2026 ASRS Annual Meeting, June 7-11th

Title:

Integrated remediation and critical-mineral recovery through co-processing of acid mine drainage sludge and coal-derived solid wastes

Authors:

Eli Miskovic & Sanja Miskovic

Affiliation:

Novex, LLC

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Who we are and why we work on problems like this

Novex, LLC is an engineering and technology development company that solves complex materials and environmental challenges through integrated process development and scale-up.

100+
YEARS OF COMBINED TECHNICAL EXPERIENCE

MULTI-DISCIPLINARY
TEAM OF ENGINEERS, SCIENTISTS & TECHNOLOGISTS

LAB TO PILOT
CAPABILITIES UNDER ONE ROOF

We help clients transform unconventional materials and waste streams into value while reducing environmental risks.

We partner with industry, academia, and government to accelerate innovation and deliver real-world solutions to today's most challenging resource, energy, and environmental problems.

CAPABILITIES THAT DIFFERENTIATE

MULTI-SCALE CHARACTERIZATION
Chemical, mineralogical, morphological, and physicochemical analysis

INTEGRATED PROCESS DEVELOPMENT
From fundamentals to pilot validation

MODELING & ENGINEERING
Flowsheet design, process simulation, equipment design

ADVANCED TESTING PLATFORMS
Hydrometallurgy, thermal processing, separations, and reactions

PILOT-SCALE SYSTEMS
Flexible systems for continuous and batch operations

SAFETY & SUSTAINABILITY
Built into every stage of development

CORE FOCUS AREAS

Critical Materials Recovery
From conventional and unconventional feedstocks

Waste Valorization & Remediation
Turning liabilities into resources and environmental solutions

Mineral Processing & Hydrometallurgy
Comminution, separations, extraction, and purification

Process Intensification
Advanced reagents, energy-efficient and compact process technologies

Advanced Diagnostics & Scale-Up
In-situ measurements, modeling, and pilot-scale validation

Automation & Digital Engineering
Data-driven systems, lab automation, and flowsheet modeling

Mining legacies are creating a new resource opportunity

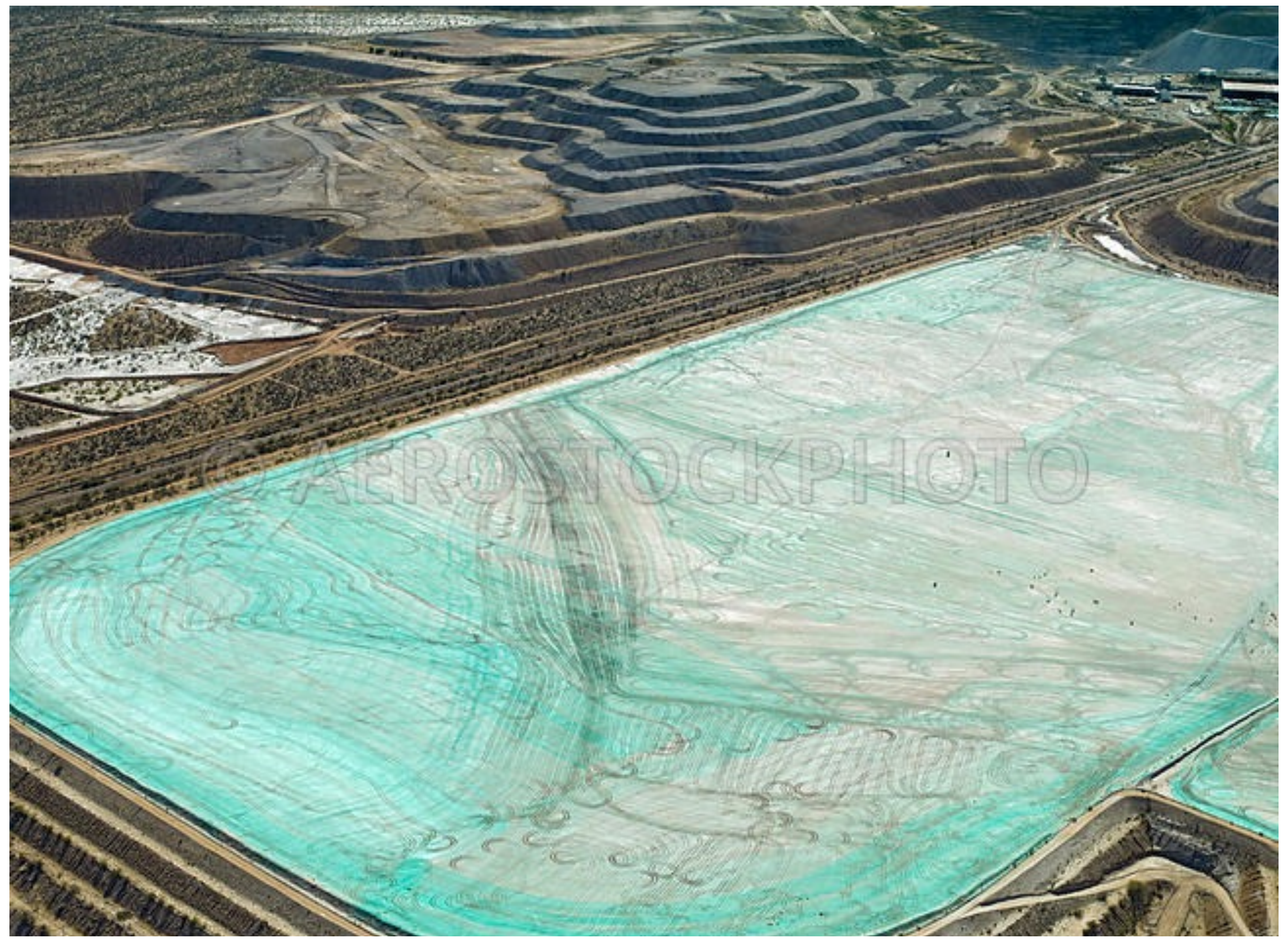
From Liability to Opportunity

- Mining and industrial activities have generated billions of tones of residual materials worldwide.
- Historically these materials have been viewed solely as environmental liabilities.
- A new question is emerging:
  Can some of these liabilities become future resources?"

Coal refuse
Underclays
Combustion ash

AMD waters
Treatment sludges
Neutralization products

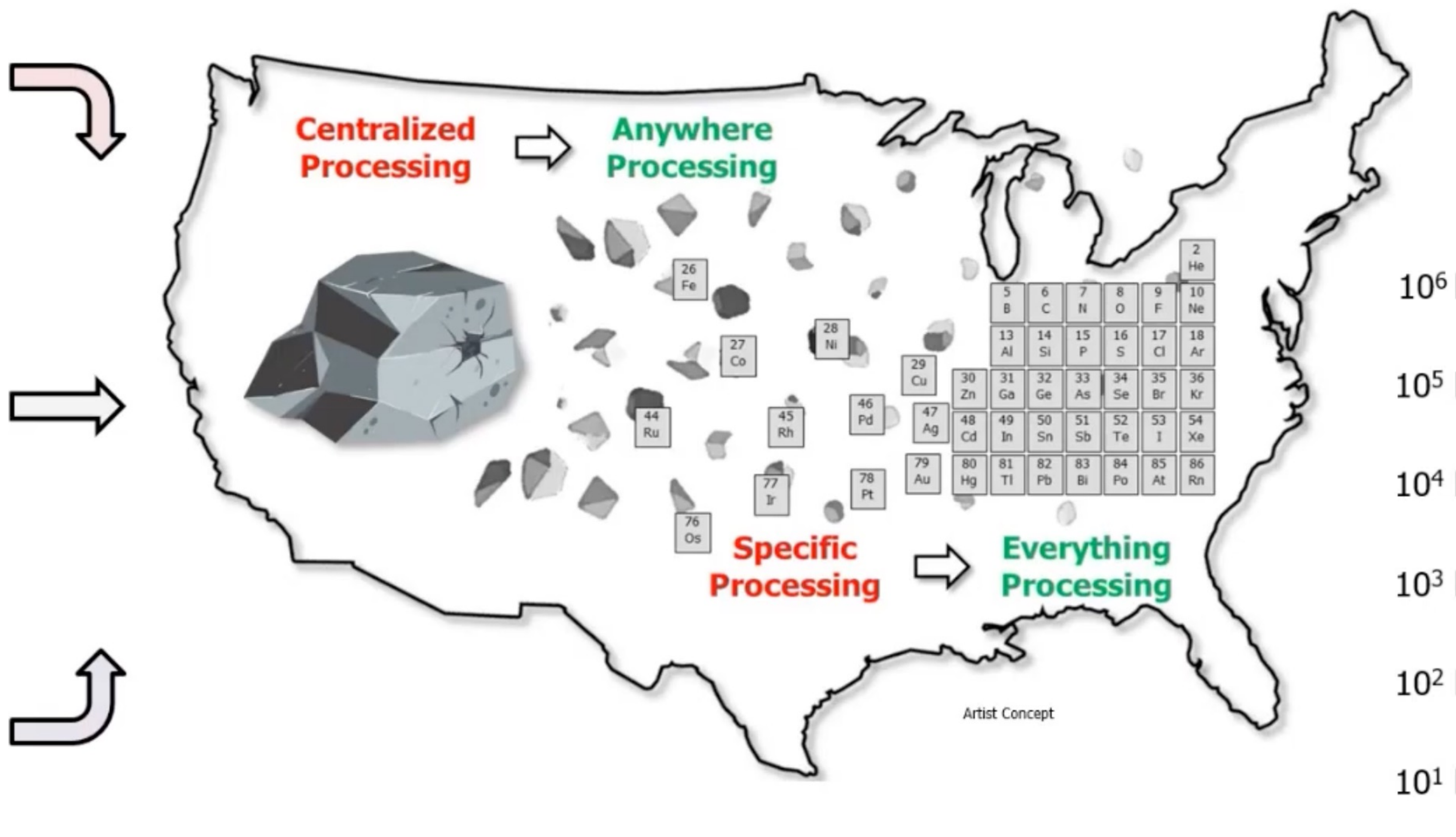
Tailings
Industrial residues
Post-consumer streams

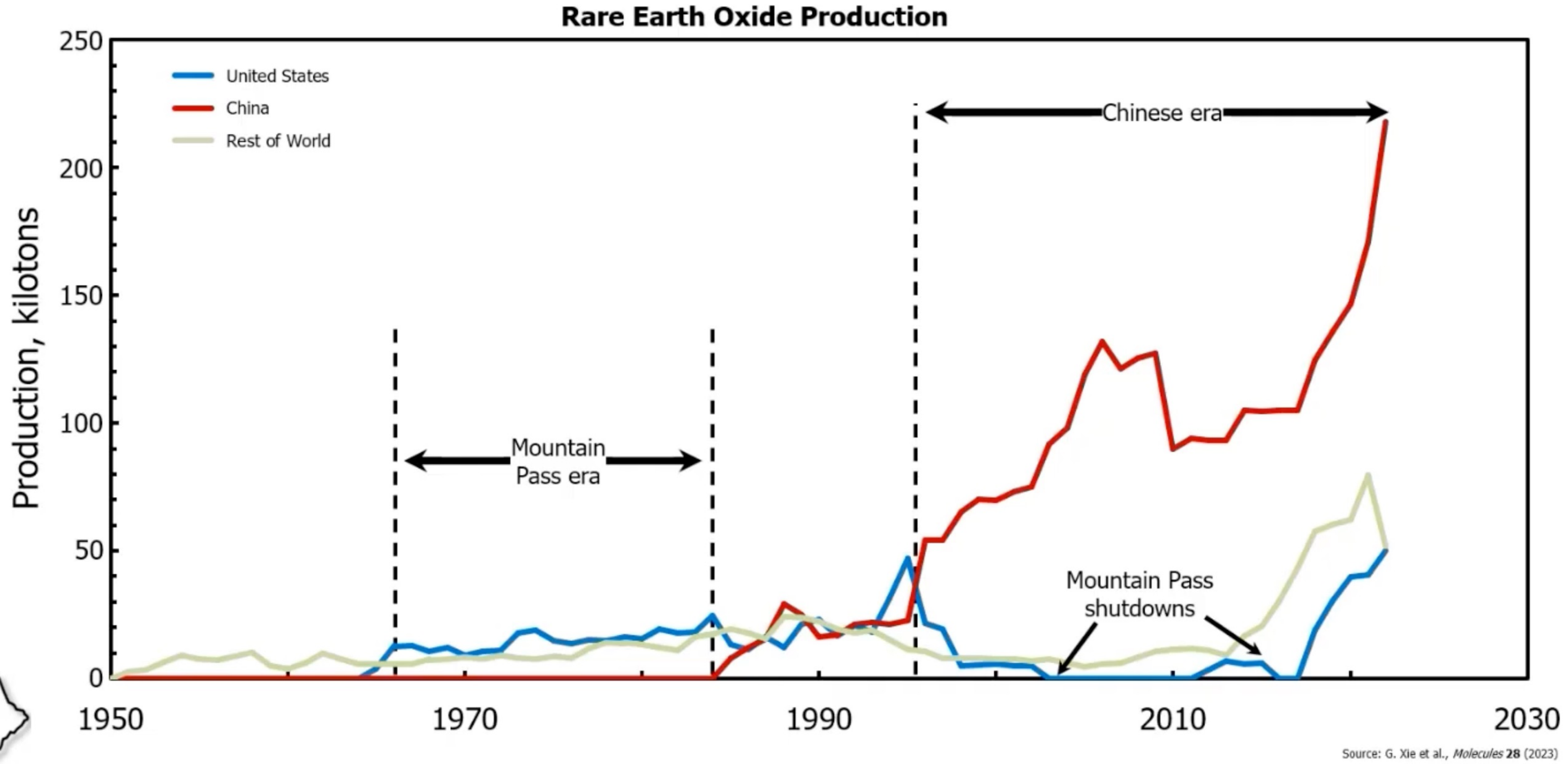


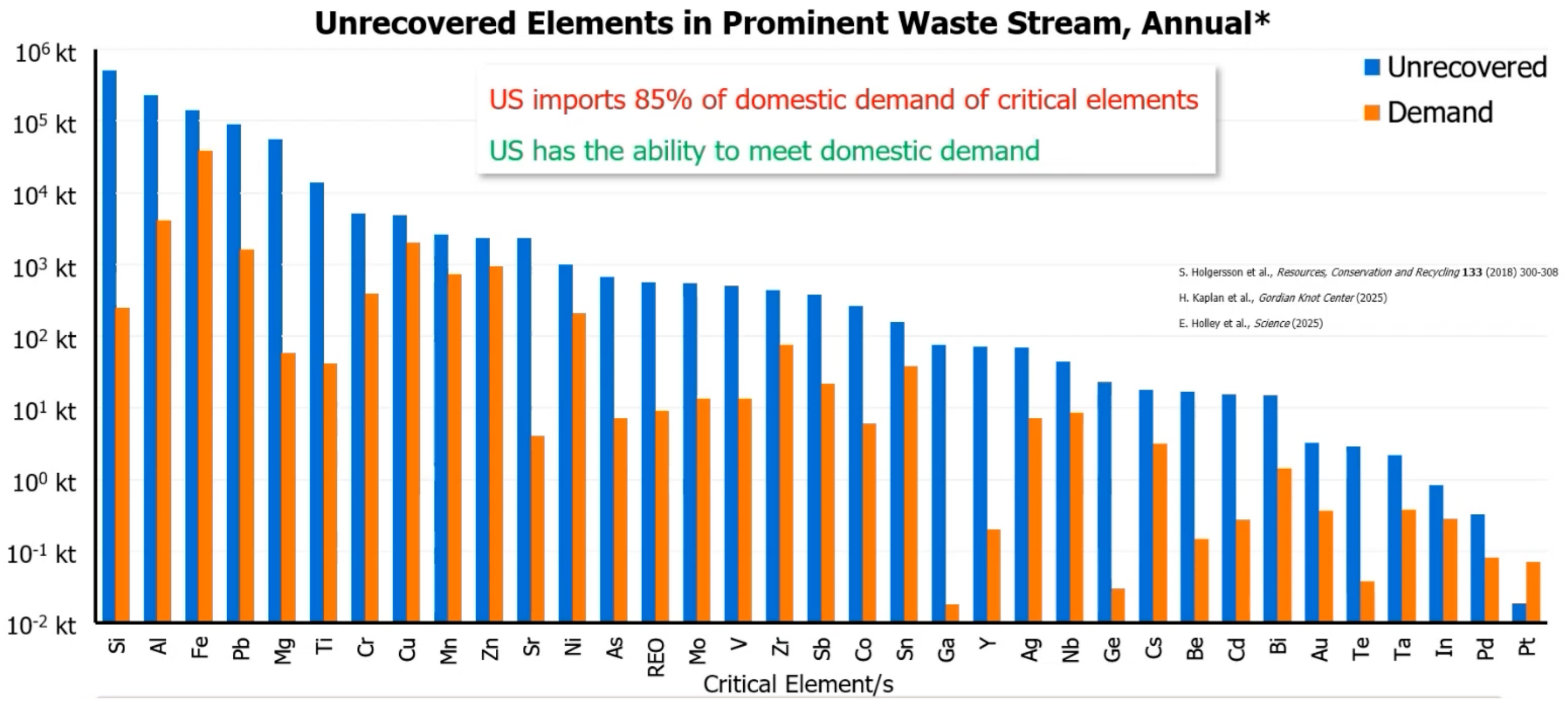
Critical minerals are driving interest in waste materials

Why Are We Suddenly Interested?

- Demand for critical minerals is increasing.
- Traditional mining alone may not satisfy future demand.

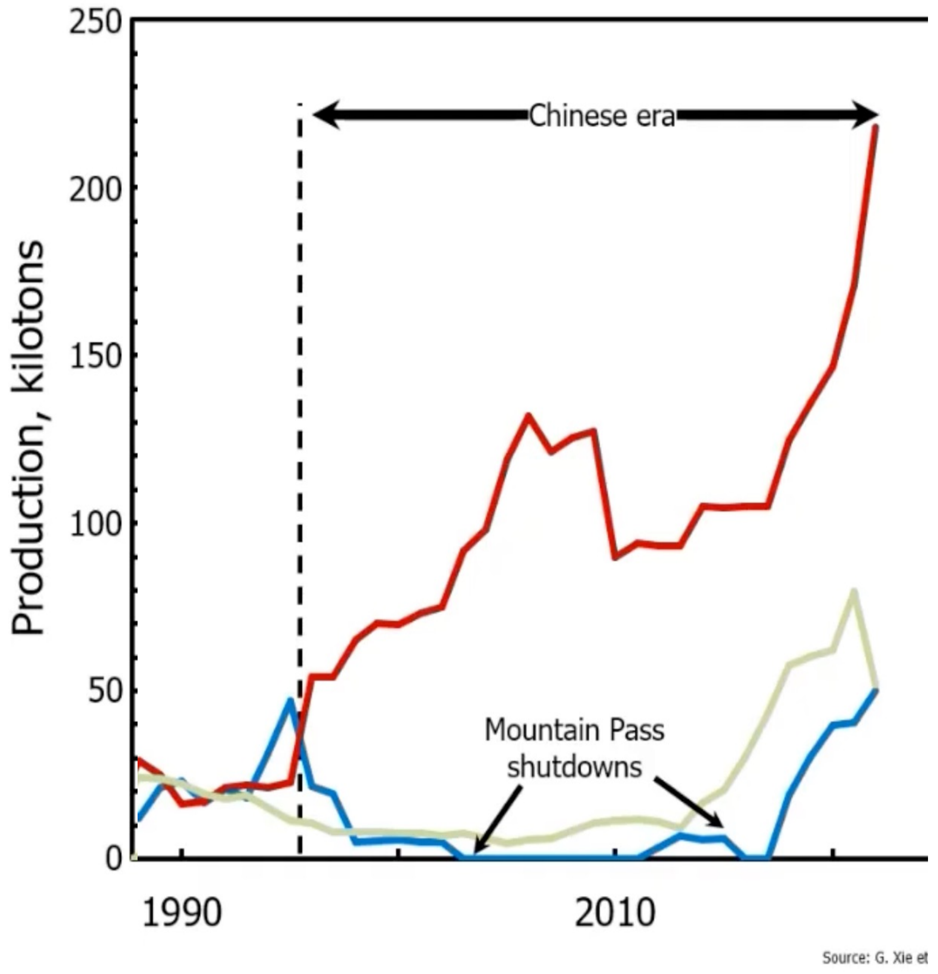


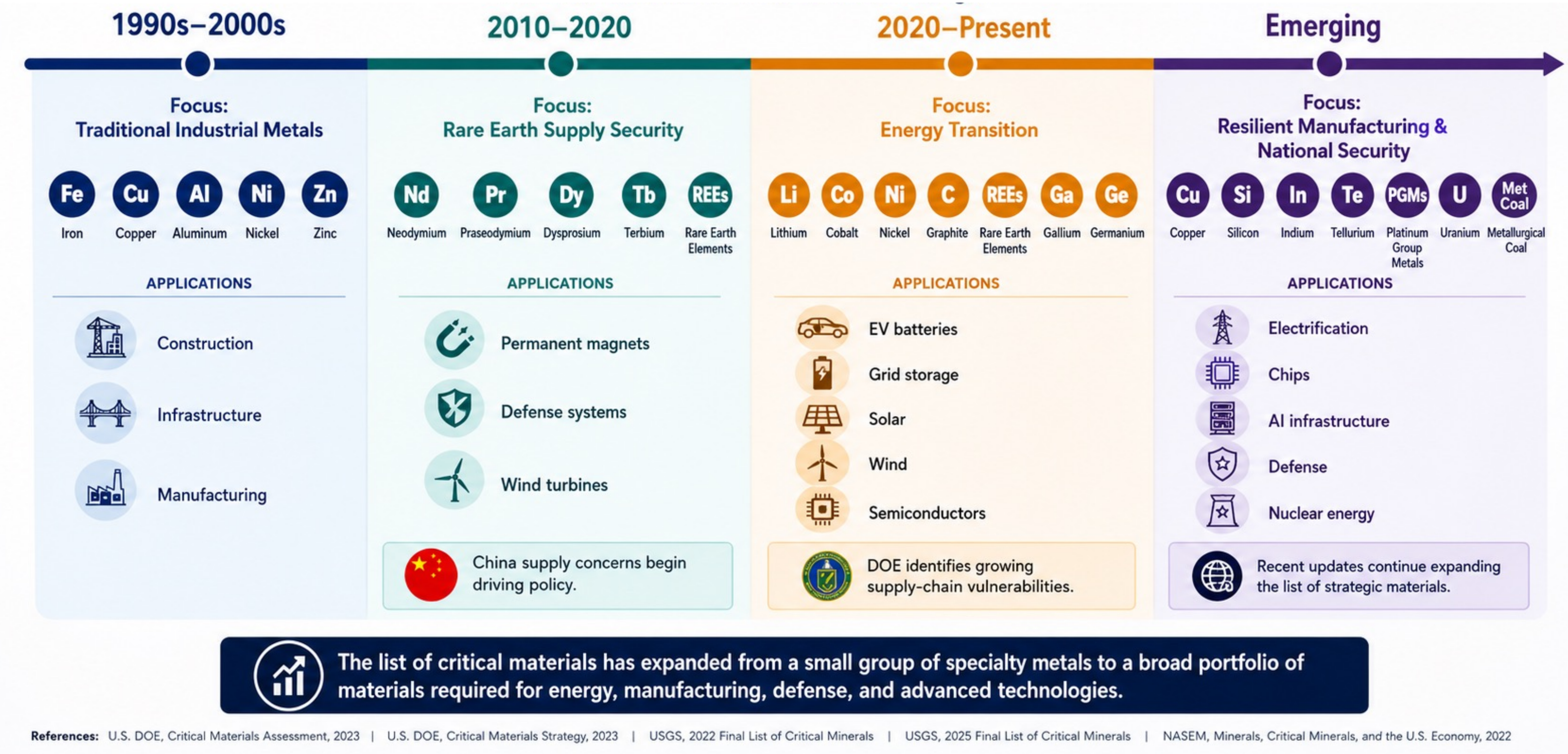




What counts as "critical" is expanding

Technology evolution and supply-chain risks continue to redefine which materials are considered strategic





Permanent magnets **REE + Sc/Y**	Battery and storage **Li, Co, Ni, Mn, graphite**	Electronics / semiconductors **Ga, Ge, In, Si, Sb**	Alloys and industrial **V, Ti, Cr, W, Nb, Ta**	Base / enabling metals **Al, Cu, Zn, Mg**

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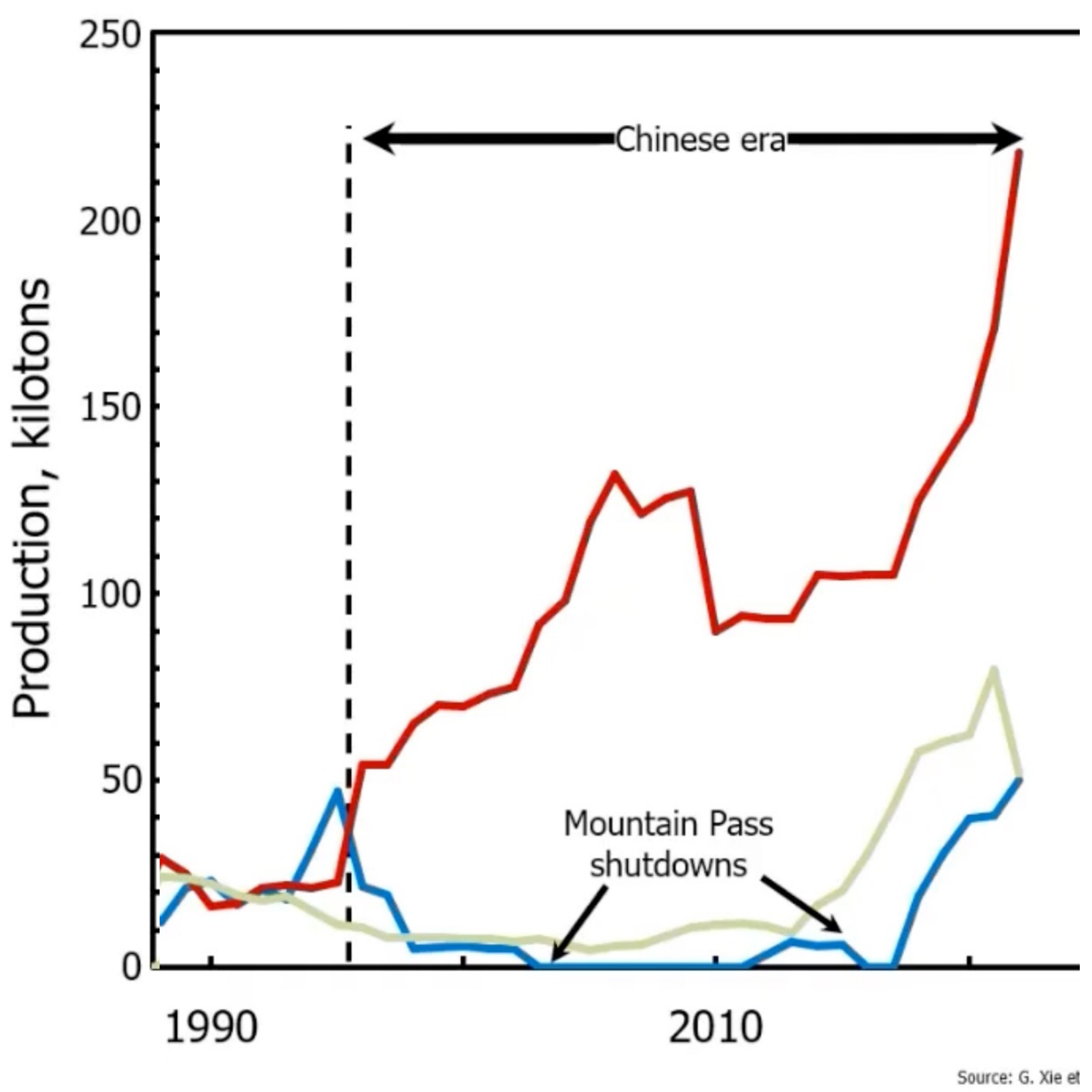
Why materials become critical

Criticality is driven by the interaction of Technology, Geopolitics, and Policy

- **Criticality** is not a geological property. It **is a moving target** driven by technology, geopolitics, and supply chains.



Criticality is dynamic – today's non-critical material can become tomorrow's strategic necessity.

Critical minerals occur in many unconventional feedstocks

Where Are These Materials Found?

- Critical materials are not limited to primary ore deposits. They are distributed across a wide spectrum of mining, energy, metallurgical, manufacturing, and consumer waste streams.

Mining & Mineral Processing Wastes

Feedstock	Potential Valuable Components
Coal refuse / gob piles	REEs, Al, Ti, Fe, Sc, Ga, Ge
Coal preparation plant (CPP) middlings	REEs, Al, Ti, Fe, Ga, Ge
Coal fines / slurry impoundments	REEs, Al, Ti, Fe, Sc
Coal underclays (seat earths)	REEs, Al, Sc, Ti, Ga
AMD treatment sludge	Fe, Al, Mn, REEs, Co, Ni, Zn
Phosphate tailings	REEs, U, Sc, Y
Abandoned uranium mine (AUM) piles	U, REEs, Sc, V, Mo
Copper tailings	Cu, Mo, Re, Co, REEs
Nickel tailings	Ni, Co, Mg, Sc
Iron ore tailings	Fe, REEs, Sc
Tin tailings	Sn, W, Ta, Nb
Gold tailings	Au, Ag, Sb, Te
Zinc/lead tailings	Zn, Pb, Ge, Ga, In

Coal related wastes

Metallurgical & Industrial Process Wastes

Feedstock	Potential Valuable Components
Red mud (bauxite residue)	Sc, REEs, Ti, Fe, Al, Ga
Phosphogypsum	REEs, Y, Sc
Steel slag	Fe, V, Cr, Mn
Electric arc furnace (EAF) dust	Zn, Pb, In, Ga
Copper smelter slag	Cu, Co, Mo, Re
Nickel smelter slag	Ni, Co
Aluminum dross	Al, Ga
Spent catalysts	Ni, Co, Mo, V, Pt, Pd
Refinery residues	V, Ni, Mo
Drill cuttings and muds*	Ba, Sr, REEs, critical metals

Manufacturing Wastes

Feedstock	Potential Valuable Components
NdFeB magnet production scrap	Nd, Pr, Dy, Tb, Fe
Battery manufacturing scrap	Li, Ni, Co, Mn, Graphite
Metal machining swarf/shavings	Ni, Ti, Co, W, Mo, Ta
Semiconductor manufacturing scrap	Ga, Ge, In, Si
Specialty glass manufacturing waste	Ge, REEs
Alloy manufacturing residues	Ni, Co, Cr, Mo, W

* For unconventional resources, the lists are only the starting point. The real question is which elements can be recovered at acceptable cost, purity, and environmental performance.

Critical materials are everywhere. Economical recovery is not.

High-grade & high-volume resource – High expectations – Hot topic – Newspaper headlines

COMMON MISTAKE

Feedstock/Waste Quantity × Critical Material Grade × Commodity Price = **Project Value**

✗ Wrong!

REALITY

Recovery × Selectivity × Throughput × Purity x Water Consumption × Energy Consumption × CAPEX × OPEX × (New) Waste Management × Market Requirements × (Many Many Other) = **Project Viability**

✓ Correct!

THE BEST RESOURCE IS NOT ALWAYS THE HIGHEST-GRADE RESOURCE.

STOCKPILE A

1,200 ppm REEs

High-grade headlines, high expectations.

Grade	✓
Mineralogy	✗
Recovery	✗ (Low)
Impurities	✗ (High)
Processing Complexity	✗ (High)
Residue Management	✗ (Challenging)

✗ NOT ECONOMIC

STOCKPILE B

350 ppm REEs

Lower grade, but favorable characteristics.

Grade	✓
Mineralogy	✓
Recovery	✓ (High)
Impurities	✓ (Low)
Processing Complexity	✓ (Moderate)
Residue Management	✓ (Manageable)

✓ ECONOMIC

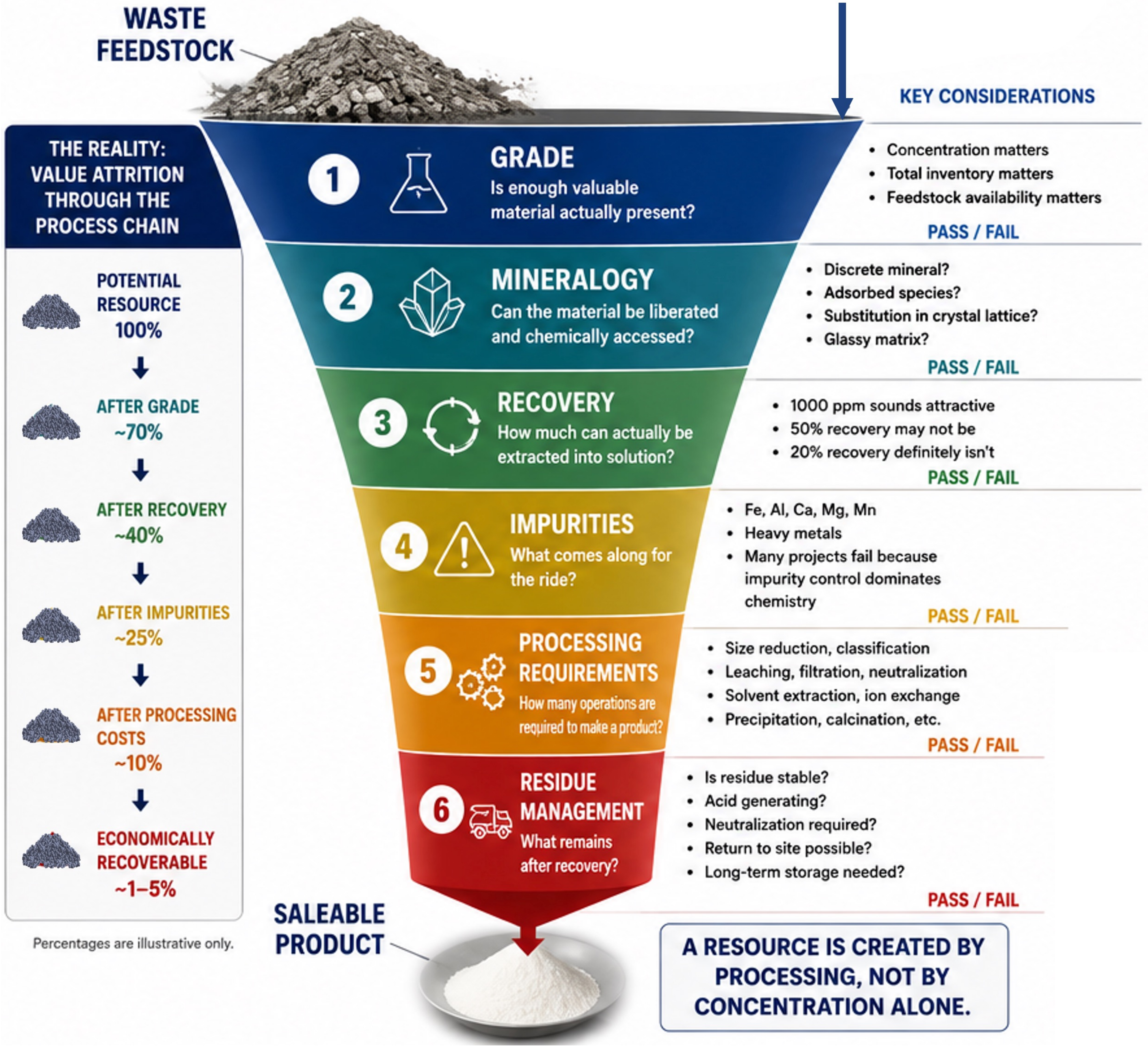
A low-grade material with the right characteristics can outperform a high-grade material with the wrong ones.

Critical materials are everywhere. Economical recovery is not.

Resource potential is determined by the entire process chain, not by feed concentration alone!

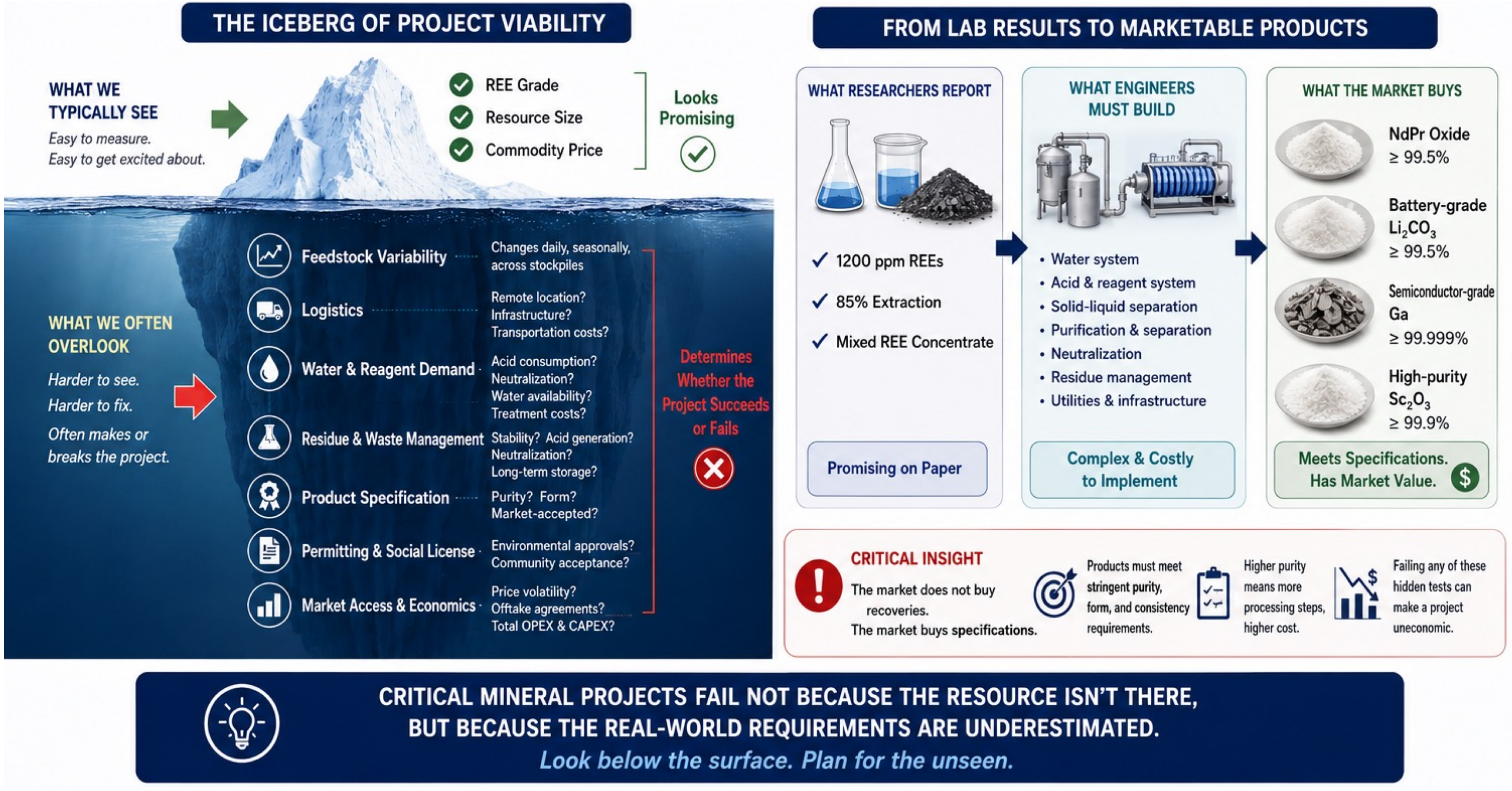
Presence does not equal recoverability.

Recoverability does not equal economic viability.



The hidden factors that determine viability

Even if the chemistry and physics work, a project can still fail.



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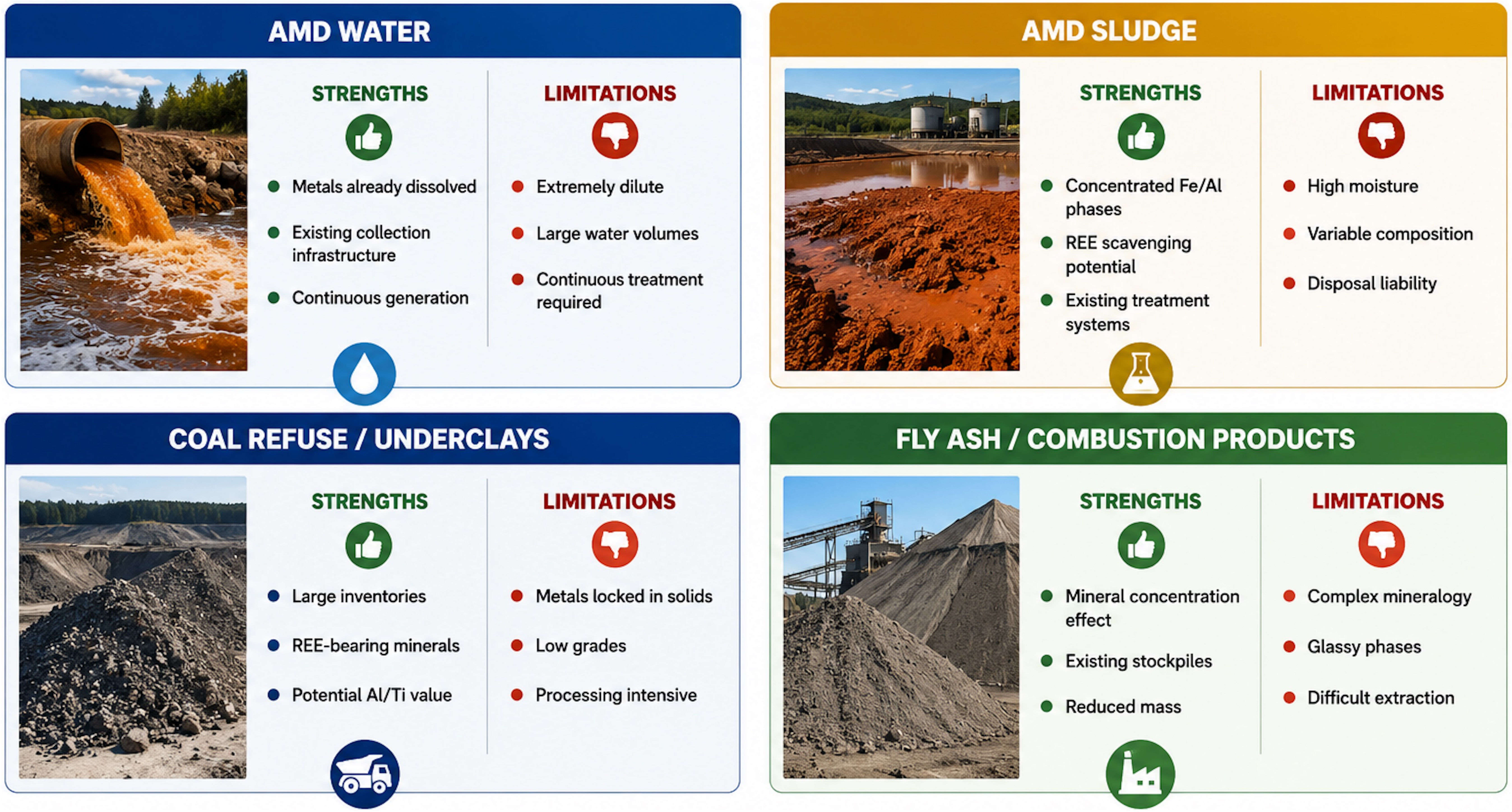
No single waste feedstock is perfect

Every waste stream offers opportunities, but also carries limitations.

- Individual waste streams often suffer from limitations that prevent economical recovery.
- Can complementary waste streams be combined in a way that improves overall process performance and economics?

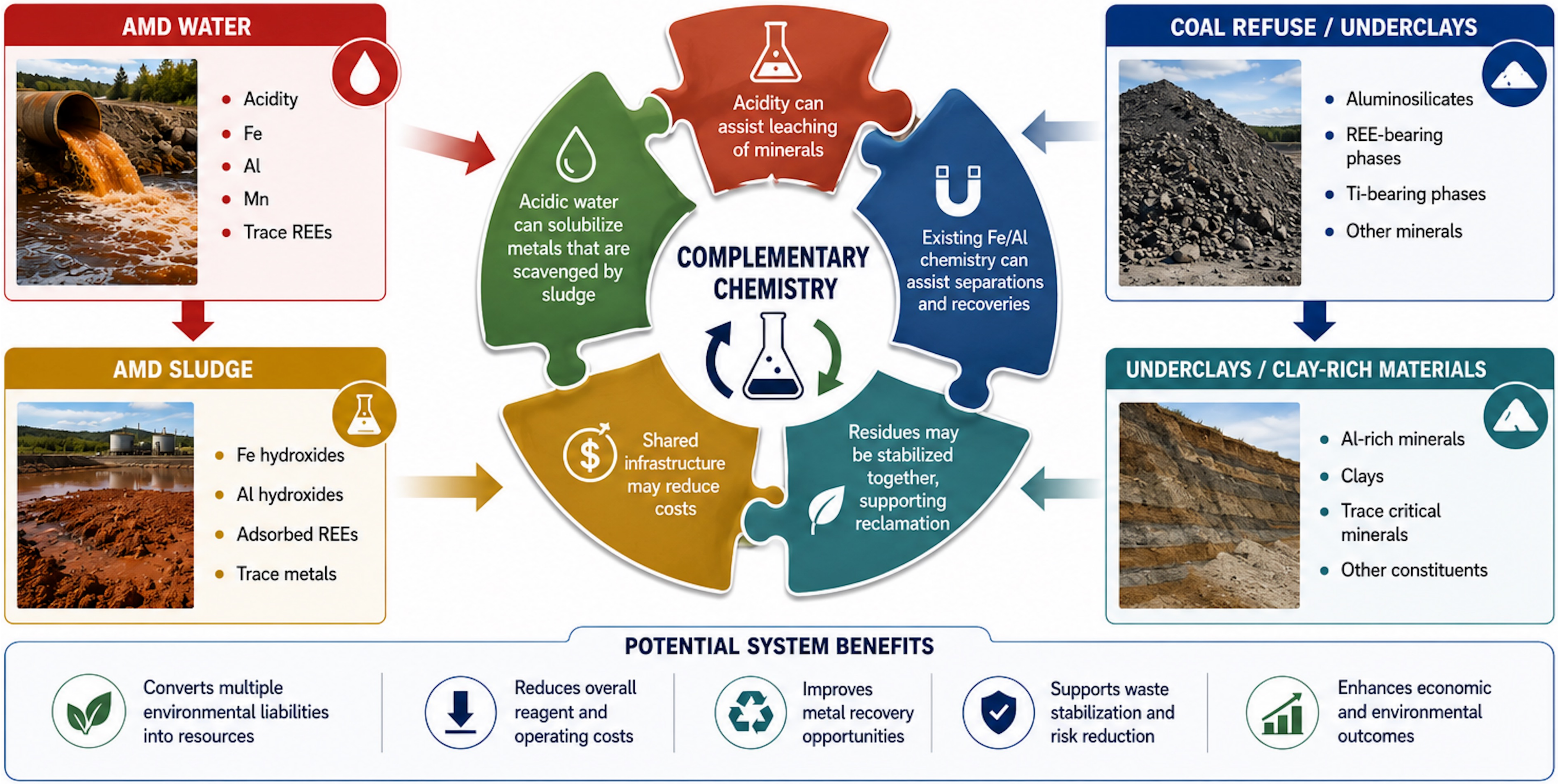


Can multiple waste streams "help" each other?

Instead of treating liabilities separately, can we design a flowsheet that exploits their complementary characteristics?

That question formed the basis of the study.

Rather than designing a recovery process around a **single feedstock**, we evaluated **whether multiple coal-related waste streams could be incorporated into a common treatment framework.**



General processing approach for coal-related feedstocks

If and when feedstock blending should occur?

Coal-related wastes are chemically complementary. Complementarity <u>does not mean</u> direct blending is recommended.

It means designing a flowsheet that uses each material where it helps the overall chemistry, and removes feedstock-specific impurities prior to stream merging.

AMD water
Dissolved Fe, Al, Mn, acidity; REE can be mobilized at low pH

Treatment sludge
Fe/Al hydroxides and oxyhydroxides scavenge REE and trace metals

Coal refuse / underclay
Aluminosilicate matrix; REE may be in clays, phosphates, zircon, oxides

Ash / combustion products
Concentrated mineral matter; variable glass/crystalline phases

Sample
Characterize
Process/Route Select

1. Transport; Size Reduction; Classification; Moisture Control
2. Physical upgrade; Carbon and magnetics removal
3. Acid baking; Leaching; Selective dissolution
4. Impurities removal; Fe conversion; Alumina production; Li, Ga, Ge production
   - Residue neutralization, stabilization; backfill
5. Mixed product precipitation / concentration from solution
6. Separation and purification of individual critical elements
7. Individual element production; metallization; reduction; electrolysis

Every arrow has a mass balance, energy balance, reagent balance, and compliance question attached to it.

Necessary bench-scale work

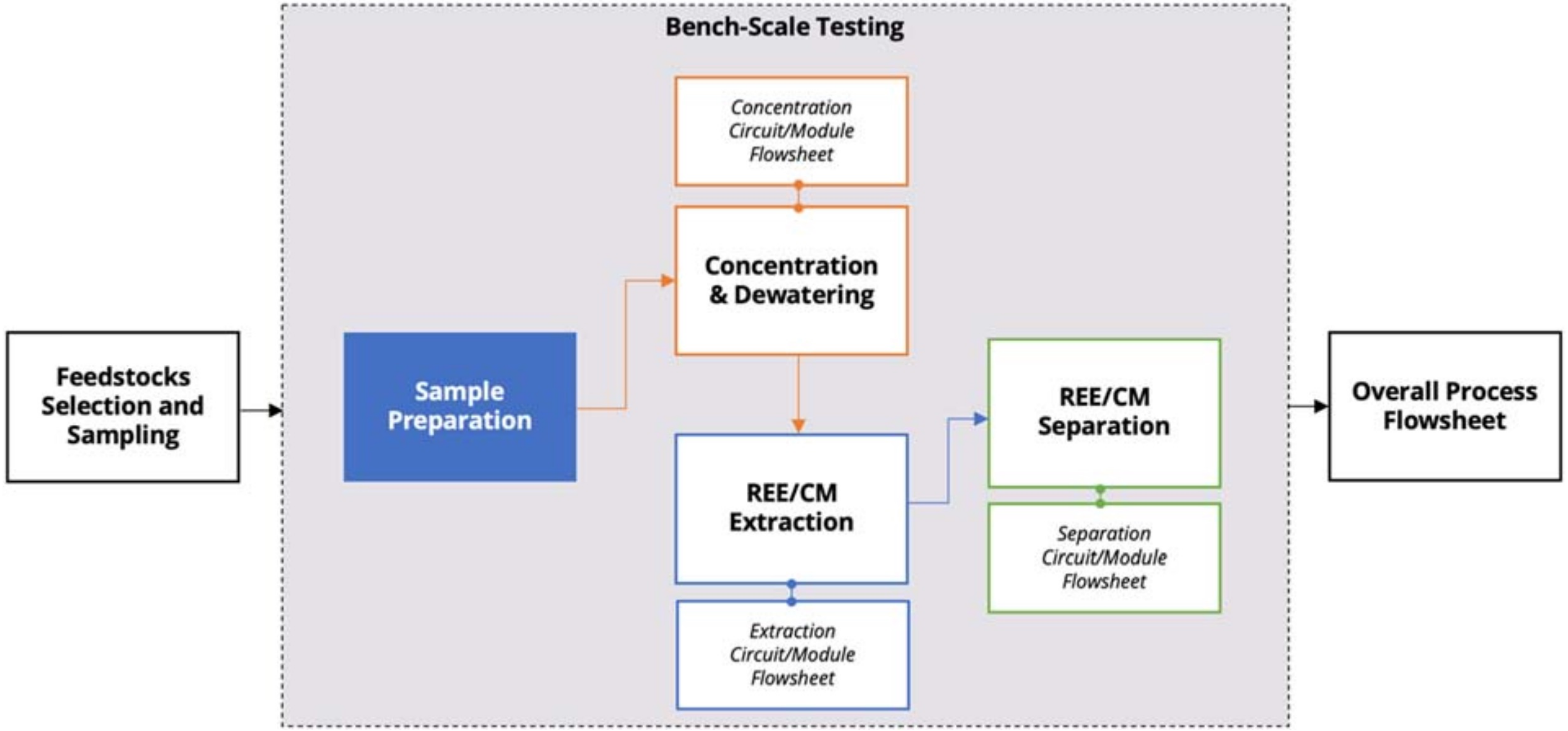
Critical process feasibility questions

Bench testing is done to answer process-design questions.

The target product may be a mixed rare earth oxide / mixed critical-mineral concentrate, or an intermediate for off-take into a downstream separator.

The most optimal solution is often not the highest extraction efficiency, but the most stable, controllable process window.

Assay	ICP-MS/XRF, mineralogy, carbon, moisture What is present and how variable is it?
Physical upgrading	screening, classification, flotation, WHIMS Can we reject mass before chemistry?
Leaching	acid bake/water leach, direct leach, thermal activation What dissolves with the targets?
Impurities Removal	pH control, staged precipitation Can impurities be removed without target loss?
Separation and Purification	SX tests, reduction, metallization Can valuables be recovered with high purity and minimal loss?
Residue tests	TCLP/SPLP leachability, ANC, geotechnical checks Can the residue return to the site?



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Illustrative Pennsylvania Coal-Waste System – Summary

Three waste streams associated with the same coal basin, but exhibiting substantially different physical and chemical characteristics

1 COAL REFUSE STOCKPILE

INVENTORY
~15,200
tons available

KEY CHARACTERISTICS (avg.)

Moisture	15%
Carbon	48%
Iron (Fe)	1.2%
Aluminum (Al)	7.0%
Titanium (Ti)	0.37%

TYPICAL REE-BEARING MINERAL PHASES

Clay minerals, Monazite, Xenotime, Zircon, Anatase (TiO_2)

OPPORTUNITIES

- Existing stockpile
- Highest Li content (130 ppm)
- Significant carbon value

2 UNDERCLAY STOCKPILE

INVENTORY
~63,300
tons available

KEY CHARACTERISTICS (avg.)

Moisture	5%
Carbon	7%
Iron (Fe)	4.8%
Aluminum (Al)	9.5%
Calcium (Ca)	<1%
Titanium (Ti)	0.34%

TYPICAL REE-BEARING MINERAL PHASES

Kaolinite, Illite, Phosphate minerals, Zircon, Oxides

OPPORTUNITIES

- Largest resource inventory
- Highest Sc concentration (20 ppm)
- Highest Ga concentration (25 ppm)
- Aluminosilicate-rich material

3 AMD TREATMENT SLUDGE

INVENTORY
CONTINUOUS GENERATION
~15 tpd
(tons per day)

KEY CHARACTERISTICS (avg.)

Moisture	57%
Iron (Fe)	16%
Aluminum (Al)	10.2%
Calcium (Ca)	Typically low (<1%)
Titanium (Ti)	0.20%

TYPICAL REE-BEARING MINERAL PHASES

Ferrihydrite, Goethite, Fe oxyhydroxides, Al hydroxides

OPPORTUNITIES

- Highest REE grade (435 ppm)
- Highest HREE content (108 ppm HREE)
- Highest Y content (94 ppm)
- Existing treatment infrastructure

COMPARATIVE SNAPSHOT

METRIC	COAL REFUSE STOCKPILE	UNDERCLAY STOCKPILE	AMD TREATMENT SLUDGE	INTERPRETATION
Inventory (tons)	15,200	63,300	15 tpd (continuous)	Underclay » Refuse > Sludge (by mass)
Carbon content			–	Refuse is carbon-rich
Iron (Fe) content				Sludge >> Underclay > Refuse
Aluminum (Al) content				Underclay ~ Sludge > Refuse
Total REE grade (ppm)				Sludge >> Underclay > Refuse

Illustrative Pennsylvania Coal-Waste System – Critical Elements

Three waste streams associated with the same coal basin, but exhibiting substantially different physical and chemical characteristics

	COAL REFUSE STOCKPILE	UNDERCLAY STOCKPILE	AMD TREATMENT SLUDGE	NOTES
FEEDSTOCK (COMPOSITION BASIS)				Concentrations are average values for each feedstock.
PROCESSING CAPACITY (assumed)	1,000 tpd	1,000 tpd	15 tpd	Significant variability occurs within and between batches.
AVAILABLE INVENTORY	~15,200 tons available	~63,300 tons available	Continuous generation (~15 tpd)	Recovery assumption for production estimates: **75% overall recovery**

CRITICAL ELEMENT CONCENTRATIONS (Average Concentration)

Element	UNITS	Coal Refuse CONCENTRATION	Coal Refuse RANK (of 3)	Underclay CONCENTRATION	Underclay RANK (of 3)	AMD Sludge CONCENTRATION	AMD Sludge RANK (of 3)	TAKEAWAY – HIGHEST IN
Total REE	ppm	163	3	210	2	435	1 ★	AMD Sludge
Nd	ppm	44	3	60	2	117	1 ★	AMD Sludge
Pr	ppm	10	3	14	2	25	1 ★	AMD Sludge
Dy	ppm	1.8	3	3.9	2	34.5	1 ★	AMD Sludge
Tb	ppm	0.32	3	0.46	2	4.44	1 ★	AMD Sludge
Gd	ppm	3.1	3	4.9	2	17.2	1 ★	AMD Sludge
Sc	ppm	12	3	20	1	19	2	Underclay
Y	ppm	11	3	16	2	94	1 ★	AMD Sludge
Li	ppm	130	1	85	2	32	3	Coal Refuse
Ge	ppm	0.93	2	1.22	1	0.10	3	Underclay
Ni	ppm	8	3	25	2	541	1 ★	AMD Sludge
Co	ppm	2	3	15	2	232	1 ★	AMD Sludge
Al	%	7.0%	3	9.5%	2	10.2%	1	AMD Sludge

ESTIMATED INDIVIDUAL PRODUCTION RATES (assuming 75% overall recovery)

COAL REFUSE STOCKPILE (1,000 tpd)
Estimated recovered amounts (kg/day)

Total REE	122	Sc	9.1
Nd	33	Y	7.9
Pr	7.6	Li	97.5
Dy	1.37	Ga	11.3
Tb	0.24	Ni	6.0
Gd	2.33	Co	1.6

Al (as metal) 52,500

UNDERCLAY STOCKPILE (1,000 tpd)
Estimated recovered amounts (kg/day)

Total REE	158	Sc	15.1
Nd	44.7	Y	12.2
Pr	10.7	Li	63.8
Dy	2.92	Ga	18.5
Tb	0.35	Ni	18.4
Gd	3.66	Co	11.0

Al (as metal) 71,250

AMD TREATMENT SLUDGE (15 tpd)
Estimated recovered amounts (kg/day)

Total REE	4.9	Sc	0.21
Nd	1.31	Y	1.06
Pr	0.28	Li	0.36
Dy	0.39	Ga	0.10
Tb	0.05	Ni	6.07
Gd	0.19	Co	2.61

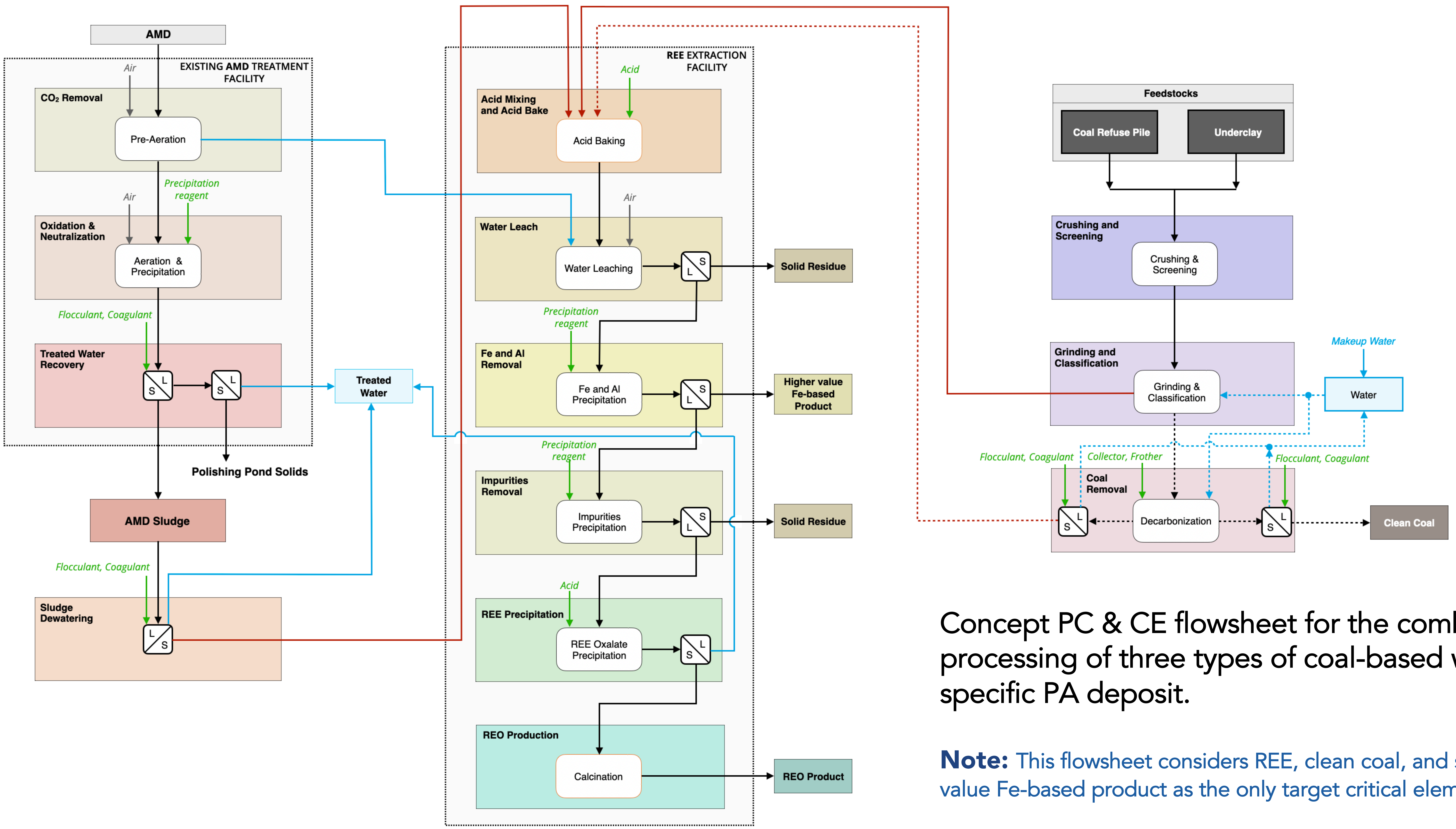
Al (as metal) 1,149

KEY TAKEAWAYS

- AMD sludge is highly enriched in REEs, HREEs, Y, Ni and Co.
- Underclay contributes strong Sc, Ga and Al with a very large inventory.
- Coal refuse provides Li, Ti (not shown in table) and carbon with moderate REEs.
- Integrating all three feedstocks maximizes total critical material recovery.

Note: Concentrations are average values. Results will vary with feed variability and seasonal conditions.

Concept Flowsheet – Physical Concentration and Chemical Extraction



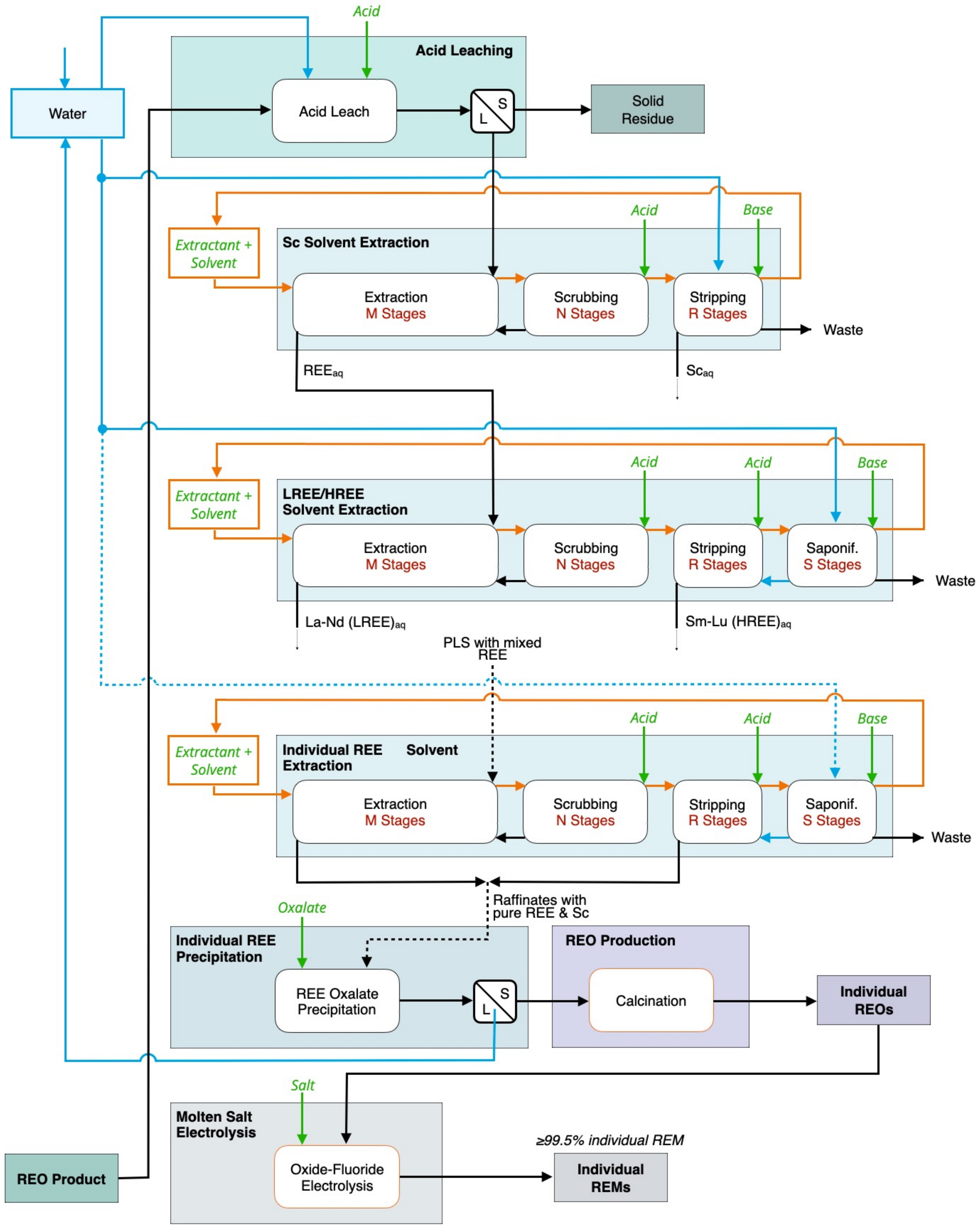
Concept PC & CE flowsheet for the combined processing of three types of coal-based wastes from a specific PA deposit.

Note: This flowsheet considers REE, clean coal, and specialized high value Fe-based product as the only target critical elements.

Concept Flowsheet –
Chemical Separation and Purification

Concept SP flowsheet for the combined processing of three types of coal-based wastes from a specific PA deposit.

Note: This flowsheet illustrates the abbreviated version of the REE Solvent Extraction (SX) plant. A total of 400 to 800 stages are necessary to produce all REEs with the purity demanded by market/customers (*only 33 stages shown in the picture above).



Techno-Economic Analysis

TEA needs the whole flowsheet; all inputs and outputs

Feedstock side
- feedstock ownership
- tipping fee potential
- liability transfer
- Long term stewardship

Revenue side
- critical elements
- industrial minerals
- high-value Fe/Al products
- remediation credits

Cost side
- feedstock handling
- energy and reagents
- water management
- Processing stages

Risk side
- feed variability
- permitting
- scale-up uncertainty
- market volatility

Remediation side
- liability reduction
- residue stability
- long-term closure costs

A waste stream becomes a resource only when recovery, economics, environmental performance, and market requirements align.

Potential Value Creation Beyond Metal Recovery
- reduced AMD treatment burden
- reduced disposal requirement
- reclamation acceleration
- improved site closure outcomes

Key takeaways

1. The future resource base extends beyond conventional ore deposits.
2. Resource potential is determined by the entire process chain.
3. Complementary waste streams may create opportunities unavailable to individual feedstocks.
4. Successful projects must simultaneously satisfy technical, economic, environmental, and market requirements.

Final message

The future of critical-mineral recovery from waste streams will depend less on discovering new resources and more on developing integrated systems that align recovery, remediation, economics, and environmental performance.

Thank you

Questions and discussion

Novex, LLC
Bellingham, Washington
info@novextech.com