The concept of circular water value and its role in the design and implementation of circular desalination projects. The case of coal mines in Poland

Xevgenos, D.; Tourkodimitri, K. Panteleaki; Mortou, M.; Mitko, K.; Sapoutzi, D.; Stroutza, D.; Turek, M.; van Loosdrecht, M. C.M.

DOI
10.1016/j.desal.2024.117501

Publication date
2024

Document Version
Final published version

Published in
Desalination

Desalination 579 (2024) 117501

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

The concept of circular water value and its role in the design and implementation of circular desalination projects. The case of coal mines in Poland

D. Xevgenos [a,b,*], K. Panteleaki Tourkodimitri [b], M. Mortou [b], K. Mitko [c], D. Sapoutzi [b], D. Stroutza [d], M. Turek [c], M.C.M. van Loosdrecht [d]

[a] Faculty of Technology, Policy & Management, Delft University of Technology, Delft, the Netherlands
[b] SEALEAU, the Netherlands
[c] Silesian University of Technology, Poland
[d] Faculty of Applied Sciences, Delft University of Technology, Delft, the Netherlands

HIGHLIGHTS

- Introducing the new concept of "Circular Water Value" to assess resource recovery in circular water projects.
- Application of the concept for the case of coal mine effluent treatment and resource recovery
- Contribution to bridging the design implementation gap in the circular economy business modeling field
- A basic chemistry based concept to mainstream the circular water economy knowledge beyond the wastewater treatment domain

ARTICLE INFO

Keywords:
Circular economy,
Desalination,
Circular business models
Coal mine wastewater
Brine treatment
Design for sustainability
Resource recovery
Water
Salts

ABSTRACT

Circular economy has become a popular subject, attracting attention from academics, practitioners, and policy-makers alike. However, despite the excitement surrounding it, the concept of circular economy has been criticized for being vague and having multiple interpretations from different fields. As a result, there is a lack of evidence and guidance for practitioners, making it difficult to put into practice. Our goal is to fill this gap by bridging the design and implementation of circular economy solutions in the water sector. Through an exploratory study of two case studies, we have shown the significance of what we call as “circular water value” in the context of coal mining. This value is strongly influenced by the chemistry, concentration levels and purity of these effluents. We compared the circular value of the two cases (ranging from 2.5 to 6 euros per cubic meter) to the cost of the novel treatment system, developed by the authors through the EU-funded project ZERO BRINE, to capture this value. This allowed us to evaluate the potential for circular economy implementation. We suggest that this circular transition can offer significant opportunities to coal mining regions in enabling a just transition implementation. This is a topic that is increasingly gaining interest among academic and practitioner communities, further triggered by the recently adopted Just Transition Mechanism. This mechanism secures targeted support of 55 billion euro for the period 2021–2027 for the most affected regions within Europe. The concept of “circular water value” introduced in this article can serve as a tool for exploring the creation of emerging circular value chains from coal mines, as well as for other wastewater treatment and resource recovery projects in general.

1. Introduction

The concept of Circular Economy has garnered significant attention from researchers, practitioners, and policy-makers across various sectors, including the water industry [1–6]. However, the progress towards implementing circular economy principles has been sluggish due to the

* Corresponding author at: Faculty of Technology, Policy & Management, Delft University of Technology, Delft, the Netherlands.
E-mail address: d.xevgenos@tudelft.nl (D. Xevgenos).

https://doi.org/10.1016/j.desal.2024.117501
Received 15 September 2023; Received in revised form 26 January 2024; Accepted 3 March 2024
Available online 5 March 2024

lack of a coherent definition and uptake of these principles in practical applications, despite the numerous definitions provided by scholars from different fields [7,8]. The adoption of circular economy principles in the water and wastewater sectors can lead to the development of new business models, improved operational efficiency, and increased market [9]. In this light, the term **circular water economy** has been suggested in recent years. Brears [10] defined the circular water economy as "an economy that optimizes water resources and extracts valuable resources from water and wastewater". Chen et al. [11] later specified that circular economy is a **business model** that targets the reuse of unconventional water as an alternative source for various purposes while extracting valuable resources to achieve sustainable production and consumption.

The implementation of a circular economy in the water sector is faced with several challenges. Recent studies point to possible tensions and uncertainties related to resource recovery from wastewater treatment [12]. Past and ongoing projects funded by the European Commission have demonstrated the advantages of applying circular economy and bio-economy principles to water systems. These projects have provided insights into how materials, water, energy, products, and components can be managed in a way that maintains their highest possible intrinsic value. However, despite these benefits, the market uptake of these solutions is yet to come [13]. Additionally, limited public knowledge of circular water solutions poses a social challenge to their adoption. In 2018, the European Commission proposed a framework to evaluate the transition towards a circular economy in EU member states [14]. Indicators were suggested to measure the circular economy's performance, including categories such as production and consumption, waste management, secondary raw materials, competitiveness, and innovation [52]. However, no indicators have been developed to assess circular performance specifically in the water/wastewater sector. Therefore, it is crucial to develop CE water indicators in order to evaluate the implementation of the circular economy in the water context.

Circular Economy Business Modeling (CBM) is an approach that integrates business modeling, resource efficiency, and circular economy principles. Despite its roots in the Business Model (BM) field, which originated in the 1970s, current literature on the subject remains fragmented and primarily focuses on theoretical barriers to implementation, as noted by Evans et al. [15]. Further, practical research on CBM is still largely unexplored, as pointed out by Diaz-Lopez et al. [16], resulting in a "design-implementation" gap as described by Geissdoerfer et al. [17]. Despite the potential benefits of CBMs, they are seldom put into practice in the marketplace, and even when they are, they often fail to meet expectations.

In this study, we have leveraged the expertise and know-how from the fields of circular economy, wastewater treatment, and circular business models to tackle the implementation challenges of circular economy. Our goal is to advance the circular water economy by conceptualizing and actualizing it in a way that can aid researchers and practitioners in devising and executing innovative solutions for circular economy in wastewater treatment. To achieve this objective, we adopted a case study research methodology and analyzed two coal mines in Poland, where we showcased a novel treatment technique as part of the EU-funded project ZERO BRINE. Our research has underscored the importance of determining the "Circular Water Value" in coal mines. Our findings provide practical and theoretical insights, including recommendations for policymakers who aim to implement the Just Transition Fund in Poland and other regions.

The upcoming sections of this paper are structured as follows: First, we will delve into the literature background on SBMI and coal mine wastewater treatment. Next, Section 3 will outline the methodology, including details on the case study research design and the chosen case studies. Section 4 will contain a thorough analysis of the case studies, with the intention of gaining the insights necessary to propose the model presented in that same section. Finally, in Section 5, we will provide concluding remarks, along with a discussion of the limitations of our work and suggestions for future research.

2. Literature review

Our work is rooted in the CBM and SBMI fields. However, the literature around the technical parts related to the proposed technical innovation is also discussed in the sections below.

2.1. Zero liquid discharge (ZLD) and coal mine effluents: from effluent treatment to circular economy

ZLD technology originated in the US during the 1970s before spreading worldwide. Typically, this technology involves an electrically-driven evaporator and crystallizer, leading to high energy consumption, OPEX, and a significant capital investment. According to a 2016 report from Global Water Intelligence (GWI), 258 ZLD projects were completed between 2000 and 2015, with a combined installed capacity of 932,000 m^3/d. General Electric accounted for 56 % of the market (146 projects), with Veolia (24 %) and Aquatec (10 %) following. Furthermore, ZLD systems generate substantial amounts of solid by-products, requiring proper disposal, which can pose a waste management challenge.

The first use of ZLD technology in the coal mining industry dates back to 1993 in Dębieńsko, Poland, where a plant has been operating since 1994. However, there is limited scientific literature available in international languages regarding this case. A detailed account of the "Dębieńsko case" can be found in publications by Masarczyk et al. [18] and Ericsson and Hallmans [19], as well as in a few publications in the grey literature by General Electric Water (which was later acquired by Suez and is now owned by VEOLIA), the technology suppliers. More recently Xevgenos et al. [20] provided updated information (in English) about the technology and marketing of products from treating coal mine effluent at Debiensko. The system had a capacity of 12,000 m^3/day and cost approximately US$ 60 million, but its high energy consumption (~970 kWh/t of salt recovered) made it an unviable business. In 2022, an environmental impact analysis was conducted for the Dębieńsko case by Tsalidis et al. using Life Cycle Assessment [53]. The project has faced several funding challenges, but in recent years, money has come from the Polish environmental fund - which is comprised of fines imposed on polluting industries, including coal mines. The system operators have confirmed that halving the energy consumption is necessary to achieve a sustainable business case.

The authors have conducted theoretical studies and laboratory tests that suggest using membrane methods, or a combination of membrane methods and the evaporation method, can significantly reduce energy consumption. Electrodialytic (ED-EDR) pre-treatment and pre-concentration of coal-mine brine with 32.8 g/L Cl– content at a current density of 344–688 A/m2 in the first step and 300 A/m2 in the second step shows energy consumption in the range of 9.4–14.4 kWh/m3 of inlet brine, depending on the applied current density. The performance of the crystallization step was then compared with data from the "Debiensko" Plant, where currently a salt crystallizer is supplied with brine concentrated by the RCC evaporation method. This comparison shows that unit energy consumption decreases from approximately 970 kWh per 1 ton of evaporated salt for brine treated by the current method to 610 kWh/t in the case of ED-EDR treated brine, and the amount of salt in lye decreases from 110 kg per 1 ton of evaporated salt produced to 20 kg/t. To decrease energy consumption and increase salt recovery, the authors proposed the use of membrane processes, such as nanofiltration (NF), reverse osmosis (RO), electrodialysis (ED), and chemical treatment. Based on laboratory results, a hybrid NF-ED-RO system was designed, and the authors discussed the plant performance and scaling risk. The results show that using the mentioned membrane system could decrease energy consumption to 425 kWh per 1 ton of evaporated salt [21]. To obtain a 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 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 the coal-mine brine RO retentate. Based on the obtained results, energy consumption in RO–NF–vapor 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/m^3 of brine with 290 g/dm^3 NaCl) was lower than in the currently used RO–VC system (213.2 kWh/m^3 of brine with 290 g/dm^3 NaCl without energy recovery and 204.6 kWh/m3 of brine with 290 g/dm^3 NaCl with energy recovery) [22].

2.2. Business models and circular economy

The field of Business Models (BM) has been established since the 1970s [23], but it gained significant development in the 1990s (Teece, 2010). The concept of a business model was introduced as an analytical and conceptual construct by Osterwalder et al. in 2005, who presented the well-known Business Model canvas. Richardson further established the centrality of value for describing business models in 2008, using three main building blocks (see Fig. 1). However, these representations of the BM domains can be viewed as static. Another research area, known as "Business Model Innovation" (BMI), is addressing the challenge of how a business model can be a dynamic process. Despite significant progress in research within both BM and BMI domains, they are currently undergoing a consolidation phase. In a recent review, this is attributed to the elusive nature of business model constructs, which attempt to connect two conflicting domains of knowledge - the physical sciences (which are based on "hard" facts) and the social or economic sciences [23].

Within these research domains, the concepts of "Sustainability" and "Circular Economy" have emerged as potential new areas of study. Recent literature [17] suggests that it is unclear how organizations can successfully transition into sustainable business models. While Circular Business Models (CBMs) have been situated within the broader business models domain, not all CBMs can be classified as sustainable business models, as some may result in decreased environmental benefits compared to the efficiency gains of a new technology. Additionally, CBMs lack a standardized definition [3,25,26]. The implementation of sustainable business models is rare and often unsuccessful, creating a research gap known as the "design-implementation gap". Despite a theoretical understanding of the barriers to CBM implementation, there is a dearth of practical research. Moreover, most studies related to the Circular Economy are still theoretical, with limited empirical validation.

While the origins of Circular Economy cannot be traced back to a specific date or scholar [27], it has deep roots in various schools of thought and domains such as regenerative design, cradle-to-cradle, industrial ecology, and environmental economics. Some scholars credit Pearce and Turner [28] (e.g. Andersen [29], Ghisellini et al. [2], and Su et al. [30], Kakwani and Kalbar [31]). In recent years, there has been increased attention to the concept, particularly after its adoption by policy makers in China and the European Union [6,32]. However, the multitude of studies from various scholars across different disciplines has resulted in a lack of clarity and dispersion of the concept.

The circular economy's potential in the water field has garnered recognition from policy-makers, practitioners, and the research community (such as [33]). Preisner et al. [33] emphasize the significance of circular economy indicators and criticize the absence of any related to wastewater in the EC's proposed monitoring framework [52]. They argue that this omission is a critical area, given the value of secondary raw materials and water that can be reclaimed to achieve circular economy goals. The European Commission's funding allocation to "circular water economy" projects highlights its importance. Under the previous framework programme (2014–2020), 84 projects received a total funding of 554 million EUR.[1] The topic's relevance continues in the new framework programme (Horizon Europe) covering 2020–2027, through initiatives such as Cluster 6, "food, bioeconomy, natural resources, agriculture and environment".

Back in 2015, McKinsey pinpointed water as the ideal "natural starting point for the circular revolution." They made the case that wastewater constitutes the biggest untapped waste category and represents the most crucial shared resource across all supply chains. In 2018, the Ellen MacArthur Foundation (EMF) released a white paper on the "circular water economy," accompanied by a butterfly diagram. While this was a noteworthy advancement, it did not account for a vital principle of the Circular Economy, namely the extraction of valuable resources beyond water from the water system.

In their review, Kakwani and Kalbar [31] argue that existing literature on circular economy (CE) lacks focus on the water sector. While much research has been conducted on water conservation and various related topics like wastewater reduction, reuse, recycle, reclamation, recovery, and restoration, there is a lack of contextualization of these efforts from a CE perspective. The authors note that while there have been significant technological advancements in wastewater reclamation, recycle, and recovery, strong business models are necessary for maintaining and sustaining these solutions. To address this, they suggest a confluence of the 6Rs concept and the principles of the British Standard on circular economy monitoring and implementation (BS8001:2017). Similarly, Qtaishat et al. [34] argue that the lack of knowledge on how to implement CE solutions in business models is a significant barrier to their implementation in the water sector. Recent literature has also proposed new terms like "circular water economy," indicating a growing interest in exploring the intersection of these fields. Brears [10] defines the circular water economy as an economy that optimizes water resources and extracts valuable resources from water and wastewater. Chen et al. [11] take this a step further, connecting it with the notion of a business model and defining it as "the business model that aims to reuse non-conventional water as an alternative water source for various purposes, while extracting valuable resources from non-conventional water to realize sustainable production and consumption".

Although it holds great significance and potential, this subject remains largely unexplored in literature.

2.3. Research gap and aims of the present research work

The primary objective of this endeavor is two-fold. Firstly, we aim to comprehend and elucidate the reason behind the "design-implementation gap" of circular business models in the (waste)water treatment and resource recovery fields. Secondly, we seek to investigate how this gap can be bridged to facilitate informed decision-making towards realizing the potential of circular economy in the water industry. To achieve this, we rely on practical research in the BMI and CBM domains, which requires a deeper understanding of why circular economy solutions often fail to gain traction in the market. Our starting point is the technical knowledge surrounding wastewater treatment and resource recovery, using the results derived from the EU-funded ZERO BRINE initiative. Additionally, we build upon the technical innovation developed in the SOL-BRINE LIFE project [35–37]. Our approach involves creating a mathematical representation of the circular water value, which we validate through two case studies in the coal mine sector. Our goal is to reformulate the industry's value proposition to align with the energy, circular, and climate transitions.

We have thoroughly assessed the innovative circular economy

[1] Source: Research Executive Agency, personal communication with Head of Unit, Mr. Arnoldas Milukas.

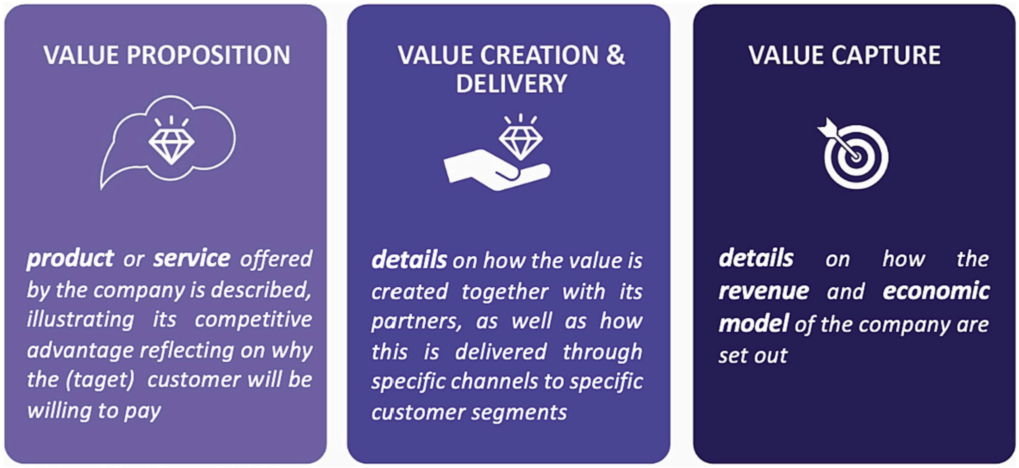

Fig. 1. Conceptual representation of business model based on three value-centred building blocks after Richardson [24].

solution showcased in this project, which aims to maximize salt recovery yields, enhance energy efficiency, and provide significant environmental and economic advantages. To achieve these objectives, we tested various cutting-edge technologies, including ultrafiltration, nanofiltration, reverse osmosis, electrodialysis, crystallization, and evaporation. Throughout the project, we successfully developed and demonstrated a pilot-scale brine treatment system in Poland, utilizing real coal mine wastewater sourced from the Bolesław Śmiały coal mine situated in the Upper Silesian Region.

In addition to our theoretical contributions in the research domains mentioned, our goal is to offer scientific evidence to the policy-making community, particularly those involved in the Just Transition Mechanism (JTM) policy. Our work seeks to bridge the gap between energy and circular transitions, offering a viable solution for the just transition of Poland's (hard) coal regions. While we acknowledge the various tenets of energy justice, such as distribution, restorative, procedural, and recognition justice, it is not the focus of our research.

3. Material & methods

This work revolved around the EU-funded ZERO BRINE (https://zerobrine.eu) project. The technical results presented relate to the large-scale demonstration that was implemented in Poland within ZERO BRINE. The research methodology for the present work is presented in detail below.

3.1. Case study research & cases selection

The present investigation was structured as an exploratory case study, following the guidelines set forth by Yin [38], and focused on two distinct coal mine cases. Case study research is often suggested as an appropriate methodology for analyzing complex research questions within their contextual framework [39,40].

In our research project, we employed a multiple-case study methodology to uncover patterns and characteristics that are present across various cases. Our selection of cases was deliberate and not random; we specifically chose cases with distinct characteristics to gain diverse insights that can inform the replicability of our findings in the larger coal mine sector [41,42]. In accordance with (with Yin's [38] categorization, our case studies are holistic, focusing on the case as a whole rather than analyzing multiple units of analysis within a single case (embedded case studies).

3.2. Data collection and analysis

In our case study research, we noticed a convergence of data analysis and data collection, a common occurrence according to Eisenhardt [43]. This convergence afforded us the opportunity to gather data in a flexible manner and to work iteratively, gathering additional data as we identified its significance during the analysis phase.

Out of the 17 currently operational coal mines, we have selected two cases for detailed analysis. The first is the Debiensko coal mine, which features Total Dissolved Solids in the range of 30,000 to 70,000 ppm. The second is the Bolesław Śmiały coal mine, which has a moderately concentrated brine effluent of around 18,000 ppm. Both of these case studies were conducted as part of the ZERO BRINE project, which allowed us to gather a wealth of information through technical demonstrations and frequent interactions with key stakeholders. To ensure the accuracy of our data, we employed a process of triangulation, which involved multiple data sources and observers. Our team had regular meetings with the coal mine operators as part of a "Community of Practice," where we discussed our results and developed conceptual models. In both case studies, we collected quantitative data to assess the circular value of the coal mine effluent and compared it with treatment costs. More information on this can be found in the following section.

3.3. Calculation of circular water value & treatment costs

Step 1) Wastewater data collection & check: The wastewater composition and flow rates have been collected for the selected coal mine sites. To ensure the accuracy of the collected data, a charge balance has been performed to check for any potential inaccuracies or incomplete datasets in the wastewater composition, based on the electroneutrality condition.

Step 2) Theoretical Circular Water Value Calculation: A process model based on Excel was utilized to calculate the mass and energy balances of all flow streams, including the recovery of different water qualities (drinking and demineralized water) and salts (magnesium hydroxide, calcium sulphate, and sodium chloride). The quantities of the materials recovered align with a new technique for treating coal mine wastewater. This technique involves ultrafiltration and decarbonization pre-treatment, followed by two-pass nanofiltration with an intermediate gypsum precipitation step. To concentrate the monovalent-rich stream obtained from nanofiltration permeate, a hybrid reverse osmosis-electrodialysis is used before final crystallization, which recovers sodium chloride (NaCl). Magnesium hydroxide and gypsum are recovered from the nanofiltration retentate. By multiplying the milliequivalents of magnesium, calcium, and sodium with the molecular weights of magnesium hydroxide, sodium chloride, and calcium sulphate, respectively, a theoretical circular water value is obtained based on the wastewater composition from Step 1. Finally, market insights and stakeholder communication were considered to determine the theoretical circular value of the coal mine wastewater effluent (calculated in Euro per cubic meter). The recovered materials were assigned the following selling prices for analysis: 60 EUR per ton of NaCl, 1000 EUR per ton of $Mg(OH)_2$, 200 EUR per ton of gypsum, and 1 EUR per cubic meter of water recovered.

Step 3) Calculation of circular water value and treatment cost: The circular value and treatment cost were calculated per cubic meter, to assess the potential economic benefits of implementing this solution. The circular economy approach was found to yield impressive rates of water recovery (circa 90 %), sodium chloride recovery (circa 93 %), magnesium hydroxide recovery (circa 95 %), and moderately high calcium sulphate recovery (circa 50 %). Based on these rates, the circular water value was calculated. To determine the treatment cost per cubic meter of coal mine wastewater, the authors took into account both total Capital Expenditure (CAPEX) and total Operating Expenditure (OPEX). The sustainability of the business case, in economic terms, can be evaluated by comparing the circular water value and wastewater treatment value. The analysis was conducted on an annual basis, with both direct and indirect capital costs factored in for the CAPEX. The total cost was then converted to annualized values, also known as capital recovery cost (CRC) in engineering literature, through the use of the amortization factor. The equation for the amortization factor is defined by the following where: [44,45].

$$a = \frac{i \bullet (1+i)^n}{(1+i)^n - 1}$$

where i is the annual interest rate and n is the plant lifetime. The amortized capital cost is calculated by multiplying the total CAPEX with the amortization factor, a. To obtain the total treatment cost, the annual amortized cost is added to the annual OPEX, and the sum is then divided by the total amount of brine effluent that needs to be treated annually. In this study, the plant lifetime considered is 20 years, and the interest rate used is 6 % [46,47].

There are several methods for assessing investment proposals and projects from an economic perspective, including Discounted Cash Flow Analysis, Net Present Value, Internal Rate of Return, and Payback Time. However, in this study, the authors have chosen to use the annualized cost methodology, also known as Equivalent Uniform Annual Cash Flow. This approach is preferred because it provides valuable information regarding unit production costs, which can be compared to the circular value of the coal mine wastewater effluent. The findings of the analysis are presented in Sections 4.1 and 4.2 on an individual case basis, followed by a cross-case comparison in Section 4.3, which offers even greater insights.

4. Results & discussion

In this paper, we have presented the assessment of two case studies to evaluate the implementation of a novel circular economy solution in the (waste)water sector. The first case study is about the "Dębieńsko desalination plant" (Section 4.1) and the second one is about the Bolesław Śmiały coal mine (Section 4.2). In Section 4.3, we have provided a cross-case comparison to assess the effectiveness of this circular economy solution. Finally, we have introduced the concept of "Circular Water Value" and its importance in the design and execution of circular projects in the (waste)water sector.

4.1. Debieńsko case study

4.1.1. Wastewater effluent composition & volumetric flow rate

The Debiensko desalination plant is equipped with one reverse osmosis unit, two evaporators, and one salt crystallizer, with a total cost of approximately US $60 million. However, the plant's high energy consumption, which amounts to around 720 kWh/t of salt recovered, has had a major impact on its financial viability. One of the plant's primary sources of income comes from the fees that coal mines pay for the desalination of their water, as stipulated in the concession documents. The Debiensko desalination plant was designed to treat roughly 14,000 m^3/day of mine drainage, comprising around 8000 m^3/day of coal mine effluent from the abandoned Debiensko coal mine, and about 6000 m^3/day of coal mine effluent from the Budryk coal mine. The plant recovered approximately 10,000 m^3/day of drinking and process water, 4500 m^3/day of distilled water, 276 tons of pure sodium chloride for sale to the chemical industry and as table salt, as well as 28 tons per day of calcium sulphate. As of late 2019, the authorities no longer require the treatment of the Debiensko coal mine. As a result, the desalination plant now only processes coal mine effluents from the Budryk coal mine. The site generates two different coal mine effluents with varying salinities due to the exploitation of coal reserves at different depths. One stream, roughly 750 m^3/day, has a Total Dissolved Solids (TDS) content of around 70 g/L (see Table 1). The other, less saline stream, often referred to as "Budryk miernie" in Polish, has a flow of approximately 3800 m^3/day and a TDS content of 30 g/L (see Table 1). Fig. 2 provides a more detailed mass balance, including the materials recovered in each case.

The treatment of brine from two levels of Budryk coal mine: Budryk miernie and Budryk, is currently being carried out at the Dębieńsko wastewater treatment plant using a design that is depicted in Fig. 3 (top drawing). To achieve this, the Budryk miernie brine is first concentrated in terms of salt, before being combined with the Budryk brine which has a much higher salinity level. Rock salt is then added, and the combined mixture is pumped and treated with evaporation to produce both saturated brine and clean water. The addition of salt enhances the efficiency of the evaporation process. The saturated brine is then treated with crystallization to recover salt (NaCl) and gypsum. Byproducts such as post-crystallization lyes are also produced during the crystallization process. Finally, the water recovered from reverse osmosis, evaporation, and crystallization units is treated to upgrade it to drinking water quality. Table 2 displays the electricity consumption per ton of recovered salt for each treatment step at the Dębieńsko wastewater treatment plant.

The ZERO BRINE project aims to minimize electricity usage across the entire plant while maximizing the recovery of materials in the brine within a circular economy framework. To achieve this, the Budryk miernie and Budryk brines are combined and subjected to a two-stage nanofiltration process. The first stage produces a retentate and a permeate at 52 bar, with the retentate treated for gypsum precipitation and magnesium recovery, and the permeate moving on to the second stage at 54 bar. The retentate from the second stage is mixed with electrodialysis (ED) dilute, while the permeate is recycled back to the first stage of nanofiltration. Next, the nanofiltration permeate of the second stage and the ED dilute are sent to a reverse osmosis unit, resulting in clean water and retentate. The ED unit produces ED dilute and ED concentrate, with the former recycled to the reverse osmosis and the latter combined with rock salt and treated with crystallization to produce salt and gypsum. During crystallization, post-crystallization lyes are also produced as a byproduct. Finally, recovered water from the reverse osmosis, evaporation, and crystallization units is treated to meet drinking water standards.

Table 1
Composition of feed waters to Dębieńsko Desalination plant.

Concentration		Budryk	Budryk miernie
Compound	Unit		
Sodium (Na^+)	mg/L	25,616	10,467
Magnesium (Mg^{2+})	mg/L	1152	665
Calcium (Ca^{2+})	mg/L	960	524
Chlorides (Cl^-)	mg/L	43,783	18,790
Sulphates (SO_4^{2-})	mg/L	1171	356
TDS	mg/L	72,682	30,802
Volume	m^3/day	750	3800

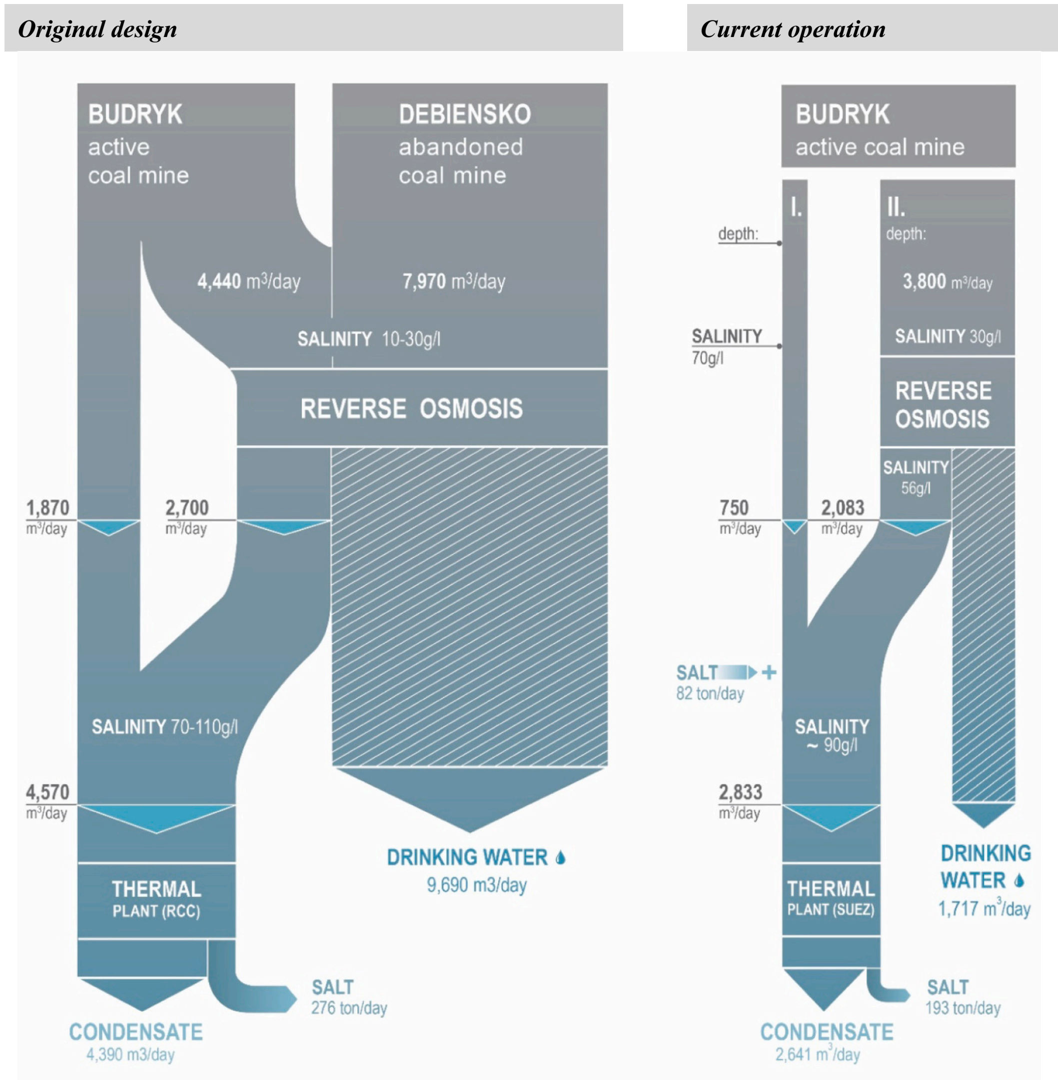

Fig. 2. Material balance of Dębieńsko case (left picture: original design, right picture: current operation).

Table 2 outlines the electricity consumption per ton of recovered salt for each step of the Zero Brine design at the Dębieńsko wastewater treatment plant. Our analysis suggests that implementing this innovative brine treatment system would cut energy consumption from 718 kWh to approximately 495 kWh per ton of salt recovered, representing a 31 % reduction.

4.1.2. *Circular water value & treatment cost*

According to Table 3, complete recovery of materials from the wastewater emitted by the Debiensko plant could yield a significant amount of (theoretical) Circular Water Value. Conversely, Table 4 provides a calculation of the Circular Water Value that can be captured and distributed utilizing the proposed novel technology, as well as the associated unit treatment costs. (See Fig. 4.)

The capital and operating expenditure is provided in Figs. 5 and 6 respectively.

By following the methodology presented in Section 3.3, we calculated the Circular Water Value and the unit treatment cost, so that the viability of the potential business case can be assessed. The results are presented in Fig. 6 below. We found that per m3 of wastewater treated 6.15 EUR can be captured, with a cost of 5.27 EUR, which results in a net benefit of 0.88 EUR (positive business case).

4.2. *Bolesław Śmiały coal mine*

4.2.1. *Wastewater effluent composition & volumetric flow rate*

The Bolesław Śmiały coal mine, located in the city of Łaziska Górne, has been in operation for over 240 years and is one of the oldest mines in Poland. Since 1945, it has operated under the name "Bolesław Śmiały" and has undergone successive modernizations to keep up with the times. Today, the mine is operated by the largest producer of hard coal in the European Union. Although it is one of the smallest mines connected to the Łaziska Górne power plant, it still produces around 1.5 million tons of coal annually and discharges over 750,000 m^3 of saline water per year with a TDS of 22.89 g/L. The composition of the wastewater effluent is reported in detail elsewhere [48], while average values per compound are provided in Table 5 below.

Currently, Bolesław Śmiały's wastewater treatment involves a settling pond to remove large suspended solids, followed by dilution with industrial wastewater from a nearby power plant. This process ensures that the saline wastewater meets regulatory thresholds for discharge into the Vistula river.

The ZERO BRINE project at Bolesław Śmiały aims to test an integrated membrane system that can recover and reuse all elements in the raw water. This includes demineralized water, salt, magnesium hydroxide, and calcium sulphate. The coal mine wastewater treatment is

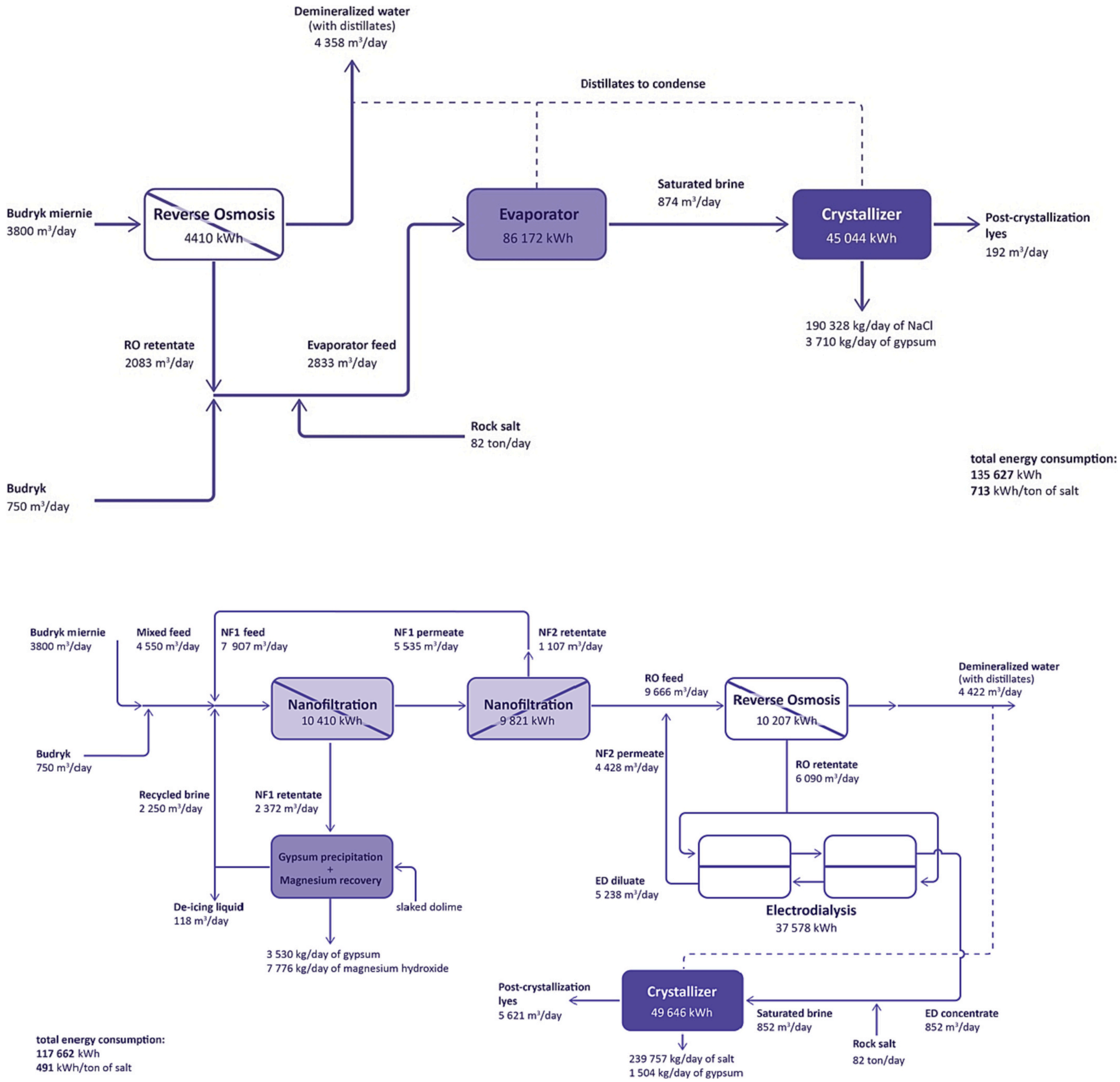

Fig. 3. Design of Dębieńsko wastewater treatment plant (top drawing) and ZERO BRINE design for Debiensko wastewater treatment plant (bottom drawing).

Table 2
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

Table 3
Calculation of theoretical circular water value per m^3 of coal mine effluent, Debiensko case.

Material recovered	Quantity	Units	Price	Units	Revenue EUR per m3
Water	0.97	m^3	1.00	EUR/m3	0.97
$Mg(OH)_2$	3.58	kg	1.00	EUR/kg	3.58
$CaSO_4$	1.76	kg	0.10	EUR/kg	0.18
NaCl	55.78	kg	0.06	EUR/kg	3.35
Savings from avoided environmental fees					0.25
					8.35

divided into three phases: initial treatment with an ultrafiltration and decarbonization unit, followed by pre-treatment and concentration (see Fig. 7). The initial treatment removes solid particles and carbonate ions.

The pre-treatment phase separates bivalent ions (Ca^{2+}, Mg^{2+}, and SO_4^{-2}) from the effluent using a nanofiltration unit and recovers $Mg(OH)_2$ and

Table 4
Calculation of Circular Water Value that can be captured per m^3 of coal mine effluent using the proposed innovative system for the Dębieńsko case.

Material recovered	Quantity	Units	Price	Units	Revenue EUR per m3
Water	0.87	m^3	1.00	EUR/m3	0.95
$Mg(OH)_2$	3.42	kg	0.50	EUR/kg	1.71
$CaSO_4$	0.78	kg	0.10	EUR/kg	0.08
NaCl	52.69	kg	0.06	EUR/kg	3.16
Savings from avoided environmental fees					0.25
					6.15

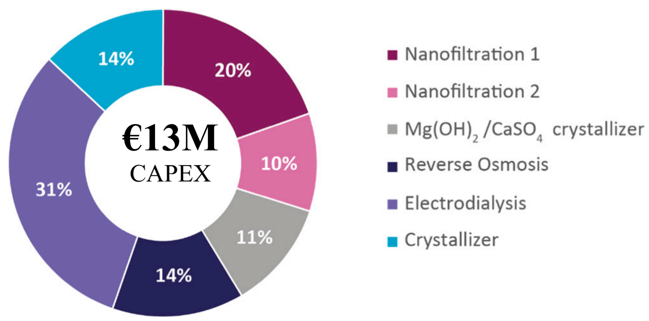

Fig. 4. Capital expenditure (CAPEX) for improved Dębieńsko desalination plant.

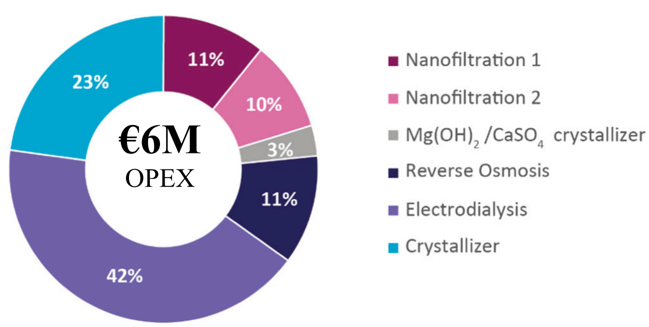

Fig. 5. Annual operating expenditure (OPEX) for improved Dębieńsko desalination plant.

$CaSO_4$ using dolime solution in the crystallization unit. The effluent is then sent to the second phase, where monovalent ions (Na^+ and Cl^-) are concentrated to obtain demineralized water and NaCl salt.

Our analysis shows that implementing the innovative brine treatment system demonstrated in the ZERO BRINE project would result in a water recovery rate of approximately 77.6 %.

4.2.2. Circular water value & treatment cost

The products that can be recovered and the respective revenues that can be obtained in the full-scale implementation scenario are provided in Table 6, levelized per cubic meter of wastewater effluent, while the circular water value that can be actually captured using the novel ZERO BRINE technology is presented in Table 7.

The capital and operating expenditure are provided in Figs. 8 and 9 respectively.

Using the approach outlined in Section 3.3, we have completed a comprehensive analysis of the Circular Water Value and unit treatment cost. This information is crucial in evaluating the feasibility of the proposed business case. Our calculations indicate that the unit treatment cost is roughly 3.5 EUR per cubic meter, while the Circular Water Value is approximately 2.44 EUR per cubic meter. Based on these findings, it

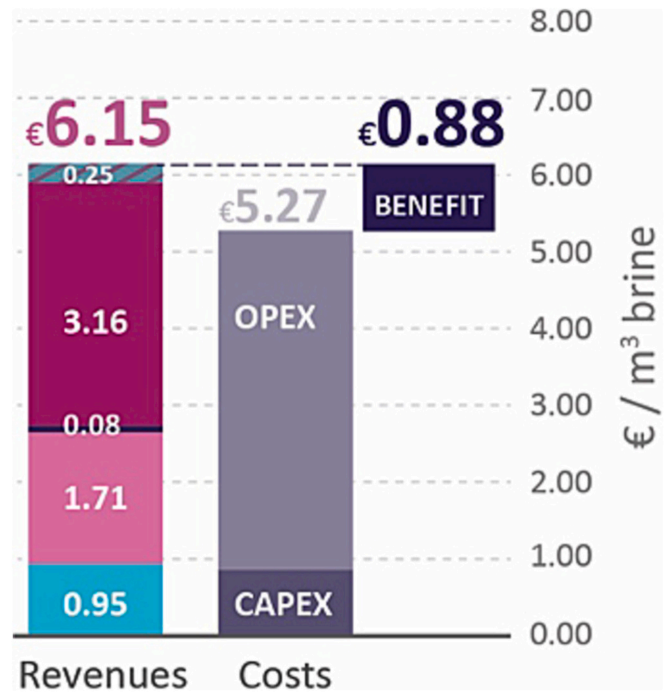

Fig. 6. Assessment of business case (net benefit) for the Debiensko case, based on the Circular Water Value and the Unit Treatment cost values.

Table 5
Composition of feed water to Bolesław Śmiały coal mine.

Concentration		Bolesław Śmiały
Compound	Unit	
Sodium (Na^+)	mg/L	8270
Magnesium (Mg^{2+})	mg/L	250
Calcium (Ca^{2+})	mg/L	260
Chlorides (Cl^-)	mg/L	13,500
Sulphates (SO_4^{2-})	mg/L	620
TDS	mg/L	22,890
Volume	m^3/day	2000

appears that the implementation of the circular economy solution may not be financially viable.

4.3. Cross-case comparison

In this study, we showcase a novel solution utilizing the ZERO BRINE findings within the coal mine industry. The "Debieńsko" and Bolesław Śmiały coal mines have been used as test cases. To begin, we determined the circular value of the coal mine effluents produced in these two case studies. The circular value for Debiensko and Bolesław Śmiały was calculated to be 5.89 EUR per cubic meter and 2.44 EUR per cubic meter, respectively, as outlined in Sections 4.1 and 4.2 (refer to Fig. 10 for further details). The difference in the circular water value is attributed to the concentration of the wastewater mine effluent generated by the Debieńsko coal mine case, which is significantly higher than that of the Bolesław Śmiały coal mine. This variance is also linked to the hydrogeological region characteristics and the depth of the coal mine activity.

In addition to the circular water value generated by the proposed solution, it's important to consider the environmental fees that can be avoided. Local and regional regulations impose fees for discharging brine to water, which amounts to 0.05 PLN or approximately 0.01 EUR per 1 kg of chlorides and sulphates. For Debiensko, based on the volume and composition of the coal mine effluent (see Table 1), an estimated 39

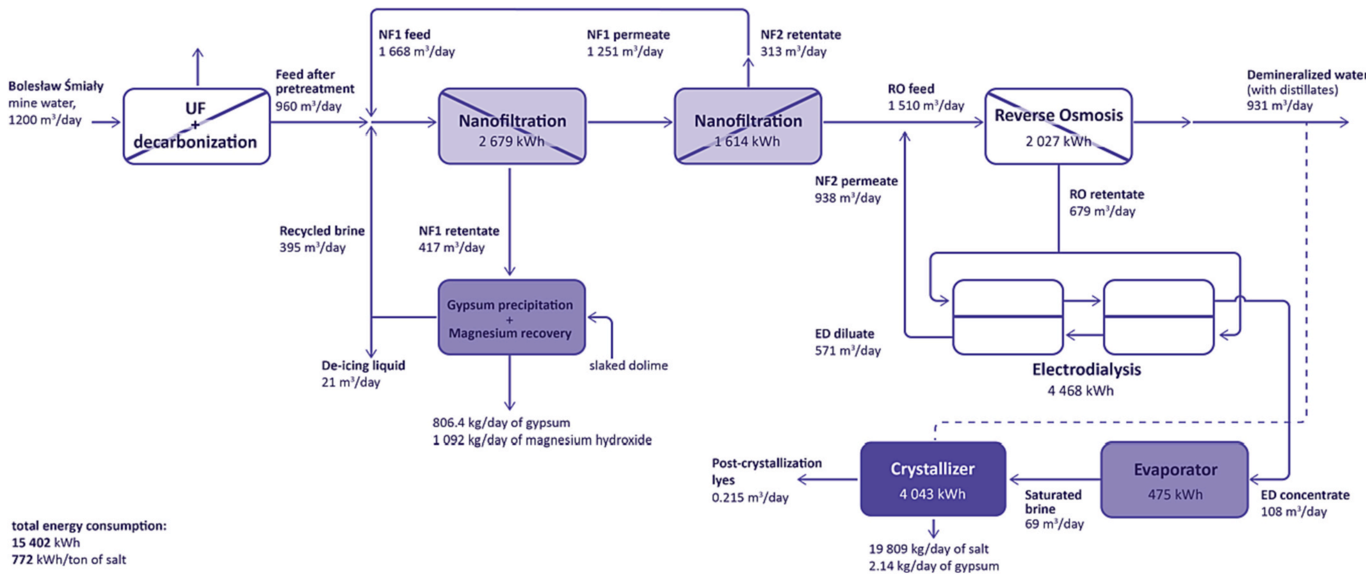

Fig. 7. Schematic overview of pre-treatment and concentration phases.

Table 6
Calculation of theoretical circular water value per m^3 of coal mine effluent, Bolesław Śmiały case.

Material recovered	Quantity	Units	Price	Units	Revenue EUR per m3
Water	0.97	m^3	1.00	EUR/m^3	0.97
$Mg(OH)_2$	1.2	kg	1.00	EUR/kg	1.2
$CaSO_4$	2.2	kg	0.10	EUR/kg	0.22
NaCl	22.2	kg	0.06	EUR/kg	1.34
					3.73

Table 7
Calculation of circular water value that can be captured per m^3 of coal mine effluent using the proposed innovative system for the Bolesław Śmiały case.

Material recovered	Quantity	Units	Price	Units	Revenue EUR per m3
Water	0.88	m^3	1.00	EUR/m^3	0.77
$Mg(OH)_2$	1.0	kg	0.50	EUR/kg	0.45
$CaSO_4$	1.1	kg	0.10	EUR/kg	0.07
NaCl	20.0	kg	0.06	EUR/kg	0.99
					2.29

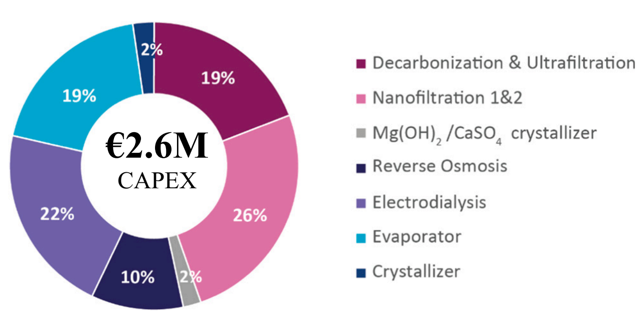

Fig. 8. Capital expenditure (CAPEX) for Bolesław Śmiały case.

million tons of chloride and sulphate discharges would result in an annual savings of approximately 412,000 EUR or 0.25 EUR per cubic meter. Therefore, the total circular value for Debiensko is estimated at

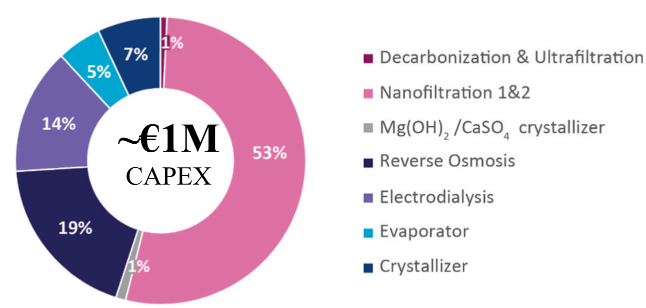

Fig. 9. Annual operating expenditure (OPEX) for the Bolesław Śmiały case.

6.14 EUR (5.89 plus 0.25) per cubic meter. For Boleslaw Smialy, an estimated 10 million tons of chloride and sulphate discharges could potentially avoid 110,000 EUR per year in environmental fees. However, it's worth noting that the coal mine has a special arrangement with a nearby power plant for wastewater management, which partially avoids this fee.

For both case studies, the authors investigated the implementation of the proposed innovative brine treatment system at full-scale. The novelty of the proposed treatment train lies in the introduction of nanofiltration (with an intermediate calcium and magnesium recovery step) to separate the monovalent from the multivalent ions, as well as electrodialysis as a pre-concentration step before applying the typical (energy-intensive) thermal brine concentrator and crystallization steps. In the Debieńsko case, the existing desalination plant is owned by PGWiR, a company that belongs to the PGG coal mines group. PGWiR offers 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 JSW to eliminate the coal mine effluent to exploit the coal reserves of this particular mine. JSW pays a fee for the treatment of the coal mine effluent based on the volume of brine generated (that is per m^3). PGWiR recovers some of the treatment costs by 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 ZLD system. This business has been sustained over the years with the help of government support through subsidies. The plant operators aim

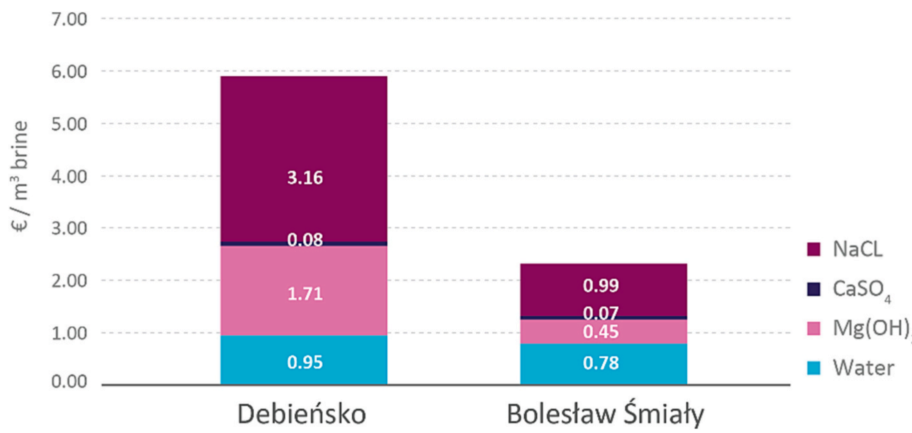

Fig. 10. Circular value of wastewater effluent generated by Debieńsko and Bolesław Śmiały coal mines.

to reduce energy consumption and recover further materials from the purge streams (lye) of the crystallizer. The proposed technical innovation/solution, based on the results obtained from the pilot demonstration within ZERO BRINE, can reduce energy consumption by around 30 %, suggesting significant improvement of the operating costs of the system, as well as creating important new value by recovering additional salts. Fig. 11 illustrates that approximately 1.8 EUR can be created per cubic meter by recovering magnesium hydroxide that was not recovered before.

When analyzing the circular business model tested in two case studies, the unit cost per cubic meter treated with the proposed circular solution (refer to Fig. 11) was found to be higher for the Debieńsko case due to both higher annualized capital and operating expenditures compared to the Bolesław Śmiały case. The operating expenditure is a significant component of the treatment cost for both cases, with the Bolesław Śmiały case representing over 90 % of the total unit treatment cost. This is because the effluent from the Bolesław Śmiały coal mine is more diluted, requiring more energy input to achieve the same result. In conclusion, evaluating the unit treatment costs against the circular value can determine the business case. The Debieńsko case has a positive business case of +0.88 EUR per cubic meter as the circular value (6.14 EUR per cubic meter) is higher than the unit treatment cost (5.27 EUR per cubic meter). Conversely, the Bolesław Śmiały case has a negative business case of −1.05 EUR per cubic meter as the circular value (2.44 EUR per cubic meter) is less than the unit treatment cost (3.50 EUR per cubic meter). Table 8 presents a summary of the results for both case studies.

The novel circular water solution presented can bring a shift in the coal mine sector, as well as in the broader value-network of secondary raw material recovery. Through the joint delivery of circular value via coal mine brines, a new value proposition is created. This proposed model could greatly benefit from the newly established Just Transition

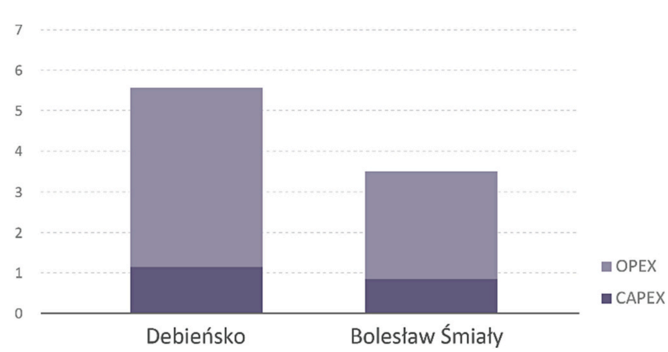

Fig. 11. Unit cost per cubic meter treated for the coal mine effluents generated by Debieńsko and Bolesław Śmiały coal mines.

Table 8
Summary table comparing results for the two case studies.

Item description	Debieńsko	Bolesław Śmiały
TDS of effluent (mg/L)	72,682	22,890
Effluent discharged (m^3/day)	~4550	2000
CAPEX of full-scale system (million EUR)	13	2.6
OPEX of full-scale system (million EUR)	6	1
Circular water value (EUR/m^3)	6.15	2.44
Unit treatment cost (EUR/m^3)	5.27	3.50
Net benefit (EUR/m^3)	0.88	−1.05

Fund, which recognizes economic disparities and varying starting points and job positions among Member States and regions impacted by fossil-fuel mining activities. With a budget of €55 billion, this fund is an instrumental tool in redirecting the most affected coal mine regions towards a more sustainable path, aligned with newly adopted policies.

4.4. *Towards a new concept: the "circular water value"*

We conducted an analysis of two case studies which led us to develop the concept of "Circular Water Value." This concept is derived from various scientific domains and is expressed as a unidimensional variable in monetary values (such as EUR) per volume of wastewater effluent (per cubic meter) (see also Fig. 12). The circular water value represents the total economic value that can be captured by treating one cubic meter of wastewater effluent to recover raw materials in a circular manner. We also discovered that communicating this concept to coal miners highlighted the "missed business opportunity" they are currently facing by managing their wastewater effluent linearly.

4.4.1. *Intrinsic & extrinsic features of the circular water value*

To calculate the quantities of target salts that can be recovered as secondary raw materials from a specific wastewater effluent, the concentrations of the compounds present in the effluent are first translated to milliequivalents. In the case of coal mines, even though the compounds present were similar, the different concentrations of the compounds led to varying potential for circular economy. This difference in circular economy potential is intrinsic to the wastewater itself and can be considered as an internal factor, as opposed to external factors that are not part of the wastewater effluent. External factors may refer to various elements that affect the recovery of raw materials, including the available technology for raw material recovery, the markets that exist to absorb these materials (or those that need to be established as emerging markets and value chains), and the policies and regulations in place. The external factors mentioned in this work were not studied in detail, but they are important to consider when assessing specific business cases. We have used market prices for the products that can be recovered from

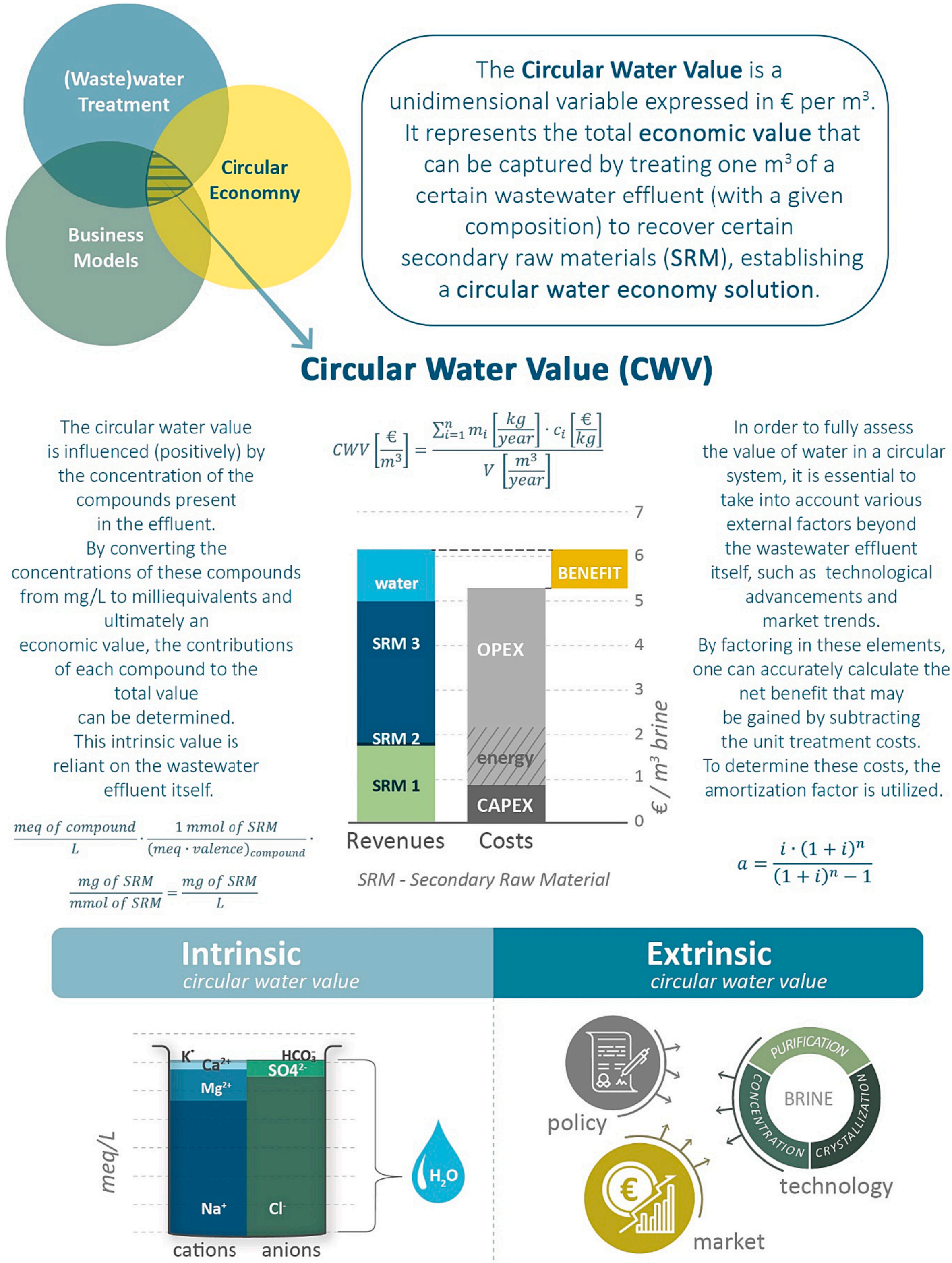

Fig. 12. Visualization of the circular water value concept introduced in this study.

treating coal mine effluent, but further exploration is needed to determine, for example, the quantities and qualities of the recovered materials that can be absorbed in the local market. We also need to investigate if there are specific off-takers who can be considered for all recovered products or only for certain ones, and what possible policy requirements need to be taken into account. For instance, do these recovered products need to meet specific criteria in line with the Waste Framework Directive to be classified as de-characterized waste?

The presented concept is strong in providing not only a new business opportunity for the recovery of all secondary raw materials but also insights into the individual contributions of these materials to the total. This proved to be interesting to stakeholders as it gave them an understanding of which products seem to be more important and can be prioritized when allocating resources, such as investments or time spent establishing contracts with off-takers. It also provides an understanding of actions that may need to be taken to de-characterize these products through end-of-waste criteria. From a technological standpoint, it is important to gain insight into the target that must be achieved to make a novel technology marketable. The cost of treatment per unit, including both capital and operating expenses, can determine whether a technology is viable by comparing it to the circular water value it can capture. We have made a deliberate choice to differentiate between capital expenditure (CAPEX) and operating expenditure (OPEX) to evaluate what factors could potentially influence the business case from being negative to positive. For instance, if the operational expenses (OPEX) are high due to the consumption of excessive energy, one possible solution could be to recover waste heat from the coal mines or neighboring industries such as a nearby power plant, as it is already done in the case of Bolesław Śmiały coal mine. By implementing the Circular Water Value concept and utilizing its intrinsic and extrinsic features, we were able to effectively communicate the benefits of our innovative techniques to the stakeholders and decision-makers. Additionally, we engaged in discussions with them regarding potential enhancements that align with their interests and objectives.

The Circular Water Value of a stream can be calculated using a simple formula that utilizes basic chemistry principles. This helps decision-makers to make informed decisions by creating different scenarios. For instance, if we have an effluent including sodium, we can, in principle, recover NaCl or NaOH, assuming chlorides and hydroxides are present in the wastewater. These secondary raw materials are two different products with distinct applications and possibilities for further market uptake. It is essential to be cautious when using the suggested mathematical formula to determine the recovered quantities of secondary raw materials. The user must verify that there are enough of the necessary compounds in the wastewater to generate these materials. For instance, Xevgenos et al. [49] provide an example of this.

It is important to note that the materials that are recovered can either be in the form of a solid material, such as NaCl, or a solution, such as NaOH. However, for using the mathematical formula consistently, it is essential that the market price should match the SRM in the form to be recovered, as well as the market specifications. Caustic soda solution, for instance, has a different market price at different molar concentrations, and the same applies to different levels of impurities. Such a novel treatment technique for recovering caustic soda from brines can be found in the literature (eg [50,51]). This is particularly important for some materials that vary drastically depending on the quality and intended end-use. For example, magnesium hydroxide (Mg(OH)2) can range from 100 to 1000 EUR/ton, for different purity levels. Therefore, it is crucial to keep this in mind when using the circular water value formula to avoid any misinterpretations or misleading results.

The circular water value is a metric that can be used to evaluate the potential benefits of recovering valuable materials from wastewater. There are different levels of analysis that can be conducted to determine this value. At the most basic level, one can calculate the theoretical value of the wastewater effluent based on its composition and the materials that are targeted for recovery. This value is mostly related to the intrinsic value of the effluent itself. To take things further, one can consider the technologies that are required to recover these materials. Technical expertise is needed to develop process flow diagrams, design a technical system with specific configuration and capacity, and obtain quotation offers to realize such a system, which includes capex and expected OPEX. After collecting this information, one can calculate the unit treatment cost, as illustrated in this work. This cost can be subtracted from the theoretical circular water value to obtain the net benefit in EUR per m^3. This variable should be distinct from the theoretical value, as it represents the "net circular water value" that can be obtained by treating a specific wastewater effluent using a specific circular water technology.

5. Conclusions

Our study introduces a new concept called "Circular Water Value" which offers a simple mathematical method to evaluate the efficiency of integrating resource recovery with wastewater treatment in a circular economy. We tested this concept on two coal mines situated in Poland where we demonstrated how wastewater treatment can play a crucial role in a circular economy. By analyzing two distinct case studies, we gained valuable insights into how this concept can be implemented in various scenarios. Our proposed concept presents a concise and clear way to visualize and measure the potential benefits of wastewater treatment, which is useful for decision-makers. By conducting interdisciplinary research, our work helps bridge the gap between design and implementation, promoting better understanding and adoption of these important concepts. We aim to make this concept accessible to other scientific domains, even those without expertise in wastewater treatment. Our method employs fundamental water chemistry principles that can be easily understood and applied by individuals without a water background. We found that advanced process modeling tools used for analyzing complex processes in circular water systems can be confusing for circular economy practitioners who may lack technical expertise in water or do not frequently work with water treatment tools and equations.

Limitations of this work: it should be noted that the concept presented in this study has only been tested with data collected from two case studies of coal mines in Poland. In order to increase the validity of the concept and identify possible areas for improvement, it is necessary to conduct further testing within the coal mine sector, as well as in the broader (waste)water sector. To address this limitation, future studies may collect data from a larger number of cases, and may also include interviews and meetings with key stakeholders in individual and group settings. We are currently conducting further research on this topic as part of the ongoing EU-funded LIFE BRINE-MINING project, which includes all coal mine industries operating in the relevant regions. Our work has practical implications, as the findings are essential for evaluating the potential of replicating the novel circular water solution in all 17 coal mines in Poland. We believe that this information will be of great significance to project developers and policymakers involved in the development of Just Territorial Plans under the Just Transition Fund.

Suggestions for future research: There are various possible research directions related to the concept of a circular water economy. One of these directions is to explore how this concept can be applied to wastewater effluents that are organically impaired. The current work, however, is focused on inorganic wastewater streams or brines. Therefore, the mathematical formulation had to incorporate basic relevant principles from basic chemistry. It is important to note that wastewater streams such as urban wastewater effluents are often treated through biological processes which may require a different approach in formulating the circular water value concept. It would be interesting to explore how the value of water in circular economy varies based on the specific value chains being studied. For example, one could examine the production of hydrogen through electrolysis of high-quality water obtained from a proposed water treatment solution or the production of chlorine using purified and concentrated brine stream.

CRediT authorship contribution statement

D. Xevgenos: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **K. Panteleaki Tourkodimitri:** Data curation, Formal analysis, Investigation. **M. Mortou:** Data curation, Formal analysis, Investigation, Project administration, Visualization. **K. Mitko:** Data curation, Formal analysis, Investigation. **D. Sapoutzi:** Visualization. **D. Stroutza:** Writing – review & editing. **M. Turek:** Writing – review & editing. **M.C.M. van Loosdrecht:** 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.

Data availability

Data will be made available on request.

Acknowledgment

This project has received funding from the European Union's Horizon 2020 - Research and Innovation Framework Programme under Grant Agreement no. 730390 (ZERO BRINE – Industrial Desalination – Resource Recovery – Circular Economy). www.zerobrine.eu. We would like to acknowledge also the LIFE BRINE-MINING project (LIFE18 ENV/GR/000019) in the framework of which this research is being continued (https://brinemining.eu/en/home/).

References

[1] F. Blomsma, G. Brennan, The emergence of circular economy: a new framing around prolonging resource productivity, J. Ind. Ecol. 21 (3) (2017) 603–614.
[2] P. Ghisellini, C. Cialani, S. Ulgiati, A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems, J. Clean. Prod. 114 (2016) 11e32.
[3] M. Lewandowski, Designing the business models for circular economy—towards the conceptual framework, Sustainability 8 (1) (2016) 43.
[4] M. Lieder, A. Rashid, Towards circular economy implementation: a comprehensive review in context of manufacturing industry, J. Clean. Prod. 115 (2016) 36–51.
[5] M. Geissdoerfer, P. Savaget, N.M. Bocken, E.J. Hultink, The circular economy–a new sustainability paradigm? J. Clean. Prod. 143 (2017) 757–768.
[6] A. Murray, K. Skene, K. Haynes, The circular economy: an interdisciplinary exploration of the concept and application in a global context, J. Bus. Ethics 140 (2017) 369–380.
[7] J. Kirchherr, R. van Santen, Research on the circular economy: a critique of the field, Resour. Conserv. Recycl. 151 (2019), https://doi.org/10.1016/j.resconrec.2019.104480.
[8] J. Kirchherr, D. Reike, M. Hekkert, Conceptualizing the circular economy: an analysis of 114 definitions, Resour. Conserv. Recycl. 127 (2017) 221–232.
[9] Arup, Antea Group and Ellen MacArthur Foundation, Water and Circular Economy: White Paper. https://nextgenwater.eu/wp-content/uploads/2018/10/Water_and_circular_economy-Co.Project_White_paper.pdf, 2018.
[10] R.C. Brears, The circular water economy, in: Developing the Circular Water Economy. Palgrave Studies in Climate Resilient Societies, Palgrave Pivot, Cham, 2020, https://doi.org/10.1007/978-3-030-32575-6_4.
[11] C.Y. Chen, S.W. Wang, H. Kim, S.Y. Pan, C. Fan, Y.J. Lin, Non-conventional water reuse in agriculture: a circular water economy, Water Res. 199 (2021) 117193.
[12] M. Palmeros Parada, P. Kehrein, D. Xevgenos, L. Asveld, P. Osseweijer, Societal values, tensions and uncertainties in resource recovery from wastewaters, J. Environ. Manag. 319 (2022), https://doi.org/10.1016/j.jenvman.2022.115759.
[13] EU Commission, Funder & tender opportunities, Retrieved from, https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl6-2023-circbio-01-3, 2023.
[14] EU Commission, A Clean Planet for All-A European Strategic Long-term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy, European Commission, Brussels, 2018, pp. 15–31. Technical report.
[15] S. Evans, D. Vladimirova, M. Holgado, K. Van Fossen, M. Yang, E.A. Silva, C. Y. Barlow, Business model innovation for sustainability: towards a unified perspective for creation of sustainable business models, Bus. Strateg. Environ. 26 (5) (2017) 597–608.
[16] F.J.D. Lopez, T. Bastein, A. Tukker, Business model innovation for resource-efficiency, circularity and cleaner production: what 143 cases tell us, Ecol. Econ. 155 (2019) 20–35.
[17] M. Geissdoerfer, D. Vladimirova, S. Evans, Sustainable business model innovation: a review, J. Clean. Prod. 198 (2018) 401–416.
[18] J. Masarczyk, C.H. Hansson, R. Solomon, B. Hallmans, Advances mine drainage water treatment, engineering for zero discharge, Desalination 75 (1989) 259–287.
[19] B. Ericsson, B. Hallmans, Treatment of saline wastewater for zero discharge at the Debiensko coal mines in Poland, Desalination 105 (1–2) (1996) 115–123.
[20] D. Xevgenos, M. Argyrou, M. Marcou, V. Louca, M. Mortou, F. Kuepper, Seawater desalination in view of marine environmental and climate change impacts: the case study of Cyprus, Desalin. Water Treat. 211 (1) (2021) 15–30, https://doi.org/10.5004/dwt.2021.26916.
[21] M. Turek, E. Laskowska, K. Mitko, M. Chorążewska, P. Dydo, K. Piotrowski, A. Jakobik-Kolon, Application of nanofiltration and electrodialysis for improved performance of a salt production plant, Desalin. Water Treat. 64 (2017) 244–250.
[22] E. Laskowska, M. Turek, K. Mitko, P. Dydo, Concentration of mine saline water in high-efficiency hybrid RO-NF system, Desalin. Water Treat. 128 (2018) 414–420.
[23] M.P. Pieroni, T.C. McAloone, D.C. Pigosso, Business model innovation for circular economy and sustainability: a review of approaches, J. Clean. Prod. 215 (2019) 198–216.
[24] J. Richardson, The business model: an integrative framework for strategy execution, Strateg. Chang. 17 (5–6) (2008) 133e144, https://doi.org/10.1002/jsc.821.
[25] E. Guldmann, N.M. Bocken, H. Brezet, A design thinking framework for circular business model innovation, Journal of Business Models 7 (1) (2019) 39–70.
[26] J.L. Nußholz, Circular business models: defining a concept and framing an emerging research field, Sustainability 9 (10) (2017) 1810.
[27] EMF, the Antea Group, Arup, Water and Circular Economy. White Paper (Draft 2-b), Ellen Macarthur Foundation, 2018 (16 April 2018).
[28] D.W. Pearce, R.K. Turner, Economics of Natural Resources and the Environment, Johns Hopkins University Press, Baltimore, 1990.
[29] M.S. Andersen, An introductory note on the environmental economics of the circular economy, Sustain. Sci. 2 (2007) 133e140.
[30] B. Su, A. Heshmati, Y. Geng, X. Yu, A review of the circular economy in China: moving from rhetoric to implementation, J. Clean. Prod. 42 (2013) 215e227.
[31] N. Kakwani, P. Kalbar, Review of circular economy in urban water sector: challenges and opportunities in India, J. Environ. Manag. 271 (2020) 111010, https://doi.org/10.1016/j.jenvman.2020.111010.
[32] V. Prieto-Sandoval, C. Jaca, M. Ormazabal, Towards a consensus on the circular economy, J. Clean. Prod. 179 (2018) 605–615, https://doi.org/10.1016/j.jclepro.2017.12.224.
[33] M. Preisner, M. Smol, M. Horttanainen, I. Deviatkin, J. Havukainen, M. Klavins, K. Roosalu, Indicators for resource recovery monitoring within the circular economy model implementation in the wastewater sector, J. Environ. Manag. 304 (2022) 114261, https://doi.org/10.1016/j.jenvman.2021.114261.
[34] Y. Qtaishat, J. Hofman, K. Adeyeye, Circular water economy in the EU: findings from demonstrator projects, Clean Technol. 4 (2022) 865–892, https://doi.org/10.3390/cleantechnol4030054.
[35] D. Xevgenos, Creating value out of seawater desalination brines through the recovery of water and salts, using renewable energy sources. Doctoral dissertation, National Technical University of Athens, Date of completion: 16 March 2016, Retrieved from, https://www.didaktorika.gr/eadd/handle/10442/37648, 2016.
[36] D. Xevgenos, P. Michailidis, K. Dimopoulos, M. Krokida, M. Loizidou, Design of an innovative vacuum evaporator system for brine concentration assisted by software tool simulation, Desalin. Water Treat. 53 (12) (2015) 3407–3417.
[37] D. Xevgenos, A. Vidalis, K. Moustakas, D. Malamis, M. Loizidou, Sustainable management of brine effluent from desalination plants: the SOL-BRINE system, Desalin. Water Treat. 53 (12) (2015) 3151–3160.
[38] R. Yin, Case Study Research: Design and Methods, fourth ed., Sage, CA, 2009.
[39] K.M. Eisenhardt, M.E. Graebner, Theory building from cases: opportunities and challenges, Acad. Manag. J. 50 (1) (2007) 25–32.
[40] B. Flyvbjerg, Five misunderstandings about case-study research, Qual. Inq. 12 (2) (2006) 219–245.
[41] P. Eriksson, A. Kovalainen, Qualitative Methods in Business Research: A Practical Guide to Social Research, Sage, 2015.
[42] M. Healy, C. Perry, Comprehensive criteria to judge validity and reliability of qualitative research within the realism paradigm, Qual. Mark. Res. Int. J. 3 (3) (2000) 118–126.
[43] K.M. Eisenhardt, Building theories from case study research, Acad. Manag. Rev. 14 (4) (1989) 532–550.
[44] H.T. El-Dessouky, H.M. Ettouney, Fundamentals of Salt Water Desalination, Elsevier, 2002.
[45] D.C. Mussatti, W.M. Vatavuk, Cost Estimation: Concepts and Methodology, 2002.
[46] M. Micari, A. Cipollina, A. Tamburini, M. Moser, V. Bertsch, G. Micale, Techno-economic analysis of integrated processes for the treatment and valorisation of neutral coal mine effluents, J. Clean. Prod. 270 (2020) 122472.
[47] M. Papapetrou, A. Cipollina, U. La Commare, G. Micale, G. Zaragoza, G. Kosmadakis, Assessment of methodologies and data used to calculate desalination costs, Desalination 419 (2017) 8–19.
[48] K. Mitko, Database of data collected during WP3 demonstration activity, in: DataverseNL V2, 2022, https://doi.org/10.34894/DKWCO8. ZEROBRINE_D3.2_DATA_BS_v0.1.docx.
[49] D. Xevgenos, K. Moustakas, D. Malamis, M. Loizidou, An overview on desalination & sustainability: renewable energy-driven desalination and brine management, Desalin. Water Treat. 57 (5) (2016) 2304–2314.
[50] A. Culcasi, R. Ktori, A. Pellegrino, M. Rodriguez-Pascual, M.C.M. van Loosdrecht, A. Tamburini, A. Cipollina, D. Xevgenos, G. Micale, Towards Sustainable Production of Minerals and Chemicals Through Seawater Brine Treatment Using Eutectic Freeze Crystallization and Electrodialysis With Bipolar Membranes, 2022, https://doi.org/10.1016/j.jclepro.2022.133143.
[51] C. Morgante, F. Vassalo, D. Xevgenos, A. Cipollina, M. Micari, A. Tamburini, G. Micale, Valorisation of SWRO brines in a remote island through a circular

approach: techno-economic analysis and perspectives, Desalination 542 (2022) 116005, https://doi.org/10.1016/j.desal.2022.116005.
[52] European Commission, Communication on the on a monitoring framework for the circular economy. COM. https://ec.europa.eu/environment/circular-economy/pdf/monitoring-framework.pdf, 2018.
[53] G.A. Tsalidis, K. Panteleaki Tourkodimitri, K. Mitko, G. Gzyl, A. Skalny, J. A. Posada, D. Xevgenos, Assessing the environmental performance of a novel coal mine brine treatment technique: a case in Poland, J. Clean. Prod. 358 (2022) 131973, https://doi.org/10.1016/j.jclepro.2022.131973.