

# Technoeconomics of the Industrial-Scale cloSURE<sup>®</sup> Biological Treatment Process

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## Abstract

Mining-influenced water in South Africa's Witbank coalfields demands regulatory-compliant sulfate removal, yet reverse osmosis is energy-intensive, costly, and produces brine. A technoeconomic assessment compares Mintek's cloSURE<sup>®</sup> process, which couples microbial sulfate reduction with biological sulfide oxidation and sulfur recovery, to reverse osmosis on a normalised capacity of 5 000 m<sup>3</sup> d<sup>-1</sup>. Discounted cash flow analysis, supported by demonstration-plant data (50 m<sup>3</sup> d<sup>-1</sup>) and Guthrie (1974) cost estimation, indicates fixed capital investment of US\$13 million for cloSURE<sup>®</sup> versus US\$15 million for reverse osmosis and operating expenditure of US\$2 million versus US\$5 million per annum, respectively.

**Keywords:** Sulfate reduction, sulfide oxidation, resource recovery, capital cost, economic indicators

## Introduction

Mining-influenced water containing elevated sulfate concentrations remains a major treatment challenge for the mining industry. Membrane-based technologies such as reverse osmosis are widely applied for sulfate removal, but their implementation is associated with high capital and operating costs, substantial reagent consumption for pretreatment and membrane conditioning, and the management of concentrated brines (van Rooyen *et al.* 2021; Dill *et al.* 1998), motivating continued investigation of biological sulfur cycling as an alternative (Kinnunen *et al.* 2017). Early pilot-scale studies demonstrated that sulfate-reducing microorganisms can generate alkalinity and precipitate dissolved metals while reducing sulfate concentrations (Dvorak *et al.* 1992), and subsequent work expanded this concept to passive and semi-passive treatment systems incorporating organic-substrate bioreactors (Neculita *et al.* 2007), carbon-source selection, reactor configuration (Dill *et al.* 2001), and sulfide management for stable operation (Harrison *et al.* 2014). More recently, Marais *et al.* (2024) reported

a semi-passive reactor integrating sulfate reduction with biological sulfide oxidation for elemental sulfur recovery. Despite these advances, the industrial implementation of biological sulfate-reduction technologies remains limited, and technoeconomic assessments of integrated sulfate-reduction and sulfide-oxidation systems are scarce. This study therefore evaluates the technical performance and technoeconomic feasibility of the cloSURE<sup>®</sup> process using operational data from a demonstration-scale plant, estimates capital and operating costs for full-scale implementation against a reverse-osmosis benchmark, and applies discounted cash-flow modelling to assess long-term financial performance.

## Site Description and Process Concept

### *Water Quality and Treatment Objectives*

The cloSURE<sup>®</sup> process was assessed against irrigation-water quality criteria defined in the South African Water Quality Guidelines (Department of Water Affairs and Forestry 1996), with selected results summarised in Table 1. The untreated water exceeds several limits for metals and acidity indicators,



confirming the need for treatment prior to agricultural reuse. Following treatment, most regulated constituents fall within irrigation-quality limits, although manganese remains elevated and would require additional polishing for full compliance. The acidic influent (pH ≈ 3) is neutralised to near-neutral conditions (pH ≈ 7), the sodium adsorption ratio (SAR) remains below irrigation thresholds indicating low soil-sodicity risk, and increased mineral saturation reflects alkalinity generation during the coupled sulfate-reduction and sulfide-oxidation reactions.

*cloSURE® Process Concept and Demonstration Plant Layout*

To achieve treatment objectives aligned with irrigation-water quality criteria, the cloSURE® process integrates sequential biological sulfate-reduction and sulfide-oxidation stages within a demonstration-scale treatment train. Figure 1 shows the configuration of the cloSURE® demonstration plant. Mining-influenced water is pumped from an upstream storage dam to feed tanks and distributed to two biological sulfate-reduction ponds, where sulfate is reduced to sulfide and dissolved metals precipitate. The sulfide-rich effluent then flows through a series of biological sulfide-oxidation channels where sulfide is converted primarily to

elemental sulfur. Treated water is collected in a sump and returned to the storage dam. The demonstration plant operates at a capacity of 50 m<sup>3</sup>d<sup>-1</sup>.

**Demonstration Plant Performance**

*Sulfate Reduction and Sulfide Oxidation Performance*

During the stable operating period beginning at approximately day 597, influent sulfate concentrations remained near 2 500 mg L<sup>-1</sup> while effluent concentrations declined from approximately 1 781 mg L<sup>-1</sup> to 600 mg L<sup>-1</sup>. Concurrently, dissolved sulfide increased from about 383 mg L<sup>-1</sup> to 652 mg L<sup>-1</sup>, which confirms sustained biological sulfate reduction. Sulfate-reduction efficiency increased from approximately 31 % (70 g m<sup>-3</sup> d<sup>-1</sup>) to a peak of 97 % (204 g m<sup>-3</sup> d<sup>-1</sup>). Sulfide concentrations entering the oxidation channels averaged 418 mg L<sup>-1</sup> and decreased to an average of 235 mg L<sup>-1</sup> following oxidation, with maximum oxidation rates of 29 g m<sup>-3</sup> d<sup>-1</sup> (≈96 %). These results confirm stable coupled sulfate reduction and sulfide oxidation during continuous operation.

**Technoeconomic Assessment**

Capital costs for the benchmark reverse-osmosis system were estimated using the Guthrie method, while a discounted cash-flow analysis was conducted to evaluate

*Table 1 Selected irrigation water quality criteria compared with cloSURE®-treated mining-influenced water.*

Parameter	Irrigation criterion	Untreated MIW	Treated MIW
pH	6.5–8.5	3.0	7.2
Langelier index	–0.2–0.2	–0.5	3.0
Ryznar index	≤6.5	4.2	0.1
SAR (mmol <sup>0.5</sup> L <sup>-0.5</sup> )	≤1.5	0.6	0.9
Al (mg L <sup>-1</sup> )	≤5.0	43.6	0.1
Cu (mg L <sup>-1</sup> )	≤0.02	0.05	0.01
F (mg L <sup>-1</sup> )	≤2.0	2.7	1.0
Fe (mg L <sup>-1</sup> )	≤5.0	206.2	5.1
Mn (mg L <sup>-1</sup> )	≤0.02	17.8	19.6
N (mg L <sup>-1</sup> )	≤5.0	8.7	0.2
Na (mg L <sup>-1</sup> )	≤70	70	109
Ni (mg L <sup>-1</sup> )	≤0.20	0.22	0.01
Zn (mg L <sup>-1</sup> )	≤1.00	0.83	0.03

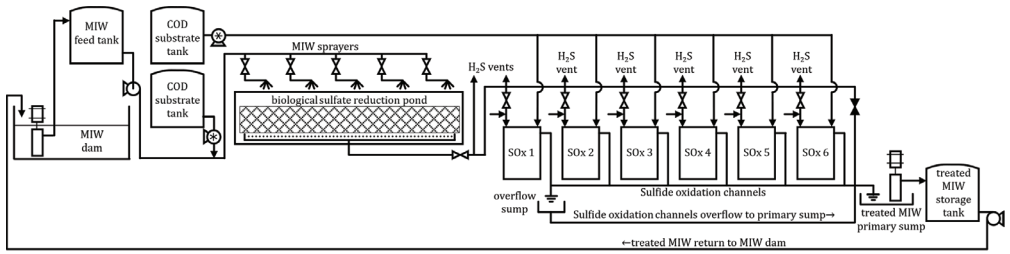


Figure 1 Process flow diagram of the cloSURE® process.

the financial performance of the cloSURE® process, incorporating detailed engineering data and reported operational information from both systems. The cloSURE® demonstration plant treats 50 m<sup>3</sup> d<sup>-1</sup> using biological sulfate reduction and sulfide oxidation, whereas the benchmark reverse-osmosis system operates at approximately 5 000 m<sup>3</sup> d<sup>-1</sup>. To enable comparison between technologies of different scale and construction period, costs were adjusted for inflation and capacity using the cost-to-capacity scaling relationship

$$C_2 = C_1 \left( \frac{P_2}{P_1} \right)^n \left( \frac{I_2}{I_1} \right)$$

where  $C_1$  and  $C_2$  represent plant costs at capacities  $P_1$  and  $P_2$ , respectively,  $n$  is a technology-specific scaling exponent, and the ratio  $I_2/I_1$  accounts for inflation and changes in equipment cost over time. The assessment considers four scenarios: (i) the cloSURE® demonstration plant, (ii) a scaled cloSURE® implementation at 5 000 m<sup>3</sup> d<sup>-1</sup>, (iii) a benchmark reverse-osmosis system based on reported engineering data, and (iv) a Guthrie-method estimate of the same. Process specifications are summarised in Tables 2 and 3, and typical industrial cost data were reclassified into standard engineering cost categories to preserve confidentiality and enable direct comparison. Abattoir waste was used as the benchmark feedstock for cloSURE®. Capital costs, summarised in Table 4, reflect the modest requirements of the demonstration plant owing to its small footprint and limited mechanical complexity; at 5 000 m<sup>3</sup> d<sup>-1</sup>, reactor packing material and civil infrastructure become the dominant cost drivers.

### Capital Expenditure Comparison

Previous studies have shown that the longevity and replacement requirements of organic substrates used as bed materials can strongly influence the economic feasibility of biological sulfate-reduction systems (e.g., Neculita *et al.* 2007; van Rooyen *et al.* 2021). The present analysis similarly indicates that, at larger scales, reactor support media becomes a dominant capital component of the cloSURE® process. For the benchmark reverse-osmosis system, the owner-reported capital expenditure and the Guthrie-method estimate fall within the same order of magnitude, indicating good agreement between the datasets. Although total capital requirements for reverse osmosis and the scaled cloSURE® process are broadly comparable, their cost structures differ. cloSURE® concentrates capital in reactor support media and large treatment basins, whereas reverse osmosis requires major investment in mechanical equipment, pretreatment systems, piping, and electrical and instrumentation infrastructure. These differences become more pronounced in the operating expenditure of the two process types.

### Operational Expenditure Comparison

Table 5 summarises operating costs for the cloSURE® process and the benchmark reverse-osmosis system. At demonstration scale, cloSURE® exhibits relatively high unit treatment costs due to small throughput and intensive analytical monitoring associated with research operation. When scaled to 5 000 m<sup>3</sup> d<sup>-1</sup>, however, the unit operating cost decreases substantially as fixed costs are distributed across a larger treatment capacity.



*Table 2 Process specifications for the cloSURE® plant at demonstration and scaled capacity.*

Specification	Demonstration Scale	Scaled Capacity
Normal production flowrate	50.0 m <sup>3</sup> d <sup>-1</sup>	5 000.0 m <sup>3</sup> d <sup>-1</sup>
Design production flowrate	57.5 m <sup>3</sup> d <sup>-1</sup>	5 750.0 m <sup>3</sup> d <sup>-1</sup>
Influent sulfate concentration as SO <sub>4</sub> <sup>2-</sup>	2 500 mg L <sup>-1</sup>	7 412 mg L <sup>-1</sup>
Effluent sulfate concentration as SO <sub>4</sub> <sup>2-</sup>	400 mg L <sup>-1</sup>	400 mg L <sup>-1</sup>
Sulfide generated as S <sup>2-</sup>	701 mg L <sup>-1</sup>	2 341 mg L <sup>-1</sup>
Effluent sulfide concentration as S <sup>2-</sup>	200 mg L <sup>-1</sup>	200 mg L <sup>-1</sup>
Sulfur extraction efficiency	85.0 %	85.0 %
Sulfur net yield	7 345 kg a <sup>-1</sup>	3 139 ton a <sup>-1</sup>
Feedstock for sulfate reduction and sulfide oxidation	Abattoir waste	Abattoir waste
Routine sampling campaign frequency	once per week	once per week
Plant lifespan	20 years	20 years
Plant commissioning duration	9 months	9 months
Planned & unplanned maintenance	20 days annum <sup>-1</sup>	20 days annum <sup>-1</sup>

*Table 3 Process specifications and capital cost breakdown for typical benchmark reverse-osmosis mine water treatment facilities based on reported plant data and a Guthrie-method estimate.*

Specification	Engineering Estimate	Guthrie Estimate
Design treatment capacity	≈5 800 m <sup>3</sup> d <sup>-1</sup>	≈5 800 m <sup>3</sup> d <sup>-1</sup>
Typical operating throughput	≈5 000 m <sup>3</sup> d <sup>-1</sup>	≈5 000 m <sup>3</sup> d <sup>-1</sup>
Recovery ratio	≈75 %	≈75 %
Permeate production	≈3 800 m <sup>3</sup> d <sup>-1</sup>	≈3 800 m <sup>3</sup> d <sup>-1</sup>
Concentrate production	≈1 300 m <sup>3</sup> d <sup>-1</sup>	≈1 300 m <sup>3</sup> d <sup>-1</sup>
Feed sulfate concentration	≈7 400 mg L <sup>-1</sup>	≈7 400 mg L <sup>-1</sup>
Permeate sulfate concentration	≈400 mg L <sup>-1</sup>	≈400 mg L <sup>-1</sup>
Concentrate sulfate concentration	≈28 000 mg L <sup>-1</sup>	≈28 000 mg L <sup>-1</sup>
pH control reagents	≈4.6×10 <sup>5</sup> kg month <sup>-1</sup>	≈2.7×10 <sup>5</sup> kg month <sup>-1</sup>
Coagulation / flocculation reagents	≈1.0×10 <sup>3</sup> kg month <sup>-1</sup>	≈3.8×10 <sup>4</sup> kg month <sup>-1</sup> )
Oxidants and disinfectants	≈3.5×10 <sup>3</sup> kg month <sup>-1</sup>	
Membrane conditioning reagents	≈4.5×10 <sup>3</sup> kg month <sup>-1</sup>	≈4.5×10 <sup>3</sup> kg month <sup>-1</sup> )
Antiscalant dosing	≈1.4×10 <sup>3</sup> kg month <sup>-1</sup>	
Design plant lifespan	20 years	20 years
Commissioning duration	9 months	9 months
Planned maintenance allowance	10 d a <sup>-1</sup>	10 d a <sup>-1</sup>
Unplanned downtime allowance	10 d a <sup>-1</sup>	10 d a <sup>-1</sup>

At commercial scale, operating expenditure for cloSURE® is dominated by utilities, maintenance, waste handling, and patent royalties, while labour and administrative costs remain comparatively low due to the semi-passive nature of the process.

In contrast, the reverse-osmosis system incurs higher operating costs due to its reliance on chemical reagents, energy consumption, and mechanical maintenance. Both the engineering data and the Guthrie-method estimate for the reverse-osmosis system yield



**Table 4** Capital expenditure for cloSURE® and benchmarked reverse-osmosis using engineering and Guthrie-method estimates.

Cost Category	cloSURE® Demo (Guthrie)	cloSURE® Scaled (Guthrie)	Reverse Osmosis	
			(Guthrie)	(Engineering Data)
Site & civil works	USD 219 759	USD 1 970 251	USD 5 543 158	USD 12 239 493
Equipment	USD 19 315	USD 323 219	USD 4 596 621	USD 1 515 197
Indirect costs	USD 285 550	USD 10 710 222	USD 3 447 525	USD 1 161 882
Contingencies	USD 51 588	USD 1 283 820	USD 1 358 730	USD 1 491 657
Total fixed capital	USD 576 212	USD 14 287 512	USD 14 946 034	USD 16 408 230

Exchange rate: USD 1.0000 = ZAR 16.4995, based on the South African Reserve Bank Selected Historical Rates as of 5 March 2026.

**Table 5** Operational expenditure for cloSURE® and benchmarked reverse-osmosis using engineering and Guthrie-method estimates per annum.

Cost Category	cloSURE® Demo (Guthrie)	cloSURE® Scaled (Guthrie)	Reverse Osmosis	
			(Guthrie)	(Engineering Data)
Direct costs	USD 115 926	USD 836 566	USD 2 416 320	USD 3 279 004
Fixed costs	USD 43 186	USD 1 070 821	USD 1 120 176	USD 1 229 765
Overhead costs	USD 5 637	USD 79 303	USD 393 479	USD 564 740
General costs	USD 11 132	USD 107 594	USD 419 298	USD 604 113
Opex	USD 175 881	USD 2 094 284	USD 4 349 273	USD 5 677 621

Exchange rate: USD 1.0000 = ZAR 16.4995, based on the South African Reserve Bank Selected Historical Rates as of 5 March 2026.

substantially higher unit treatment costs than those calculated for cloSURE®. Although capital investment is broadly comparable, the biological process has much lower long-term operating costs, indicating a more favourable economic trajectory.

### Discounted Cashflow and Financial Indicators

A discounted cash-flow analysis was conducted for the full-scale cloSURE® process to evaluate its long-term financial performance relative to reverse-osmosis treatment. The model incorporates capital investment, operating costs, revenue from elemental sulfur production, and the operating-cost savings associated with replacing membrane-based treatment. Elemental sulfur sales, valued at USD 508 070 per year, contribute appreciably to the economic performance of the process. When combined with the operating-cost advantage over reverse osmosis, these revenues drive the positive financial outcome. Based on a median

South African inflation rate of 5.1 % over a 20-year operation horizon with an average real discount rate of 10.5 %, the analysis yields a net present value of approximately -USD 1.8 million, an internal rate of return of 8.5 %, a return on investment of 10.2 %, and a payback period of approximately 10.4 years. The analysis reflects only the direct economics of the cloSURE® process and does not include wider operational or environmental benefits. Abattoir waste was used as the benchmark feedstock for the technoeconomic assessment because it is produced as a disposal liability at slaughterhouses. Instead of incurring disposal costs, the producer only bears the cost of transporting the waste to the treatment facility, resulting in a net feedstock cost of approximately zero. By contrast, reverse osmosis – which generates no revenue or saleable co-products – is not amenable to payback period analysis. Assessed instead on a net present cost basis, reverse osmosis incurs a discounted lifetime expenditure of approximately -USD 48 million over



the same horizon, reflecting its character as a compliance cost rather than a value-generating asset. On a unit-cost basis, the total cost to treat mining-influenced water using cloSURE® was estimated at USD 0.92 m<sup>-3</sup> (Table 6) compared to USD 2.97 m<sup>-3</sup> for reverse osmosis, representing a reduction of approximately 69 %. This comparison underscores the economic advantage of the cloSURE® process, where resource recovery partially offsets treatment costs and produces a positive long-term financial outcome.

A comparison with alternative substrates shows that feedstock cost strongly influences the overall treatment economics. Fruit juice represents the lowest-cost purchasable substrate, with a feedstock price of approximately USD 21 ton<sup>-1</sup>, corresponding to a treatment cost of USD 1.04 m<sup>-3</sup> and annual operating expenditure of about USD 2.3 million. Ethanol and crude glycerol are substantially more expensive, with feedstock prices of approximately USD 1 578 ton<sup>-1</sup> and USD 740 ton<sup>-1</sup>, resulting in treatment costs of USD 7.72 m<sup>-3</sup> and USD 8.14 m<sup>-3</sup>, respectively. Acetate represents the least favourable option due to its high material cost (≈USD 5 818 ton<sup>-1</sup>) and a treatment cost of USD 39.46 m<sup>-3</sup>). These results highlight the importance of low-cost carbon sources for the economic feasibility of biological sulfate reduction processes. However, feedstock costs may vary regionally due to differences in availability, transport distance, and substrate quality. In addition, reliable supply and appropriate storage conditions are necessary to ensure continuous substrate availability and prevent premature degradation of organic feedstocks prior to use. Fruit juice was the only alternative substrate that produced favourable financial

indicators, yielding an NPV of -USD 1.6 million, IRR of 8.7 %, ROI of 10.4 %, and a payback period of 10.2 years.

**Conclusions**

The cloSURE® demonstration plant successfully improved mining-influenced water quality through biological sulfate reduction and sulfide oxidation, increasing pH, removing metals and substantially reducing sulfate concentrations. Sulfate-reduction efficiencies of up to 97 % were achieved during stable operation, although performance was sensitive to COD availability and operational continuity. At full scale, the cloSURE® process requires capital investment comparable to reverse-osmosis treatment but exhibits substantially lower operating expenditure due to reduced chemical demand, passive operation and lower labour requirements. Financial analysis indicates favourable long-term performance: annual operating-cost savings combined with approximately USD 508 070 per year in elemental-sulfur revenue yield a net present value of about USD 4 million over twenty years at an inflation rate of 5.1 %. The resulting internal rate of return (8.2 %), return on investment (10.2 %) and payback period (~10.4 years) indicate economically viable deployment. Reverse osmosis generates no revenue or saleable co-products and is not amenable to payback period analysis; assessed on a net present cost basis, it incurs a discounted lifetime expenditure of approximately -USD 48 million over the same horizon, confirming its character as a compliance cost rather than a value-generating asset. Safety considerations are primarily associated with hydrogen

*Table 6 Operating cost estimates for cloSURE® using alternative carbon substrates.*

Scenario	Material Cost	Treatment Cost	Operational Cost
Reverse osmosis	-	USD 2.97 m <sub>MiW</sub> <sup>-3</sup>	USD 5 677 621 a <sup>-1</sup>
cloSURE® (abattoir waste)	USD 0 ton <sup>-1</sup>	USD 0.92 m <sub>MiW</sub> <sup>-3</sup>	USD 2 094 284 a <sup>-1</sup>
cloSURE® (fruit juice)	USD 21 ton <sup>-1</sup>	USD 1.04 m <sub>MiW</sub> <sup>-3</sup>	USD 2 305 569 a <sup>-1</sup>
cloSURE® (ethanol)	USD 1 578 ton <sup>-1</sup>	USD 7.72 m <sub>MiW</sub> <sup>-3</sup>	USD 13 819 231 a <sup>-1</sup>
cloSURE® (glycerol)	USD 740 ton <sup>-1</sup>	USD 8.14 m <sub>MiW</sub> <sup>-3</sup>	USD 14 546 477 a <sup>-1</sup>
cloSURE® (acetate)	USD 5 818 ton <sup>-1</sup>	USD 39.46 m <sub>MiW</sub> <sup>-3</sup>	USD 68 570 822 a <sup>-1</sup>



sulfide exposure, mine-water handling and operational interruptions, emphasising the need for appropriate monitoring and operational support. Overall, the results demonstrate that the cloSURE® process provides a technically viable and economically competitive alternative to membrane-based mine-water treatment.

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