltration, reverse osmosis, electrodialysis, crystallization and evaporation were tested. Our results showed that improving energy efficiency and environmental performance is possible. The new plant design offers the opportunity to recover salt, pure water, gypsum and magnesium hydroxide and its energy efficiency of Dębieńsko plant is improved by approx. 30% (approx. 500 kWh/t of salt recovered). Coal mines located within the hydrogeological subregion boundary (e.g. Bolesław Śmiały, Knurów-Szczygłowice, Piast-Ziemowit, Mysłowice-Wesoła, Janina, Silesia) show good potential for replicability of the Dębieńsko circular economy approach. This will be further investigated together with the coal mine industries operating these mines. Policy tools, most importantly the Just Transition Fund and the Structural & Cohesion funds, can play a crucial role in paving the right way of the most affected regions towards energy transition and carbon neutrality.

KEYWORDS

Coal mine wastewater; Brine treatment; Circular Economy; Design for Sustainability; Resource Recovery; Water; Salts; Just Transition, Sustainable Business Models.

1 INTRODUCTION

Background problem

Coal mines comprise an important sector in the EU. The European Union is the world's sixth largest producer (see also Table 1) and the fourth largest coal consuming region, after China, India and the United States of America. The total hard coal production in Europe in 2019 was 67 million tons. Poland is the dominant European hard coal producer accounting for approx. 92% (or 61.6 million tons) of the production in EU-28 (Figure 1), followed by Czech Republic with 5% (or 3.4 million tons) and UK with 3% (or 2.2 million tons). In the wider area of Europe, Ukraine comprises also a significant hard coal producer with 25.5 million tons produced in 2018. If brown coal is also considered, the list of producing countries is further enlarged to include Germany, Serbia, Greece, Bulgaria, Hungary, Romania Slovenia and Slovakia. Overall, coal is produced in 11 EU countries while it continues to make a major contribution to energy security in approximately half of the member countries (EURACOAL, 2020). Further, coking coal has been identified as one of the 30 critical raw materials for 2020 by the European Commission (EC), since the supply risk is high, linked to high concentration of supply in China and Australia and because its economic importance is calculated as high due to use in the metallurgy sector (European Commission, 2020). In 2018, the EU consumption of coking coal was 49 million tons (Eurostat, 2019). Base metal production (metallurgical sector) accounts for approx. 95% of the total coking coal consumption. The remaining 5% is used for other applications such as alumina refineries, paper manufacturing, and the chemical and pharmaceutical industries. As a result, even though the energy-related uses of coal will soon phase-out, the metallurgical coking coal needs will remain as it is essential for the iron and steel industry. Furthermore, the hard coal mines capable of producing this type of coal will continue to operate purely by serving this sector (Dias et al., 2018). According to EURACOAL (2020) countries that benefit from their own indigenous coal and lignite resources like Poland and Greece are more dependent on coal. In these countries, the energy transition will take longer than in other EU countries.

Poland delivers high value to the EU because it is by far the largest coal producer. However, coal production comes with a high environmental cost at regional (or even national) level. The exploitation of hard coal mines leads to the generation of vast amounts of salty wastewater effluents (brines) which have severe environmental impacts. Currently, there are 18 hard coal mines in Poland, owned and operated by 5 coal mine companies, while several abandoned mines need still to be pumped to avoid flooding risks. The total mine water discharge in the Upper Silesian Coal Basin (USCB) is around 350,000 m^3/day, with the amount of chlorides and sulphates discharged to the rivers being approximately 4,000 tons/day. Brines from these mines are typically discharged into tributaries of the upper Wisła (Vistula) and upper Odra (Oder) rivers causing environmental and economic impacts (Strozik, 2017). The high salinity of the river water makes it often unfit to be used as drinking water, agricultural or industrial water. More recent scientific papers have been published by the Polish Central Mining Institute, presenting the occurrence and quality of the mine water in the USCB area (Janson, 2008; Bondaruk, 2015; Gzyl, 2017).

This problem is known at least since the 1980s when the large environmental project of the "Debiensko" desalination plant started (Sikora et al, 1989) with the aim to eliminate the coal mine discharges generated by Budryk and Debiensko coal mines. Since then, the operation of the "Debiensko" desalination plant has changed, receiving nowadays only coal mine water from the Budryk coal mine. The main drawback is the extremely high energy consumption (approx. 955 kWh/t of salt recovered), which has a high impact on the business viability and financial outcome.

Table 1. *World's largest coal producing (top) and coal consuming (bottom) countries (2018) (EURACOAL, 2020)*

	Country	Coking coal (Mt)	Steam coal (Mt)	Lignite (Mt)	Total (Mt)
1	China	3026.4	523.7	-	3550.1
2	India	676.4	49.2	45.3	770.9
3	United States	561.7	71.9	51.7	685.4
4	Indonesia	543.0	5.6	-	548.6
5	Australia	257.8	179.4	46.0	483.1
6	EU-28	15.5	60.2	366.9	442.6
7	Russia	245.4	93.0	81.4	419.8
8	South Africa	254.2	4.4	-	258.7
9	Kazakhstan	96.4	10.8	6.4	113.7
10	Turkey	1.9	0.7	85.2	87.8
	others	298.1	34.4	120.3	452.6
	World	5976.8	1033.3	803.2	7813.3

	Country	Coking coal (Mt)	Steam coal (Mt)	Lignite (Mt)	Total (Mt)
1	China	587.4	3157.8	-	3745.1
2	India	97.4	842.3	45.3	985.0
3	United States	16.7	545.4	52.4	614.5
4	EU-28	55.0	175.9	368.6	599.6
5	Russia	64.5	93.4	73.8	231.7
6	South Africa	3.3	186.1	-	189.4
7	Japan	46.7	139.3	-	186.0
8	South Korea	36.9	106.9	-	143.8
9	Turkey	7.7	33.1	84.9	125.7
10	Indonesia	7.5	107.6	-	115.1
	others	69.0	547.8	168.5	785.3
	World	992.1	5935.6	793.5	7721.2

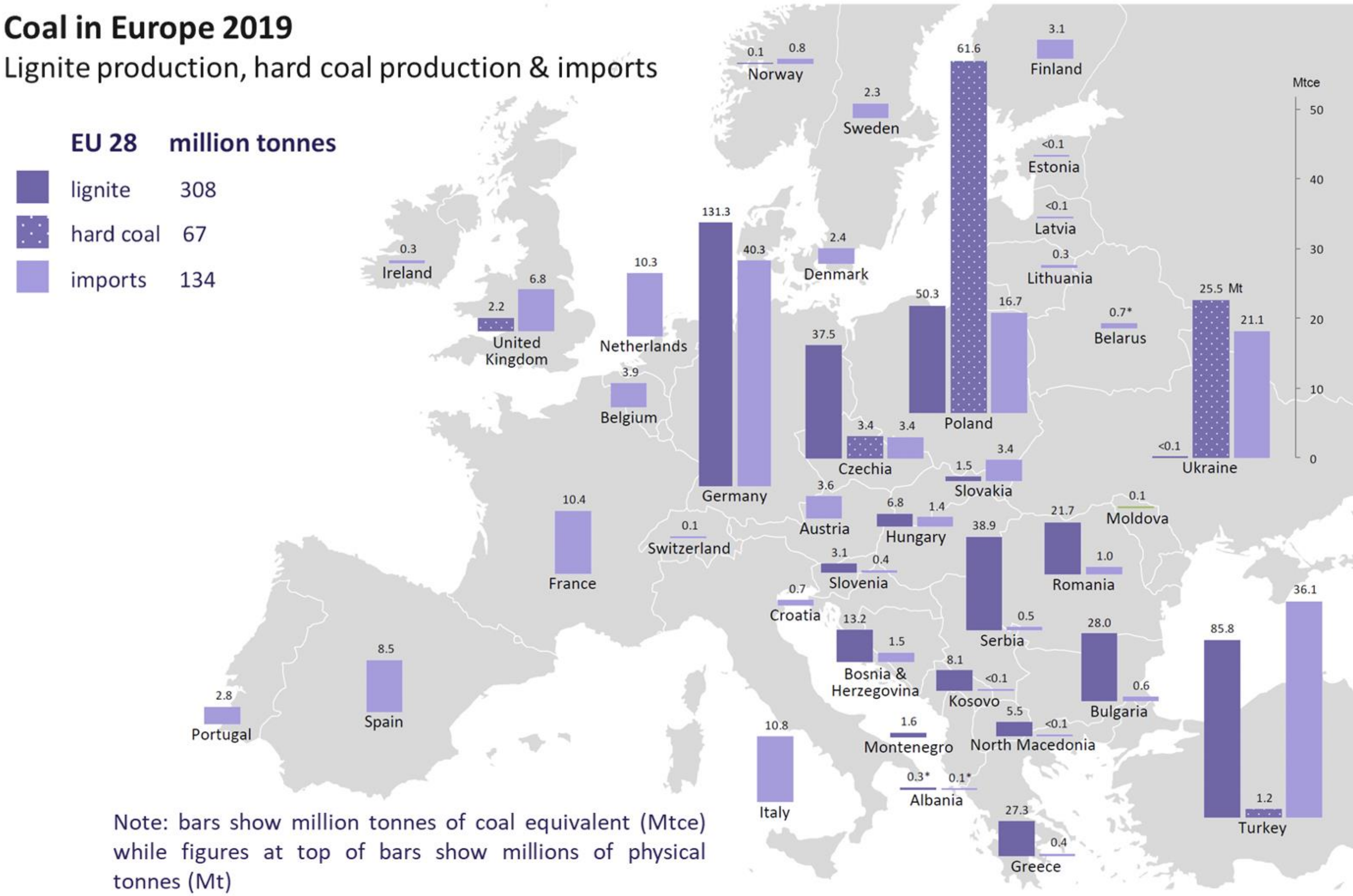


Figure 1. *Hard coal and lignite production in Europe (2019 data) (EURACOAL, 2020)*

Literature Review

The ZLD technology was evolved in the US, in the '70s and later grew globally. It normally comprises an electrically-driven evaporator and crystallizer which results in high energy consumption and thus high OPEX and is very capital intensive. According to Global Water Intelligence (GWI, 2016), 258 ZLD projects were implemented in the period 2000 - 2015 (total installed capacity: 932,000 m^3/d), with General Electric representing 56% (or 146 projects) of the market, followed by Veolia (24%) and Aquatec (10%). What is more, ZLD systems create significant volumes of a solid by-product that must be inevitably disposed of in a landfill, creating again a waste management problem.

In the coal mining sector, the first ZLD application of this technology dates back to 1993 in Dębieńsko, Poland. This plant operates since 1994. Yet very little reading scientific material is being made available in international languages, thus being largely ignored by the international scientific community. A thorough description of the "Dębieńsko case" is presented by Masarczyk et al. (1989) and Ericsson and Hallmans (1996). There are also a couple of publications within the grey literature about this case study published by General Electric Water (acquired later on by Suez), which were the technology suppliers. The ZLD system installed had the capacity to treat 12,000 m^3/day and its cost was approx. US$ 60 million. Its main drawback is the extremely high energy consumption (~970 kWh/t of salt recovered), which made the business not viable. The project has been halted countless times due to lack of funds. In recent years, money has come from the Polish environmental fund, which is made up of fines imposed upon polluting industry, including the coal mines. The authors have contacted the system operators in Poland, and they have confirmed that the energy consumption should be halved in order to make the business case sustainable.

Theoretical studies and laboratory tests performed at the Silesian University of Technology have shown that energy consumption can be significantly reduced by using membrane methods or their combination with the evaporation method instead of the evaporation method alone. ED-EDR electrodialytic pre-treatment and pre-concentration of coal-mine brine with 32.8 g/L Cl^- content at a current density of 344–688 A/m^2 in the first step and 300 A/m^2 in the second shows energy consumption in the range for 9.4–14.4 kWh/m3 of inlet brine depending on applied current density. The performance of crystallization step was then estimated based on chemical compositions of ED concentrates and compared with data from the ''Debiensko'' Plant, where currently a salt crystallizer is supplied with brine concentrated by RCC evaporation method. This comparison shows that unit energy consumption decreases from ca 970 kWh per 1 ton of evaporated salt for brine treated by RCC method to 610 kWh/t in the case of ED-EDR treated brine. At the same time the amount of salt in lye decreases from 110 kg per 1 ton of evaporated salt produced to 20 kg/t (Turek et al, 2005). To decrease the energy consumption and increase the salt recovery of the existing plant, the application of membrane processes – nanofiltration (NF), reverse osmosis (RO), electrodialysis (ED) – and chemical treatment was proposed. Based on the laboratory results, a hybrid NF-ED-RO system was designed, and the plant performance and the scaling risk were discussed. The result shows, that application of mentioned membrane system could decrease the energy consumption to 425 kWh per 1 ton of evaporated salt (Turek et al, 2017). To obtain higher concentration of sodium chloride than in reverse osmosis (RO), the hybrid RO–nanofiltration (NF) system was considered. The use of RO retentate pressure as a driving force in NF decreased the energy consumption in the brine concentration process and increased RO permeate recovery. In such a hybrid system, NF could be regarded as an alternative method of energy recovery. NF membranes were tested on the synthetic sodium chloride solution, and on the coal-mine brine RO retentate. Based on the obtained results, energy consumption in RO–NF–vapour compression (VC) system was estimated and compared with the RO–VC system. The energy consumption in the RO–NF hybrid system with VC (123.3 kWh/m3 of brine with 290 g/dm3 NaCl) was lower than in the currently used RO–VC system (213.2 kWh/m3 of brine with 290 g/dm3 NaCl without energy recovery and 204.6 kWh/m3 of brine with 290 g/dm3 NaCl with energy recovery) (Laskowska et al, 2018).

Research gap and aims of the present research work

The main objective that this research work has is to answer to the research question of "*How the coal mine sector value proposition can be redesigned towards a Sustainable Business Model based on circular economy principles*". This research work presents selected results from the ZERO BRINE project related to the demonstration of innovative brine treatment technologies that were used to treat coal mine wastewater. Within this project, a pilot-scale brine treatment system was developed and demonstrated in Poland using real coal mine wastewater sourced by the Bolesław Śmiały coal mine that is located in the Upper Silesian Region.

The paper is also addressed to the policy-makers community, and in particular the community related to the Just Transition Mechanism (JTM) policy that has been established in the context of the European Green Deal to "ensure that the transition towards a climate-neutral economy happens in a fair way, leaving no one behind." The JTM, with a budget of at least €150 billion over the period 2021-2027, is an important tool to help the coal mine regions that are the most affected to redirect into a more sustainable path, aligned with the new policies adopted. With our work, we are establishing an update on the current status quo of the sole coal mine case that implements a circular economy approach in Europe, that is the "Dębieńsko desalination plant" and we connect this with the advances proposed based on the project results achieved within ZERO BRINE project. Further work is currently being done to extrapolate the pilot-scale data to full-scale implementation for the case of "Dębieńsko desalination plant" using a powerful software platform that was developed by the German Aerospace Center (DLR) within ZERO BRINE project. This work is not part of this conference paper.

2 METHODS

This work revolved around the ZERO BRINE (zerobrine.eu) project which aims at facilitating the implementation of the Circular Economy package and the SPIRE Roadmap in various process industries by developing the necessary concepts, technological solutions and business models to redesign the value and supply chains of minerals. The project involves four large scale demonstrations in the Netherlands, Spain, Turkey and Poland, while this work presents findings related to the demonstration in Poland that relates to the coal mines wastewater treatment.

The research methodology for the present work is based on the following steps.

First, a **recording of the operating coal mines** in Poland is made. Within the last years, a lot of mines in Poland are being shut down as they are no longer competitive. In order to identify the operating coal mines currently in Poland, first, a literature review was made, while further validation was made using the central Geological Database (Centralna Baza Danych Geologicznych or CBDG in short) (Layer: Obszary górnicze)[1] and finally through personal communication with Polish Central Mining Institute (GIG) experts.

[1] http://bazagis.pgi.gov.pl/website/cbdg/viewer.htm

The second step is the **identification and evaluation of success stories** on following circular economy practices in the coal mine sector. The coal mines that are still operating in Poland, identified in Step 1, are being assessed regarding the treatment of the wastewater generated in view of circular economy and in particular, in view of resource recovery from the brine effluent generated.

The third step was the **technical evaluation of the identified success story** (Dębieńsko desalination plant) in order to (a) identify lessons learnt from the 20-year operation period & challenges that may hinder adoption this solution at a wider scale; and (b) **suggest improvements** on technical, economic and environmental terms in light of the ZERO BRINE results.

As one of the main purposes of this paper is to come up with a sustainable business model for the coal mine sector, in this **fourth and final step** we integrate the outcomes of the previous steps into developing a circular business model for the sector in question. With the ultimate goal of enabling a potential wider deployment of such a model, we incorporate the interests and needs of key stakeholders by forming a "Community of Practice" (CoP). The CoP involves the key stakeholders, such as technology suppliers, regulators, investors and policy makers. We also try to leverage on current policy developments, most importantly the Just Transition Mechanism. The first results from the validation of the proposed Circular Business Model are presented in this paper.

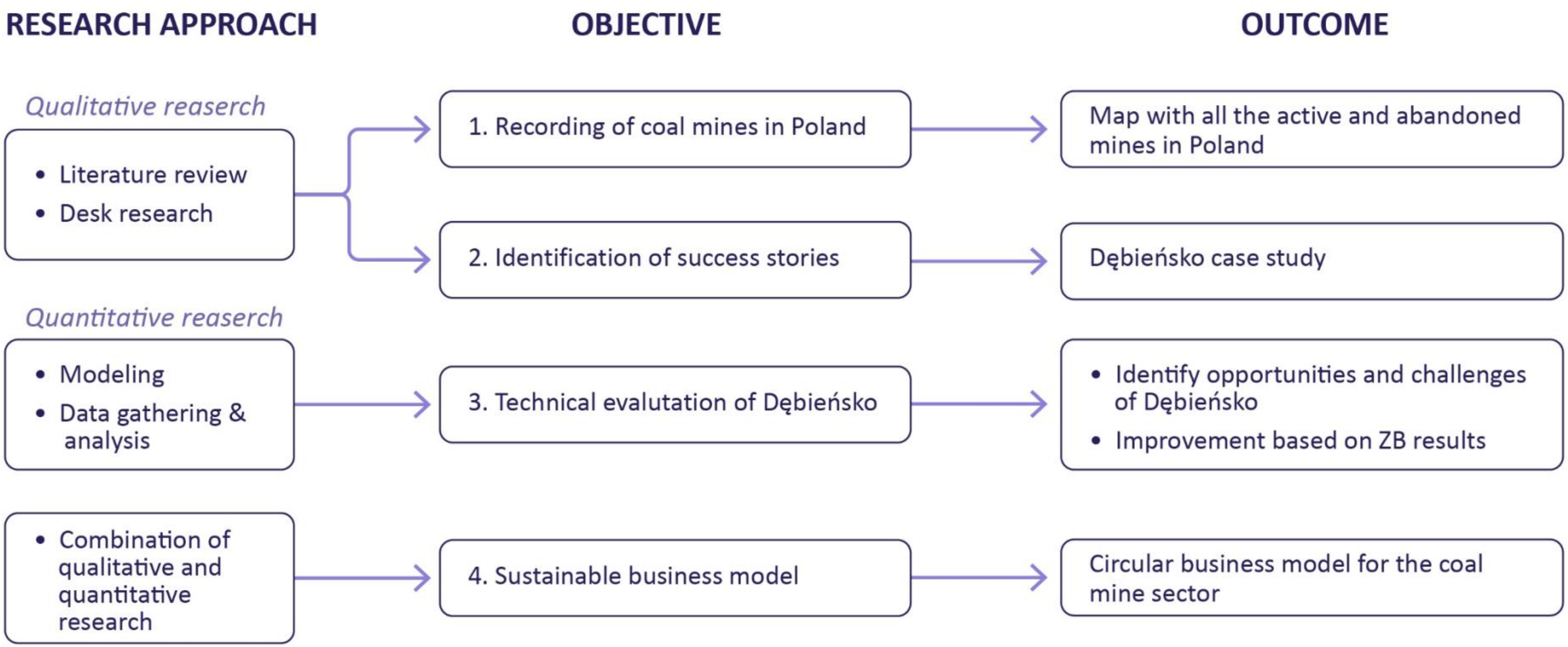


Figure 2. *Research Flow Diagram*

3 RESULTS & DISCUSSION

In this paper we present the results from the literature review related to the recording of active and abandoned mines in Poland (Section 3.1), the results from the identified success story called "Dębieńsko desalination plant" (Section 3.2) and results from the evaluation of this case study, in light also of the results from ZERO BRINE project (Section 3.3). At the end of this section, we present selected results from the proposed Sustainable Business Model for the coal mine sector (Section 3.4)

3.1 Results on the recording of active and abandonned coal mines in Poland

Poland hosts the largest number of coal mines, followed by Czech Republic. In 2019, 61.6 out of the 67 million tons were produced in Poland (see also Figure 1). The exploitable hard coal reserves are concentrated in two regions, namely Upper Silesia Coal Basin (USCB) and in the Lublin Basin at the eastern part of Poland (see also Figure 3), with the USCB hard coal reserves accounting for 78.9% of the total (EURACOAL, 2020). There are some hard coal deposits in the Lower Silesian Coal Basin, but their exploitation has stopped since the 90's.

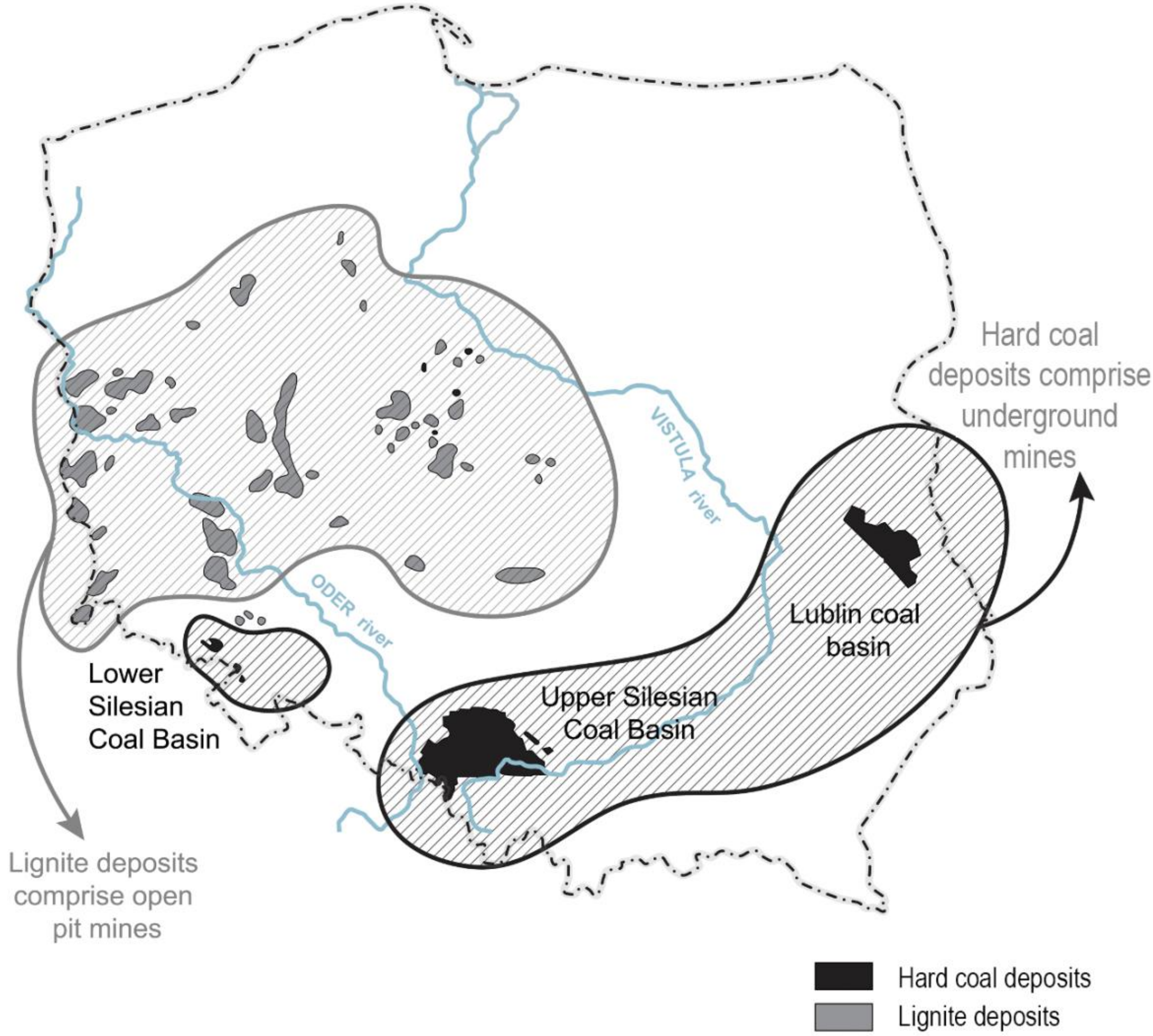


Figure 3. *Hard coal and lignite deposits in Poland (Adapted from Musial et al., 2016)*

There are approx. 400 coal seams at USCB and Lublin basin, with almost half of them being economically workable. The lignite mines are located in the western part of the country. All lignite mines are open pit mines, as such their exploitation does not generate wastewater effluent. On contrary, all bituminous (hard) coal mines comprise underground mines (average working depth: 600 meters, with some over 1,000 meters); their exploitation generates salty wastewater effluents (brines); the discharge of which causes environmental degradation of the receiving water bodies.

With reference to the coal production in Poland, there is a clear downward trend from approx. 131,400 thousand tons produced in 1993 to approx. 61,500 thousand tons in 2019. The data for coal production in Poland between 1993 and 2018 both in physical tons and tons of oil equivalent are provided in Figure 4. Through exponential regression we estimated the following equation (with R-squared value: 95.2%):

$$y = 140{,}080 \cdot e^{-0.0308 \cdot x}$$

Using the above equation, we may estimate by extrapolation the coal production to approx. 43,000 thousand tons by 2030 and to approx. 23,530 by 2050. What is especially important in the aspect of the European Green Deal willing to make Europe climate-neutral by 2050.

Figure 4. *Hard coal production in Poland in physical tons (left axis) and tons of oil equivalent (right axis) (1993 – 2019)*

With reference to the coal consumption, industry and the residential sector account for the largest share. For example, in 2017 the residential sector consumed 6,554 ktoe accounting for approx. 55.7% of total coal consumption in Poland, followed by the industrial sector with 3,584 ktoe (or 30.4%), the agriculture & forestry with 969 ktoe (8.2%) and the commercial & public services sector with 668 ktoe (5.7%) (IEA, 2017).

With reference to the coal consumption by type, other hard coal represents by far the largest share of the domestic consumption in Poland. In 2017, 10,521 ktoe of other hard coal were consumed in Poland accounting for approx. 90.7% of total domestic coal consumption, followed by coke even coke with 532 ktoe (or 4.6%), blast furnace gas with 269 ktoe (or 2.3%), anthracite with 148 ktoe (or 1.3%), lignite with 116 ktoe (or 1%) and patent fuel, BKB and coking coal accounting for the remaining 20 ktoe (or 0.2%) (IEA, 2020)

The coal reserves by different type are as follows: hard coal approx. 22.3 billion tons and lignite reserves around 1 billion tons, with a further 61.4 billion tons and 2.3.3 billion tons in resources respectively. With reference to the hard coal reserves, steam coal accounts for approx. 71.6%, followed by coking coal with 27% and other types accounting for the remaining (1.4%).

Today there are 18 hard coal mines in Poland, owned and operated by 5 coal mine industries (Table 2), and several abandoned mines (Figure 6), most of which are still being pumped. The total mine water discharge in USCB is around 350,000 m^3/day, with the amount of chlorides and sulphates discharged to the rivers being approximately 4,000 tons/day. Mine waters from these mines are typically discharged into tributaries of the upper Wisła (Vistula) and upper Odra (Oder) rivers (Janson et al., 2009).

Table 2. *List with operating coal mines and companies in Poland*

N°	Coal Mine	Coal mine company
1	KWK Borynia-Zofiówka	**Jastrzębska Spółka Węglowa JSW Group (5 mines)**
2	KWK Budryk	
3	KWK Knurów-Szczygłowice	
4	KWK Pniówek	
5	KWK Jastrzębie-Bzie	
6	KWK ROW	**Polska Grupa Górnicza PGG (8 mines)**
7	KWK Ruda	
8	KWK Piast-Ziemowit	
9	KWK Sośnica	
10	KWK Bolesław Śmiały	
11	KWK Staszic-Wujek	
12	KWK Myslowice-Wesola	
13	ZG Brzeszcze	**Tauron Wydobycie (3 mines)**
14	ZG Janina	
15	ZG Sobieski	
16	KWK Silesia	**Przedsiębiorstwo Górnicze "Silesia" Sp. z o.o. (owned by BUMECH S.A.)**
17	KWK Bobrek-Piekary (Ruch Bobrek)	**Węglokoks Kraj Sp. z o.o.**
18	KWK Bodganka	**Lubelski Węgiel Bogdanka S.A.**
*	**Small private mines**	

3.2 Debieńsko case study

Desalination of saline mine water in USCB was proposed since the 1970s, when the need for a large environmental project of the "Debiensko" desalination plant is reported (Sikora et al, 1989) with the aim to eliminate the coal mine discharges generated by Budryk and Debiensko coal mines. The contract for materializing this project was signed in 1988, while the first salt production started only in August 1993. In Figure 5 more details are provided the different stages of this project development, reaching different milestones.

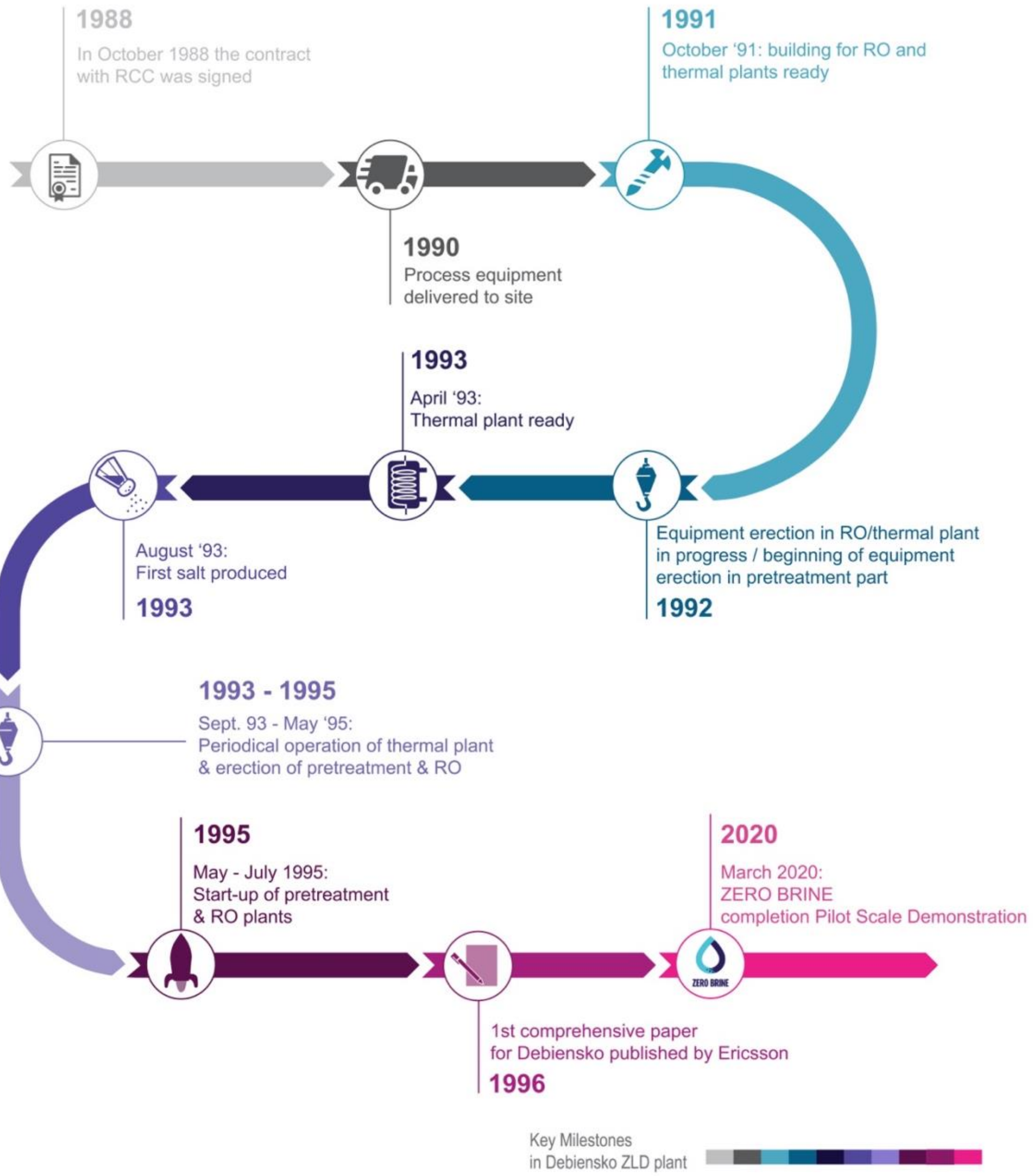


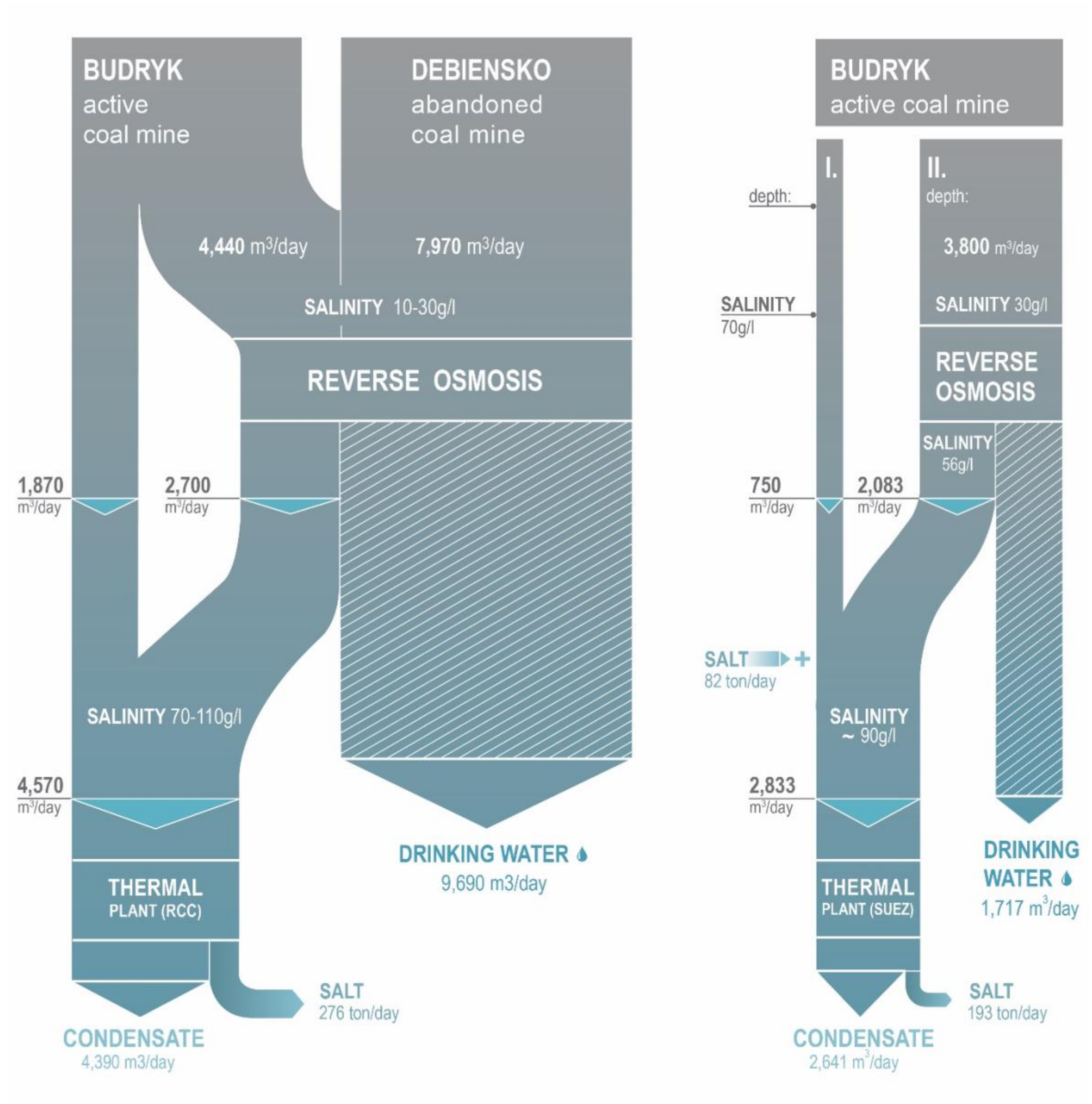
Figure 5*. Milestones of Debiensko case study (period: 1988 – 2020) (Source: Xevgenos et al., 2020)*

The Debiensko desalination plant comprises 2 evaporators and 1 salt crystallizer. The cost of the equipment was approx. US$ 60 million. Its main drawback is the extremely high energy consumption (~720 kWh/t of salt recovered), which had a high impact on the business viability and financial outcome. One important revenue stream for the desalination plant comes from the fees from the coal mines which need to desalinate their water according to the signed concession documents.

According to the original design, around 14,000 m^3/day of mine drainage was treated in the desalination plant at Debiensko, receiving around 8,000 m3 of coal mine effluent from the Debiensko coal mine (an abandoned coal mine) and around 6,000 m3 of coal mine effluent from Budryk coal mine, per day. The plant was recovering about 10,000 m^3/day of drinking and process water, 4,500 m^3/day of distilled water, 276 tons of pure sodium chloride for sale to the chemical industry and as table salt and 28 tons per day of calcium sulfate.

Since late 2019, the treatment of the Debiensko coal mine is no longer requested by the competent authorities. Today the desalination plant started to treat coal mine effluents only from Budryk coal mine. Two different coal mine effluents are generated from the exploitation of the coal reserves, at two different depths at Budryk site, which results in two different salinities, a stream of approx. 750 m3/day with a Total Dissolved Solids (TDS) content of approx. 70 g/L, and a less saline stream (often called in Polish as “Budryk mierne”) with a flow of approx. 3,800 m3/day at 30 g/L TDS content. A more detailed mass balance is provided in the figure below, presenting also the materials recovered in each case.

Original design	***Current operation***



		Feed water	
		Budryk	Budryk miernie
C_{Cl-}	kg/m³	43.783	18.790
C_{Ca2+}	kg/m³	0.960	0.524
C_{Mg2+}	kg/m³	1.152	0.665
C_{SO42-}	kg/m³	1.171	0.356
C_{Na+}	kg/m³	25.616	10.467
TDS	kg/m³	72.682	30.802
V	m³/day	750.000	3800.000

Nº	Coal Mine
1	KWK Borynia-Zofiówka
2	KWK Budryk
3	KWK Knurów-Szczygłowice
4	KWK Pniówek
5	KWK Jastrzębie-Bzie
6	KWK ROW
7	KWK Ruda
8	KWK Piast-Ziemowit
9	KWK Sośnica
10	KWK Bolesław Śmiały
11	KWK Staszic-Wujek
12	KWK Myslowice-Wesola
13	ZG Brzeszcze
14	ZG Janina
15	ZG Sobieski
16	KWK Silesia
17	KWK Bobrek-Piekary (Ruch Bobrek)
18	KWK Bodganka
*	**Small private mines**

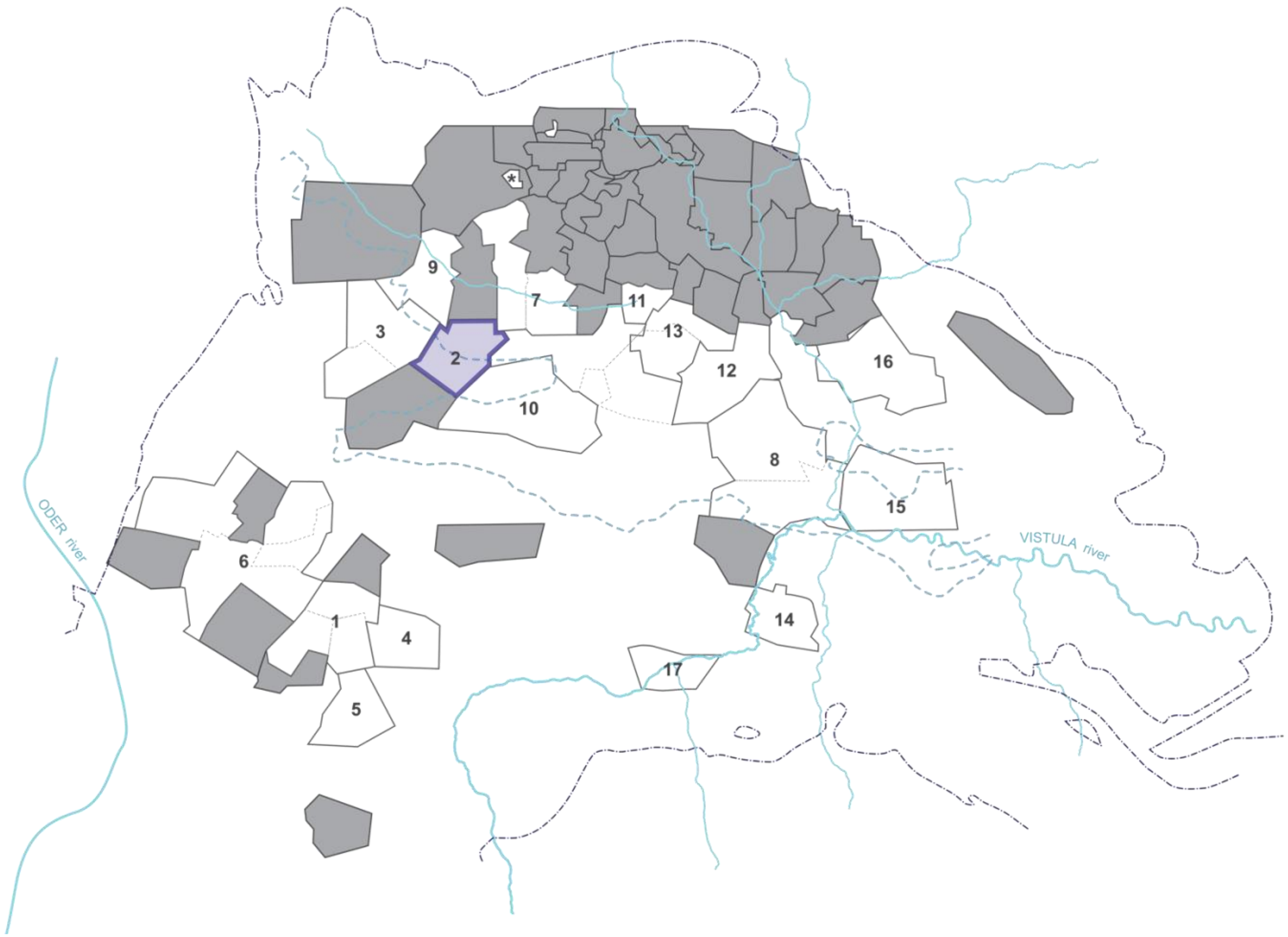


Figure 6. *Map with active and abandoned coal mines in Poland (Source: Xevgenos et al., 2020)*

3.3 Evaluation of Dębieńsko case and suggestions for improvement

The current design of Dębieńsko wastewater treatment plan (see Figure 7) treats brine from two levels of Budryk coal mine: a) Budryk miernie and b) Budryk. The first step consists of concentrating the Budryk miernie brine in terms of salt in order to mix it with the Budryk brine which has a much higher salinity level. Rock salt is then added, and then the combined flow is pumpted and treated with evaporation to produce saturated brine and clean water. The salt addition takes place to increase the efficiency of the evaporation step. The saturated brine is treated with crystallization to recover salt (NaCl) and gypsum. Post crystallization lyes are also produced as a byproduct during crystallization. Lastly, recovered water from reverse osmosis, evaporation and crystallization units is treated to upgrade it to drinking water quality. Table 3 and Table 4 show the chemicals and electricity consumption per ton of recovered salt for each treatment step at Dębieńsko wastewater treatment plan, respectively.

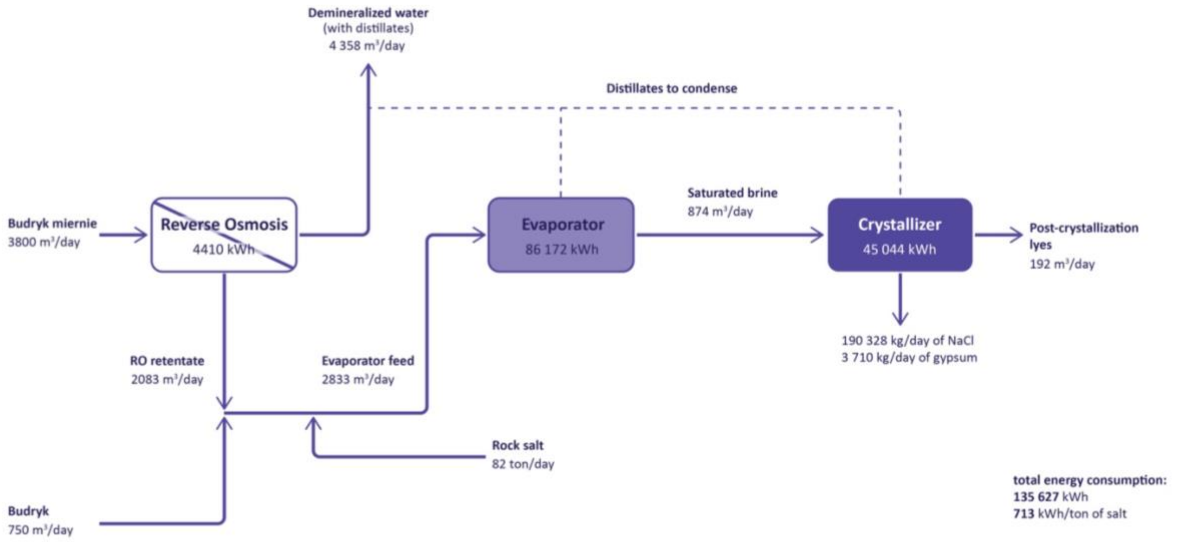


Figure 7. *Design of Dębieńsko wastewater treatment plant*

The ZERO BRINE design (see

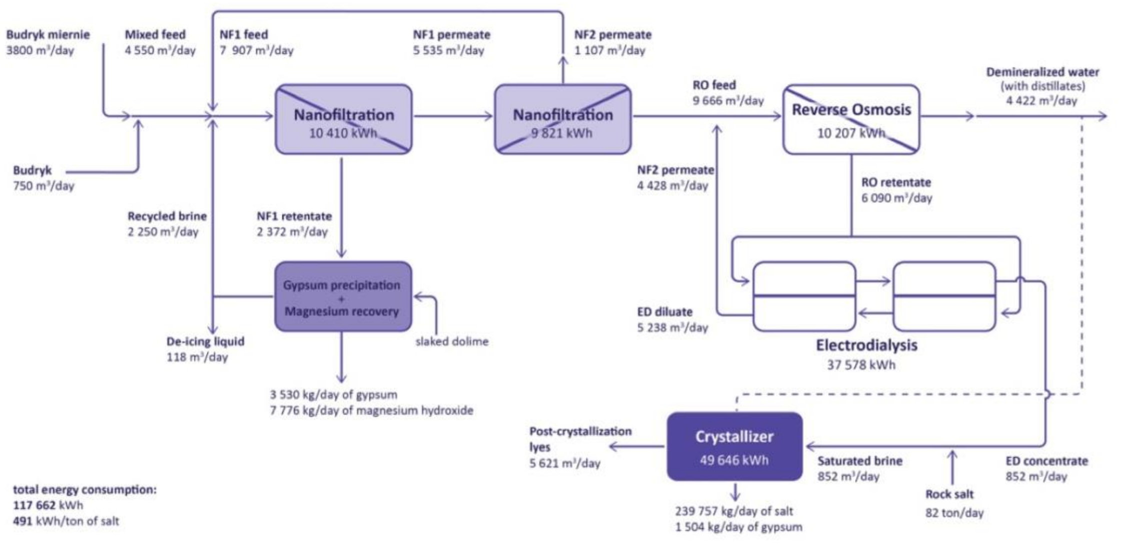


Figure 8) aims at decreasing the electricity consumption of the entire plan while maximizing the recovery of materials in the brine in a circular economy context. Budryk miernie and Budryk brines are mixed and fed to a two-stage nanofiltration. The first stage nanofiltration produces NF1 retentate and permeate at 52 bar. The NF1 retentate is treated with a gypsum precipitation and magnesium recovery step to separate magnesium and calcium from the main flow and recover magnesium hydroxide and gypsum, respectively. The NF1 permeate is fed to the second stage nanofiltration to produce NF2 retentate and permeate at 54 bar. The former is mixed with electrodialysis (ED) dilute and the latter is recycled to the first stage nanofiltration. NF2 permeate and ED dilute are then fed to a reverse osmosis unit to produce clean water and retentate which is directed to the ED unit. The ED unit produces ED dilute and ED concentrate. The former is recycled to the reverse osmosis and the latter is mixed with rock salt and treated with crystallization to produce salt and gypsum. Post crystallization lyes are also produced as a byproduct during crystallization. Lastly, recovered water from reverse osmosis, evaporation and crystallization units is treated to upgrade it to drinking water quality. Table 3 and Table 4 show the chemicals and electricity consumption per ton of recovered salt for each treatment step based on the Zero Brine design for Dębieńsko waste water treatment plan, respectively.

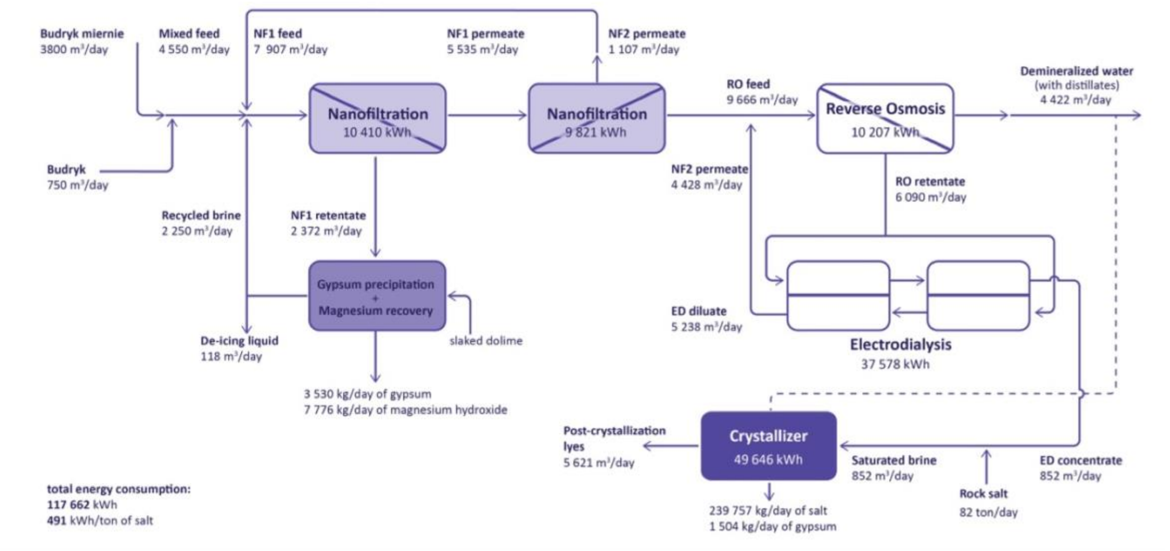


Figure 8. *Zero Brine design for Debiensko wastewater treatment plant*

Table 3. Material consumption at Debiensko treatment plant design and Zero Brine design in kg per ton of recovered salt

Chemicals	Process				
	Pre-treatment	RO	Evaporator	Crystallizer	Post-treatment
According to Masarczyk et al. (1989) (kg/m³ feed water in each process)					
Sulphuric acid (96%)	0.22		0.875		
Sodium Hydroxide (50%)			0.0033		
Scale inhibitor: Sodium hexametaphosphate		0.01	0.01		
Antifoam			0.006		
Crystallizer				0.1	

Chemicals	Process				
	Pre-treatment	RO	Evaporator	Crystallizer	Post-treatment
Rock Salt			0.029		
Aluminium sulphate	0.075				
Polyelectrolyte	0.0003				
Sodium bisulphite	0.005				
Chlorine (if used)	0.001				0.001
Calcium hydroxide					0.037
Calculated per ton of salt recovered					
Sulphuric acid (96%)	4.39		13.02		
Sodium Hydroxide (50%)			0.05		
Scale inhibitor: Sodium hexametaphosphate		0.20	0.15		
Antifoam			0.09		
Crystallizer				1.49	
Rock salt			431.84		
Aluminium sulphate	1.50				
Polyelectrolyte	0.01				
Sodium bisulphite	0.10				
Chlorine (if used)	0.02				0.01
Calcium hydroxide					0.33

Table 4. Electricity consumption at Debiensko treatment plant design and ZERO BRINE design in kWh per ton of recovered salt

Process	Dębieńsko	ZERO BRINE
Nanofiltration (dual pass)	-	84.4
RO	23.17	42.57
Evaporator	452.76	-
ED	-	156.73
Crystallizer	236.67	207.07
Post treatment	4.99	4.62
Total	717.6	495.4

According to our analysis (see also table above), the application of the innovative brine treatment system demonstrated within ZERO BRINE project, would result in reducing the energy consumption from 718 kWh to around 495 kWh per ton of salt recovered, or **by approximately 31%.**

3.4 Circular business model for the coal mine sector

Within the coal mine sector an innovative solution based on the ZERO BRINE results is presented in this work. The project builds also on the technical innovation developed within a previous LIFE project called SOL-BRINE (LIFE09 ENV/GR/000299) where an innovative Zero Liquid Discharge system was developed (Xevgenos, 2015; Xevgenos, 2015b & Xevgenos, 2016). Within SOL-BRINE project, the circular value of brines was explored in the field of seawater desalination, estimating the value of this brine around 6 euro per m3 (Xevgenos, 2017). The circular business model is tested around the case of "Debiensko" desalination plant, which comprises the first Zero Liquid Discharge system for coal mine effluents at a global scale.

This plant is owned by PGWiR, a company that belongs to the PGG coal mines group. The value proposition of this company is based on offering the service of brine treatment to a neighboring coal mine called Burdyk. This mine is owned by Jastrzębska Spółka Węglowa (JSW). The local regulator requires that JSW eliminates the coal mine effluent in order to be able to exploit the coal reserves of this particular mine. As such, JSW is paying a fee for the treatment of the coal mine effluent on the basis of the volume of brine generated (that is per m^3). Apart from this revenue stream, PGWiR recovers some of the treatment costs through selling the materials recovered, namely salts. The water recovered is discharged into the river, without further market exploitation. Although the "Debiensko" desalination plant runs for several years using this business model, the owners suggest that this model suffers from marginal (if non existent) profit margins, due to the high energy requirements for the operation of the Zero Liquid Discharge system. This business has been sustained over the years also with the help of governmental support through subsidies. The plant operators indicate as a target the reduction of the energy consumption, as well as the recovery of further materials from the purge streams (lye) of the crystallizer. We estimate that our proposed technical innovation/solution, based on the results obtained from the pilot demonstration within ZERO BRINE, can reduce the energy consumption around 30%, suggesting significant improvement of the operating costs of the system. Further improvements for the energy requirements are now being tested within ZERO BRINE project, as well as meetings with the relevant stakeholders are being planned to further discuss the value proposition, as well as how this value will be further captured and delivered. This is an ongoing work and is not part of this conference paper.

The innovation creates significantly reduced negative impacts for (i) the environment, through elimination of the coal mine water discharges to surface waters as well as reduced energy requirements for the treatment of this water; and (ii) for society through creation of new job opportunities in the coal mine regions that are the most affected from the energy transition, related to the climate targets. From the analysis made within this paper, it is clearly indicated that the Slaskie region (PL22) comprises almost the most affected region in Europe which comprises the focus of this paper. This region has intense hard coal activity; an activity that will need to be sustained to a certain level due to its importance for the metallurgical sector. It is clear that out of the 18 active coal mines today, some will shut down in the next 30 years ahead, while few will need to remain open for coking coal production. All closed mines, and especially those that will be neighboring to the few mines that will remain open, will need to be still dewatered to avoid flooding. This will generate salty wastewater streams that need to be treated properly, to ensure environmental protection.

The mines (from West to East) marked as: 3, 9, 10, 7, 11, 12, 13, 8, 16 and 15 (Figure 6) have relatively high loads of salt and considerable amounts of mine water pumped. The mines 6, 1, 5, 4, 17, 14 have less water inflow, but high salinity of mine water. In some cases the selective pumping system, to separate most saline mine water from the less saline would be recommended in order to achieve good economical potential of desalination process. This should be further investigated together with the coal mine industries operating these mines. Coal mines located within the hydrogeological subregion boundary, namely, Bolesław Śmiały, Knurów-Szczygłowice, Piast-Ziemowit, Mysłowice-Wesoła, Janina, Silesia, show good potential for replicability of Debiensko circular economy approach. This will be further investigated together with the coal mine industries operating these mines, to make the action plan that is being developed together with relevant stakeholders, and thus enable the transition of the coal mine sector into a sustainable pathway stimulating circular economy activities. The policy tools, most importantly the Just Transition Fund and the Structural & Cohesion funds, can play a crucial role in paving the right way of the most affected regions towards energy transition and carbon neutrality.

According to JRC (2017) coal activities provide jobs to about 112,500 people in Poland, followed by Germany (35,700 jobs), Czech Republic (21,600 jobs), Romania (18,600 jobs), Bulgaria (14,500 jobs), Spain (6,700 jobs), Greece (6,500 jobs), the United Kingdom (6,100 jobs) and with the remaining 15,300 jobs being in other EU countries with contributions less than 2,000 (Italy, Hungary, Slovenia, Finland, Denmark, Netherlands, Portugal, France, Austria, Ireland, Croatia and Sweden). What is of particular value is that these numbers are concentrated in certain regions of these countries (Figure 9). Poland has 112,500 direct jobs related to coal activities, with 73% (or 82,500 direct jobs) concentrated in the Slaskie region (PL22) that is the focal point of our study.

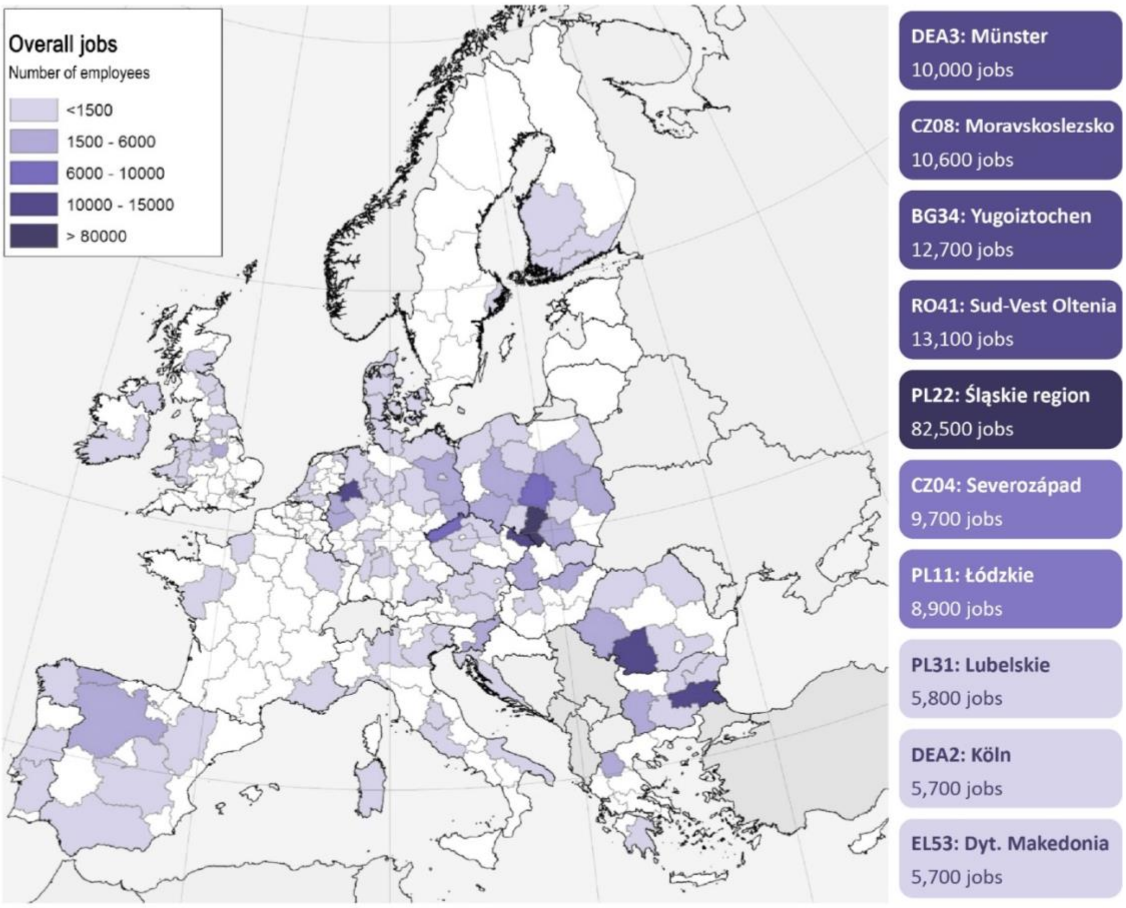


Figure 9. *EU map highlighting the NUTS-2 regions with job positions in coal related activities. The 10 regions with the highest number of jobs are presented in the boxes around the map.*

The proposed circular business model changes the way not only the coal mine sector operates, but a broader value-network related to the recovery of secondary raw materials (water and salts) and how these can jointly deliver a new value proposition, by delivering and capturing circular value through coal mine brines. The proposed model may well benefit from the new Just Transition Fund that has been established by the European Commission, in recognition of the economic disparities as well as the different starting points of the Member States and the job positions of different regions around fossil-fuel mining activity. The Just Transition Fund with a budget of **€5 billion** is an important tool to help the coal mine regions that are most affected to redirect into a more sustainable path, aligned with the new policies adopted.

4 CONCLUSION

This work adds to the Circular Economy Business Modelling and Sustainable Business Innovation fields by showing how theory can be applied in the context of collaborative projects. Specifically, this has been done through studying how business innovation can be used to generate economic value in the coal mines sector, while addressing societal and environmental issues. With this work, we integrate the needs and interests of key stakeholders and users into the design of a new sustainable business model revolving around the coal mine wastewater treatment sector. We study the case of the first Zero Liquid Discharge system treating coal mine effluent, called Dębieńsko. By using the results derived from the demonstration of a pilot system within the EU funded project called ZERO BRINE, we estimate the reduction of the energy consumption of the plant by approx. 30%, suggesting significant improvement of the costs related to the operating costs for running the system. Through interviews and meetings in individual and group settings of key stakeholders, we explore the possibility of delivering circular value within the coal mine sector. The ambition is to further expand this circular economy approach within the coal mine sector that is facing currently significant pressures in view of the decarbonization and climate policy in Europe and at global scale. We investigate possibilities for applying this approach in the USCB region in Poland, where most of the coal mining activity is concentrated. We believe that this information can become also highly relevant to project developpers and policy makers that are active currently on the development of the Just Territorial Plans within the Just Transition fund.

5 ACKNOWLEDGMENT

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