Knowledge Integrity Service

From Reservoir to Brines:

Adapting Petroleum Evaluation Principles to Solution-Mined Mineral Resources

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The Energy Transition Imperative

Introduction

138%
Projected lithium demand increase by 2030

2.7M
Tonnes LCE needed globally by 2030

~54%
Of global lithium resources held by the Lithium Triangle

Why should petroleum engineers care?

- Brine production uses petroleum reservoir engineering — Darcy flow, well design, reservoir management
- Mineral extraction at surface is a separate processing step (DLE, evaporation)
- Latin America's salars are proving grounds for global brine evaluation
- Major O&G companies (ExxonMobil, Equinor) are entering lithium brine production

Global Lithium Demand

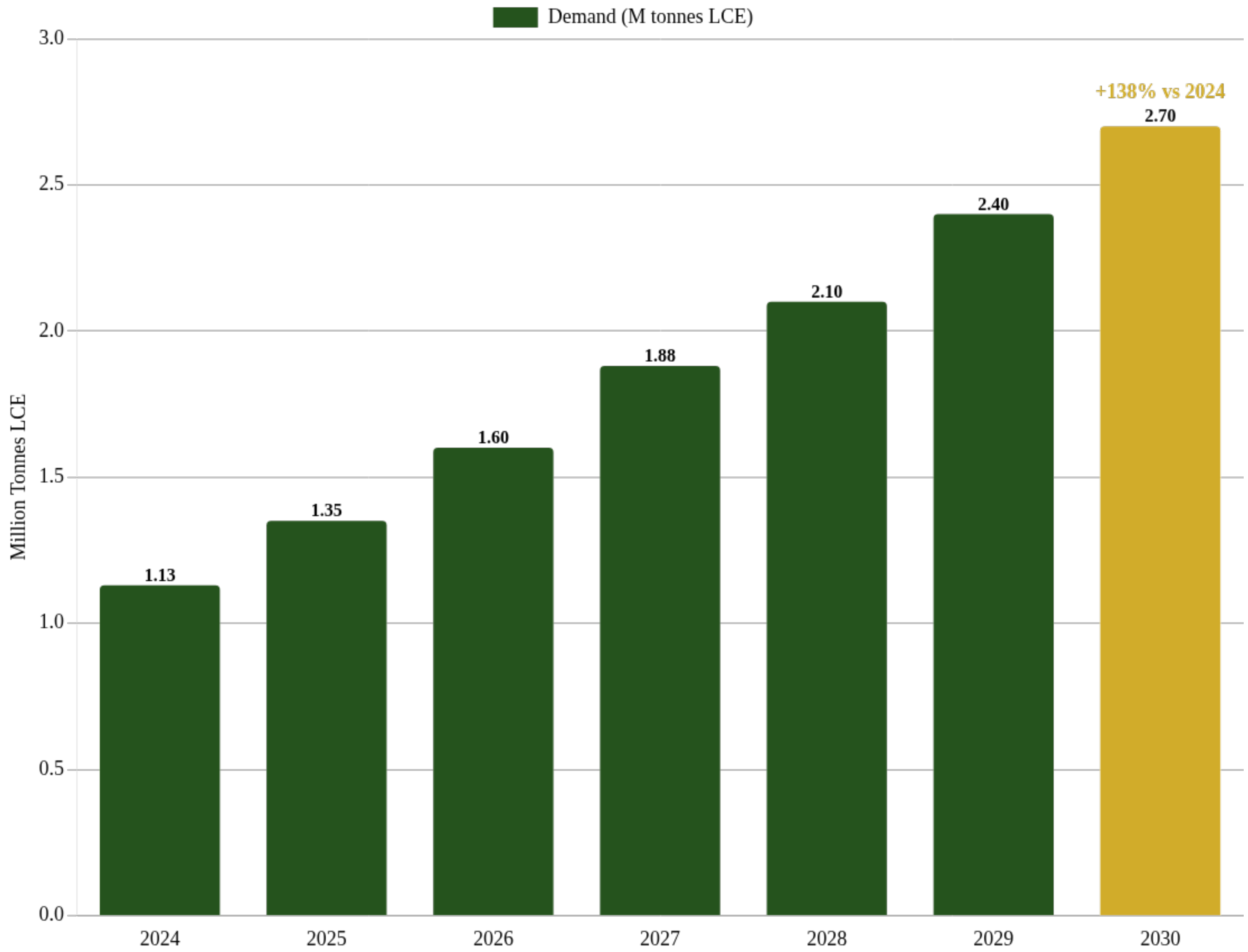
Projections & Drivers — 2024 to 2030

Demand Drivers

- Electric vehicles — primary growth engine
- Portable electronics & grid storage
- Battery gigafactory buildout

2024 baseline: ~1.13M tonnes LCE

2030 target: 2.7M tonnes LCE



The Solution Minerals Landscape

Introduction | Solution Minerals Resources

Mineral	Primary Use	Current Market	Growth Rate (Annual)	Latin America
☆ **Lithium**	EV batteries, energy storage	**~$325B ecosystem**	**+16% YoY**	**>50% resources (Triangle)**
Potassium - Potash	Fertilizers, agriculture	$62–63B	4.5–5.3%	**Brazil: top importer**
Sodium (Salt/NaCl)	Food, chemical, de-icing, chlor-alkali	~$30B	2–3%	**AR, CL: Salinas Grandes, Atacama**
Rare Earth Elements	EV magnets, electronics	$4–18B	7.6–8.7%	—
Magnesium	Lightweight alloys, aerospace	$5–6B	5.1–5.6%	—
Bromide	Flame retardants, water treatment	$3.7–4.0B	4.0–6.1%	—
Iodine	Pharma, contrast media	$1–3.8B	4.4–7.5%	**Chile: ~60% global supply**

Why Lithium Leads

+16% YoY growth

9x by 2040

58% from EVs

- Strategic critical mineral status
- DLE technology investment focus
- Supply deficit anticipated by 2030s

Framework Applies to All

The petroleum evaluation framework adapts to every solution mineral — lithium is our primary case study.

LatAm supplies lithium, iodine, potash and more

Where the Lithium Is

Global Brine Resource Landscape

☆ Lithium Triangle — Argentina, Chile, Bolivia

~54% of global resources

World's highest-grade salars; 9.1M t at Atacama alone

Argentine Salars (Hombre Muerto, Olaroz, Cauchari)

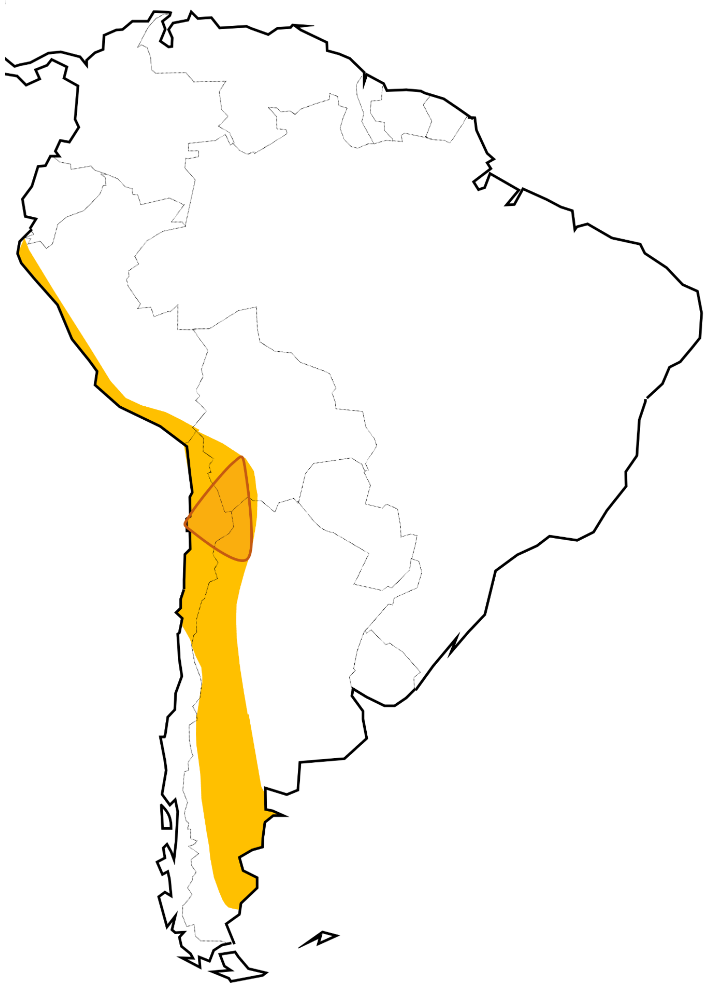
Multiple active projects

~690 mg/L average Li; expanding rapidly toward 16% global share by 2030

Smackover Formation, S. Arkansas (USA)

~437 mg/L avg Li

Deep subsurface brine; DLE processing; analogous evaluation framework



The Methodological Gap

Why Mining Frameworks Fall Short for Fluid Brine Systems

SOLID ORE ≠ FLUID BRINE

Mining Approach (CRIRSCO)

Designed for excavating solid ore bodies

- ✗ Estimates run-of-mine **tonnage & grade** — not flow rates
- ✗ **No provision** for fluid flow, Darcy's Law, or dynamic recovery
- ✗ Single deterministic estimate — **no P10/P50/P90** uncertainty range
- ✗ **No decline curves**, material balance, or reservoir simulation
- ✗ Geological confidence only — **ignores production dynamics**

Petroleum Approach (PRMS)

Built for fluids produced through wells

- ✓ Treats brine as a **produced fluid** — not solid ore
- ✓ **Darcy flow**: porosity × permeability governs resource & rate
- ✓ **Dynamic modeling**: DCA, material balance, numerical simulation
- ✓ **Uncertainty ranges**: Low/P90 – Best/P50 - High/P10
- ✓ Commerciality classified by **maturity & production potential**

→Petroleum professionals have the tools to fill this gap — and brines demand it

Brines Are Subsurface Fluids — Not Hard Rock

Fundamental Reservoir Physics Apply

Lithium-bearing brine occupies pore space in rock formations — governed by Darcy's Law, porosity, and permeability — the same physics as oil and gas.

Fluid in Pore Space

Brine held in rock porosity — like oil in a reservoir

Darcy Flow

$Q = -KA(dh/dl)$ — flow rate driven by pressure differential via pumping

Porosity & Permeability

Volume (porosity) and extractability (permeability) define commercial viability

Brine Reinjection

Spent brine reinjected to maintain pressure — analogous to waterflooding

Brine Reservoir Systems: Open vs. Closed

System Classification Drives Evaluation Methodology & Resource Sustainability

Closed Systems (Salars)

Definition

Surface salt flats with **subsurface brine in porous sediments** — finite resource, minimal recharge

Key Considerations

- **Drilling production wells** required (10–200m typical, 600m+)
- Depletion risk — material balance critical
- Higher Li grades: 1,000–5,000+ mg/L

Examples

Atacama (Chile) · Hombre Muerto (Argentina) · Uyuni (Bolivia)

90%+ of Current Brine Production

Semi-Closed Systems

Definition

Limited recharge — hybrid characteristics between closed and open systems

Key Considerations

- Balance between depletion and recharge
- Detailed hydrogeological modeling required
- Moderate Li concentrations

Examples

Some Argentine salars with partial recharge from surrounding ranges

Requires Hybrid Evaluation

Open Systems (Aquifers)

Definition

Active groundwater recharge from surrounding formations — potentially renewable resource

Key Considerations

- Must model recharge rates & sustainability
- Renewable resource potential — long-term supply
- Lower Li grades: typically <500 mg/L

Examples

Smackover Fm (Arkansas, USA) · European aquifer projects

Emerging — Sustainability Advantage

All systems require subsurface well drilling — direct petroleum engineering parallel

Environmental impact depends on extraction method (DLE vs. evaporation), not reservoir type

Reservoir Characterization — Transferred Workflows

Well Logging · Core Analysis · Fluid Sampling

Well Logging & Core Analysis

- Continuous logs map porosity & lithology
- Core plugs give direct permeability measurements
- Smackover: ooid/peloidal grainstones are prime zones
- Data from hundreds of existing O&G wells

Geochemical Sampling

- Brine samples analyzed for Li concentration
- Spatial distribution modeled across formation
- Geostatistical modeling (kriging) interpolates Li concentration between wells
- Impurity characterization for DLE design

3D Geological Modeling

- Seismic + well logs + core + geochemistry integrated
- Visualizes porosity, permeability, and Li concentration
- Basis for development planning & simulation
- Geostatistical 3D models map reservoir properties and Li distribution

Dynamic Production Modeling

Forecasting Brine & Lithium Recovery Over Time

Decline Curve Analysis (DCA)

- Empirical fit to historical production data
- Exponential, hyperbolic, or harmonic decline
- Estimates EUR and well life
- Rapid, low-data-requirement screening tool

Material Balance Equation (MBE)

- Reservoir treated as a pressure-volume 'tank'
- Pressure depletion vs. production history
- Estimates total brine-in-place
- Predicts future performance scenarios

Numerical Simulation

- 3D model gridded into simulation cells
- Solves fluid flow equations at each timestep
- Optimizes well count, spacing & pump rates
- Most rigorous; used for development planning

Lithium Extraction Methods

Evaporation Ponds vs. Direct Lithium Extraction (DLE)

Petroleum Analogy: DLE is analogous to **surface separation facilities** — gas processing plants (amine treating, NGL recovery), produced water treatment, or oil-water separation (FWKO, three-phase separators). Pump brine to surface → selective extraction → reinject depleted brine.

Traditional: Evaporation Ponds

- **Process:** Brine pumped to large surface ponds; solar evaporation 12–24 months; sequential salt precipitation; chemical processing
- **Recovery:** 30–50% lithium recovery
- **Timeline:** 12–24 months
- **Footprint:** Hundreds of hectares
- **Water:** High evaporative loss
- **Examples:** Atacama, Hombre Muerto

Established technology — weather dependent

Modern: Direct Lithium Extraction

- **Process:** Surface facility with selective extraction — ion exchange, adsorption, or solvent extraction
- **Recovery:** 80–90% lithium recovery
- **Timeline:** Hours to days
- **Footprint:** Compact surface facility
- **Water:** Minimal loss (brine reinjection)
- **Examples:** Smackover, new Argentine projects

Technology innovation — higher efficiency

Industry Trend: Shift toward DLE for new projects • Hybrid approaches emerging • DLE enables lower-grade resources • Smaller footprint, less water consumption

Estimating Uncertainty Ranges — Two Approaches

Deterministic & Probabilistic Methods in Brine Resource Assessment

Both deterministic and probabilistic methods produce uncertainty ranges. The choice depends on data availability, field maturity, and project stage.

Deterministic (Scenario-Based)

- **Method:** Define discrete scenarios with specific input values for each case
- **Scenarios:** Low Case (P90) · Best Case (P50) · High Case (P10)
- **Typical use:** Developed fields, mature assets, production history available
- **Inputs:** Conservative → Most Likely → Optimistic
- **Output:** Three discrete estimates defining the uncertainty range

✓ **Transparent, easy to audit, well-suited when parameters are known**

P90 — Low	P50 — Best	P10 — High
Conservative inputs	Most likely values	Optimistic inputs

Probabilistic (Monte Carlo)

- **Method:** Assign probability distributions to inputs, run thousands of simulations
- **Distributions:** Normal, log-normal, triangular, uniform per parameter
- **Typical use:** Exploration, discovery, early appraisal, limited data
- **Inputs:** Distributions (porosity, area, Li conc., RF, etc)
- **Output:** Full probability distribution — P90/P50/P10 from cumulative curve

✓ **Captures full range of uncertainty and complex dependencies**

P90	P50	P10
90% exceedance	Median outcome	10% exceedance

Both approaches are standard petroleum practice and fully applicable to mineral brine evaluation

Economic Assessment — Petroleum Toolkit Applied

DCF · NPV · Royalties · Fiscal Terms · Depletion

$ DCF / NPV Analysis

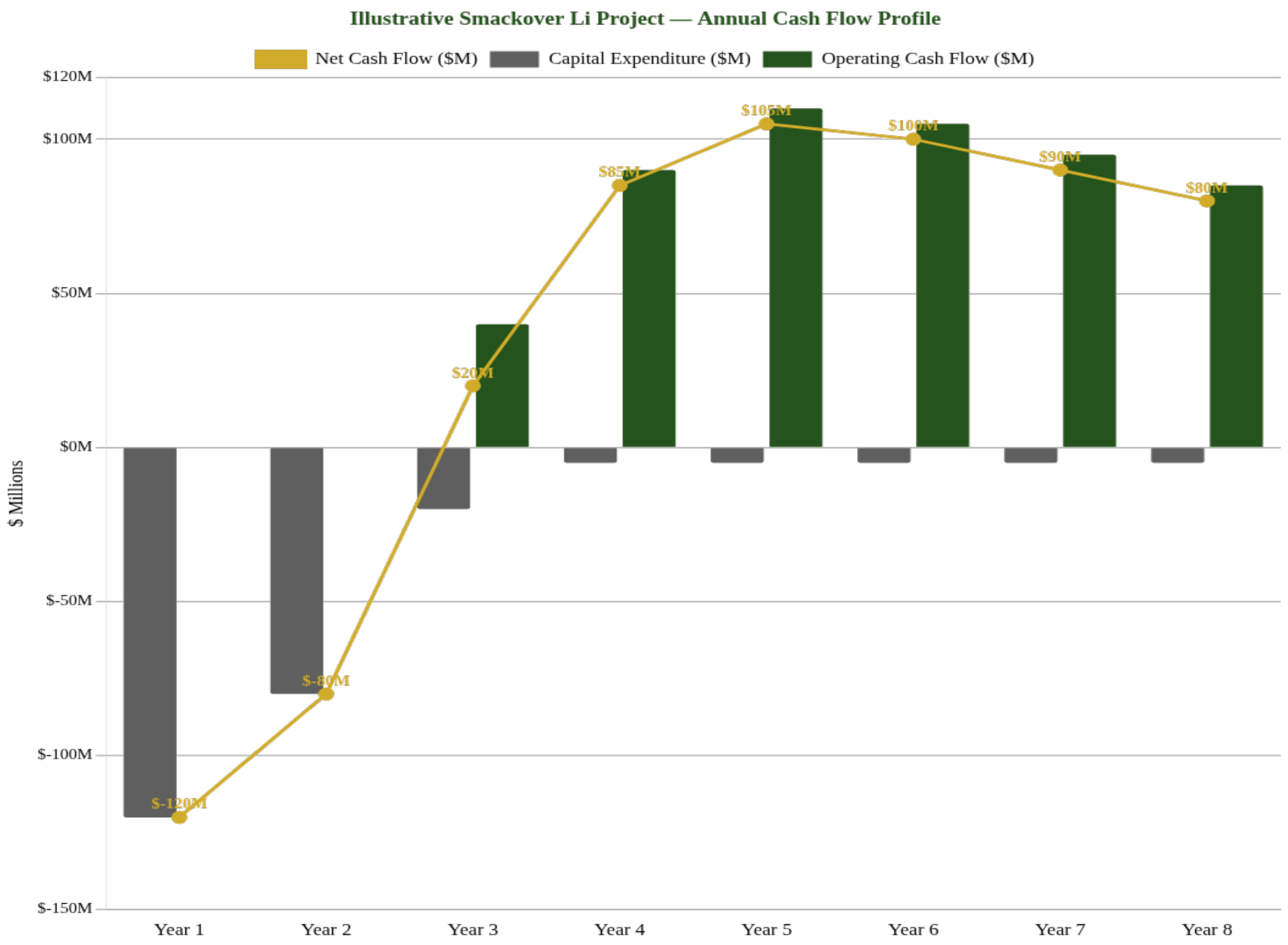
Project future Li revenues and costs; discount to NPV. Positive NPV = viable project.

% Royalty Structures

- NSR — Net Smelter Return (% revenue after costs)
- Gross Revenue Royalty
- Net Profit Interest (NPI)
- Sliding Scale — adjusts with Li price

Depletion Allowance

Tax deduction for finite resource drawdown — analogous to depreciation.



Why PRMS? — Framework Comparison

Brines Are Fluids, Not Solid Minerals

PRMS — Petroleum Framework

Designed for: Fluids (Oil, Gas, Brines)

- **Well-based production** — subsurface fluid extraction via drilled wells
- **Darcy flow dynamics** — porosity, permeability, hydraulic conductivity
- **Material balance & decline curves** — standard reservoir tools apply
- **Numerical simulation** — 3D reservoir models with deterministic/probabilistic forecasting
- **Dual uncertainty axes** — chance of commerciality + range of recoverable quantities
- **Production optimization** — well spacing, injection/production rate management

HIGH suitability for brine systems

CRIRSCO — Mining Framework

Designed for: Solid Minerals (Ore, Rock)

- **Excavation-based extraction** — open pit or underground mining
- **Static geological tonnage** — grade × volume, no flow dynamics
- **No production forecasting tools** — no decline curves or material balance
- **Single confidence axis** — geological knowledge only (Measured → Indicated → Inferred)
- **Mining extraction ratios** — recovery tied to physical excavation, not fluid flow
- **No reinjection concept** — mined material is removed permanently

LIMITED suitability — not designed for fluid production

SEC Disclosure: Two Separate Pathways

Mining S-K 1300 vs. Oil & Gas Regulation S-X

Mining — Regulation S-K 1300

Implemented 2021

- Aligned with global CRIRSCO standards
- Requires disclosure of both Mineral Resources AND Mineral Reserves
- All disclosures backed by a Technical Report Summary
- Prepared by a Qualified Person (QP) — min. 5 yrs experience
- Explicitly excludes oil and gas resources

Oil & Gas — Regulation S-X

Established framework

- Separate rules, different reserve definitions
- Focus on proved reserves for public disclosure
- Qualified technical expert involvement required
- PRMS-aligned reserve categories
- Does NOT cover solution mineral resources

Brine projects must navigate BOTH frameworks — expertise from petroleum AND mining disciplines required.

Latin America: Active Lithium Brine Projects

The World's Dominant Brine Production Region

Argentina

- Arcadium Lithium — Hombre Muerto: 25,000 tpa → 40,000+ tpa LCE
- Ganfeng / Lithium Argentina — Cauchari-Olaroz: 40,000 tpa target
- POSCO — Sal de Oro (Hombre Muerto): ~25,000 tpa target (Phase 1)
- Eramet — Centenario-Ratones: ~30,000 tpa planned

Production share rising from 6% (2021) to 16%+ by 2030

Chile

- SQM — Salar de Atacama: contract with Codelco to 2060
- Albemarle — Atacama: world's largest Li producer; contract to 2043
- BYD — $290M LFP cathode plant, Antofagasta

National Lithium Strategy: DLE mandatory for all new projects

Bolivia

- YLB — Salar de Uyuni: world's largest Li deposit
- CATL consortium — $1B DLE investment, 25,000 tpa target
- CITIC Guoan / Uranium One — Pastos Grandes & Uyuni

$2.8B in signed DLE partnerships; high Mg brine remains a challenge

Key Takeaways

From Reservoirs to Brines

01

Petroleum evaluation frameworks transfer directly to brines — reservoir characterization, simulation, and probabilistic classification all apply.

02

Latin America holds the majority of global lithium brine resources — the Lithium Triangle hosts ~54% of world resources.

03

Adapted petroleum evaluation frameworks (like PRMS) addresses maturity, uncertainty, and commerciality for solution minerals.

04

DLE is transforming recovery — Chile mandates it for new projects; Bolivia's $2.8B program is DLE-based; Argentina is rapidly adopting it.

05

Active projects across the Triangle validate the methodology — from Arcadium at Hombre Muerto to CATL at Uyuni, and the Smackover in Arkansas.

Questions?

We welcome your thoughts on adapting petroleum evaluation methodologies to Latin American brine resources — and beyond.

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