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Process Design and Techno-Economic Assessment of Selective Lithium Recovery from Caspian Oilfield Produced Water Using Hybrid Membrane-Electrochemical Systems

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Abstract. A conceptual hybrid membrane-electrochemical process is designed for selective lithium recovery from Caspian oilfield produced water. It combines deoiling, ceramic microfiltration, divalent-selective nanofiltration, electrochemical lithium capture-release, and membrane-assisted product conversion. As no validated field-wide Caspian lithium assay is available, 20, 50, and 100 mg/L are treated as design cases. At 1,000 m^3/day, 330 days, and 85% recovery, they yield 29.9, 74.7, and 149.3 t/year of Li_2CO_3. With USD 5.6 million fixed capital and USD 1.878 million net annualized cost, levelized costs are USD 62.9, 25.1, and 12.6/kg. The scenario model identifies feed grade, pretreatment, and component life as pilot-validation priorities rather than claiming commercial readiness.

Keywords: *produced water; direct lithium extraction; nanofiltration; electrochemical intercalation; techno-economic assessment; Caspian oilfields*

1. Introduction

Produced water is the largest aqueous by-product of oil and gas production. Salinity, hydrocarbons, scale-forming ions, solids, and production chemicals make it difficult to treat, but high flow can turn dissolved critical minerals into a secondary resource. Resource potential therefore depends on water volume, salinity, competing ions, treatment demand, and infrastructure as well as lithium grade [1-3].

Direct lithium extraction is faster than solar evaporation. Membranes remove oil, colloids, hardness, or selected ions, while electrochemical transport or intercalation captures lithium with limited chemical regeneration. Decoupled cells, redox-couple electrodialysis, and selective membranes have processed low-quality brines [4-

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7], but fouling, resistance, electrode life, and polishing determine plant cost.

The South Caspian is relevant because produced water already enters hydrocarbon infrastructure. Public literature, however, establishes no representative lithium grade for Azerbaijani fields. Rather than invent one, this paper tests a coherent train across feed assays and identifies pre-investment measurements.

2. Research objective and contribution

The study designs a sequence for oily, mineralized water, applies reproducible mass and cost equations, and identifies economic thresholds. Membranes reduce divalent competition, electrochemical capture separates lithium from monovalent ions, and membrane conversion supports product formation and reagent recycling.

3. Methodology and design basis

The study combines conceptual process design with scenario-based techno-economic assessment. Twelve peer-reviewed sources from 2023-2026 were selected for evidence on produced-water resource quality, lithium-selective membranes, electrochemical recovery, scale-up, and economics [1-12]. A steady-state mass balance was prepared for 1,000 m^3/day. Low, base, and high cases use 20, 50, and 100 mg/L lithium, 330 operating days, and 85% overall recovery so that the effect of feed grade remains visible.

Daily lithium feed is $M_{Li} = Q \times C_{Li}/1000$, where Q is m^3/day and C_{Li} is mg/L. Lithium carbonate equivalent is $M_{LCE} = M_{Li} \times R \times 73.89/(2 \times 6.94)$. The economic boundary begins at receipt of separated produced water and ends at dry Li_2CO_3. New pretreatment, membranes, electrochemical stacks, conversion, utilities, and residue handling are included; upstream oil production is excluded. The capital-recovery factor uses a 10% real discount rate and 15-year life. Base fixed capital is USD 5.6 million, electricity demand is 3.2 kWh/m^3 at USD 0.09/kWh, and the water-management credit is USD 0.35/m^3. These are screening assumptions, not vendor quotations.

4. Proposed hybrid process architecture

The author-developed process is shown in Figure 1. A compact separator or hydrocyclone, walnut-shell filter, and ceramic microfiltration remove oil, particles, and iron solids before they block nanofiltration or coat electrochemical surfaces. Ceramic media tolerate backwashing, hydrocarbons, and salinity.

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Divalent-rejecting nanofiltration passes most Li^+ and other monovalent ions while retaining Mg^{2+}, Ca^{2+}, Ba^{2+}, sulfate, and colloidal silica. It improves the lithium-to-hardness ratio rather than separating Li^+/Na^+. Subnanometre and nanochannel advances remain limited by permeability-selectivity trade-offs, salinity screening, fouling, and manufacturability [8-11]; a staged, cleanable array is therefore preferred.

Softened permeate enters electrochemical capture-release. A selective intercalation electrode takes up Li^+; switching it to a low-volume recovery solution and reversing potential releases concentrated LiCl. Paired or redox-couple cells reduce parasitic reactions. High Mg/Li ratios and recovery have been demonstrated, although current efficiency and capacity fade remain decisive [5-7, 12].

Polished LiCl is processed by bipolar-membrane electrodialysis, carbonation, solid-liquid separation, washing, and drying. Depleted water supports internal reuse or reinjection; divalent-rich reject requires controlled brine management and may later support magnesium or bromine recovery.

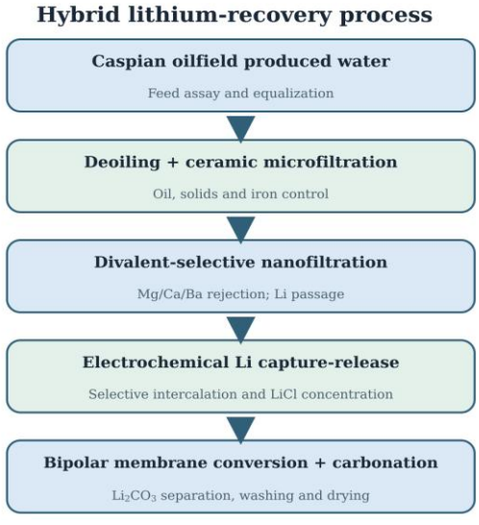

Figure 1

Hybrid membrane-electrochemical process for selective lithium recovery from Caspian oilfield produced water (developed by the author)

5. Mass balance and technical performance

At 50 mg/L, the plant receives 50 kg/day of elemental lithium. Recovery of 85% gives 42.5 kg/day of lithium,

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equivalent to 226.2 kg/day or 74.7 t/year of Li_2CO_3. The low and high assays yield 29.9 and 149.3 t/year. Overall recovery may be represented by 95% lithium passage through pretreatment and nanofiltration, 95% capture-release efficiency, and 94% conversion and product recovery. Each factor must be verified with real water because oil films, silica, barium sulfate, and salinity can reduce performance.

A product-purity target above 99.5% is consistent with recent electrochemical demonstrations, but is not a demonstrated Caspian result [5, 7]. Sodium and potassium leakage, boron, residual magnesium, and carbonate co-precipitation require a polishing loop and product washing. Lithium selectivity must not be treated as automatic battery-grade quality.

6. Techno-economic assessment

Base fixed capital comprises USD 0.9 million for feed conditioning, USD 1.1 million for nanofiltration, USD 1.7 million for electrochemical stacks, USD 0.7 million for product conversion, USD 0.6 million for utilities and control, and USD 0.6 million for contingency and commissioning. The annual capital charge is USD 0.736 million. OPEX is USD 1.257 million/year: electricity USD 0.095 million, chemicals USD 0.215 million, membrane and electrode replacement USD 0.400 million, labor and quality control USD 0.320 million, maintenance USD 0.168 million, and residue handling USD 0.059 million. After a USD 0.116 million credit, net annualized cost is USD 1.878 million.

Table 1 shows the dominant grade effect. Raising lithium from 20 to 100 mg/L multiplies output by five while most costs remain tied to treating the same water volume. Levelized production cost falls from USD 62.9 to 12.6/kg; the base result is USD 25.1/kg. A recent geothermal-brine design estimated USD 4.6/kg of $LiOH \cdot H_2O$ under its own scale and electrode-life assumptions [7]. The values are not interchangeable; they show why feed, scale, product route, and component lifetime must accompany any cost claim.

If Li_2CO_3 were assigned a hypothetical value of USD 25/kg, the screening model requires about 50.3 mg/L lithium; at USD 20/kg it requires about 62.9 mg/L. These are not price forecasts. They demonstrate that small energy savings cannot rescue very low feed grade, whereas longer electrode life, lower replacement cost, co-recovery, and greater scale can lower the threshold.

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Table 1

Design basis and techno-economic scenario results (calculated by the author)

Parameter	Low case	Base case	High case
Produced-water flow (m^3/day)	1,000	1,000	1,000
Lithium concentration (mg/L)	20	50	100
Overall lithium recovery (%)	85	85	85
Operating time (days/year)	330	330	330
Li_2CO_3 production (t/year)	29.9	74.7	149.3
Specific electricity (kWh/m^3)	3.2	3.2	3.2
Fixed capital (USD million)	5.6	5.6	5.6
Net annualized cost (USD million/year)	1.878	1.878	1.878
Levelized cost (USD/kg Li_2CO_3)	62.9	25.1	12.6

7. Environmental and operational implications

The process avoids evaporation ponds and couples mineral recovery with water management, but electricity, chemicals, spent components, and concentrated reject carry burdens. Reinjection quality, corrosion, radioactive material, and discharge restrictions are site-specific. Assessment must compare the plant with the actual reinjection, disposal, or treatment baseline. Reliability requires equalization and monitoring of oil, turbidity, hardness, lithium, pressure drop, cell voltage, and current efficiency. Long tests must quantify fouling, cleanability, reject loss, electrode fade, and recycle impurities; environmental claims require these losses in the balances.

8. Discussion

The Caspian decision path should begin with representative sampling across fields, seasons, and production ages because mixing can hide high-value streams.

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Speciation and scaling tests should determine whether lithium-rich water can be segregated before dilution. Bench tests should then compare lithium passage and hardness rejection for robust nanofiltration membranes before electrochemical cycling is optimized with real pretreated water.

The hybrid design distributes risk: nanofiltration performs monovalent/divalent fractionation, while the electrochemical stage addresses Li^+/Na^+. Its weakness is interface complexity, because each stage adds pumping, cleaning, control, and yield losses. A suitable next scale is a modular 5-20 m^3/day pilot operated for several months, closing lithium, water, sodium, magnesium, calcium, carbon, and energy balances and producing enough material for impurity analysis.

8.1. Pilot-scale validation and decision criteria

For pilot validation, the process should be evaluated under stepwise loading rather than only at a nominal steady state. The first phase should establish oil and turbidity limits for the ceramic barrier; the second should quantify lithium passage, magnesium and calcium rejection, and normalized membrane permeability; the third should measure coulombic efficiency, specific energy consumption, and capacity retention during repeated capture-release cycles. Sampling at the inlet and outlet of every unit would permit a closed lithium balance and reveal whether apparent selectivity is caused by true separation or by unmeasured precipitation and adsorption [5-7].

A go/no-go decision should combine technical, economic, and environmental criteria. The pilot would advance only if total lithium recovery remains close to the design target during realistic feed fluctuations, the product meets the impurity specification after recycle closure, and cleaning restores membrane and electrode performance without excessive reagent demand. Costs should then be recalculated from measured flux, stack productivity, component replacement frequency, reject volume, and operator requirements. This staged evidence structure prevents short laboratory tests from being extrapolated directly to plant economics and provides a defensible basis for selecting field location, module size, and water-management strategy [8-12].

9. Limitations and research priorities

The study uses published analogues and assumed Caspian feed cases; it does not report field sampling, pilot

operation, or vendor quotations. Constant recovery and capital across assays simplify nonlinear transport. Future work should establish a regional geochemical database, measure membrane and electrode life under oil and scale exposure, and couple probabilistic techno-economic analysis with life-cycle assessment.

10. Conclusion

A hybrid membrane-electrochemical train offers a technically coherent route for lithium recovery from Caspian oilfield produced water. At 1,000 m^3/day, 50 mg/L lithium, and 85% recovery, the model produces about 74.7 t/year of Li_2CO_3 at approximately USD 25.1/kg. This is a screening threshold, not a commercial forecast. Feed grade is the strongest economic driver, while pretreatment and membrane-electrode durability control sustained recovery. Field-resolved assays and a long-duration modular pilot are therefore required before investment.

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