HIGH ENERGY-VALUE MATERIALS RECOVERY FROM AQUEOUS WASTE STREAMS

WORKSHOP INTRODUCTION

CHARLIE WERTH, PROGRAM DIRECTOR, ARPA-E

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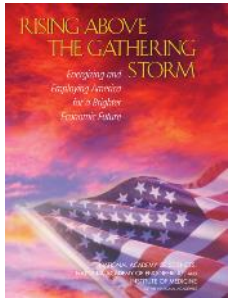
ARPA-E Was Formed in 2009 to Address U.S. Competitiveness

In 2007, The National Academies recommended Congress establish an Advanced Research Projects Agency within the U.S. Department of Energy to fund advanced energy R&D.



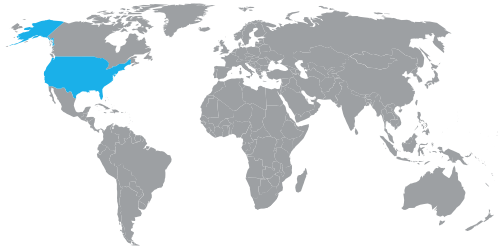
2007

Rising Above the Gathering Storm **Published** - warning policymakers that U.S. advantages in science and technology had begun to erode

America COMPETES Act **Signed** – authorizing the creation of ARPA-E

2009

American Recovery & Reinvestment Act **Signed** – Providing ARPA-E its first appropriations of $400 million, which funded ARPA-E's first projects

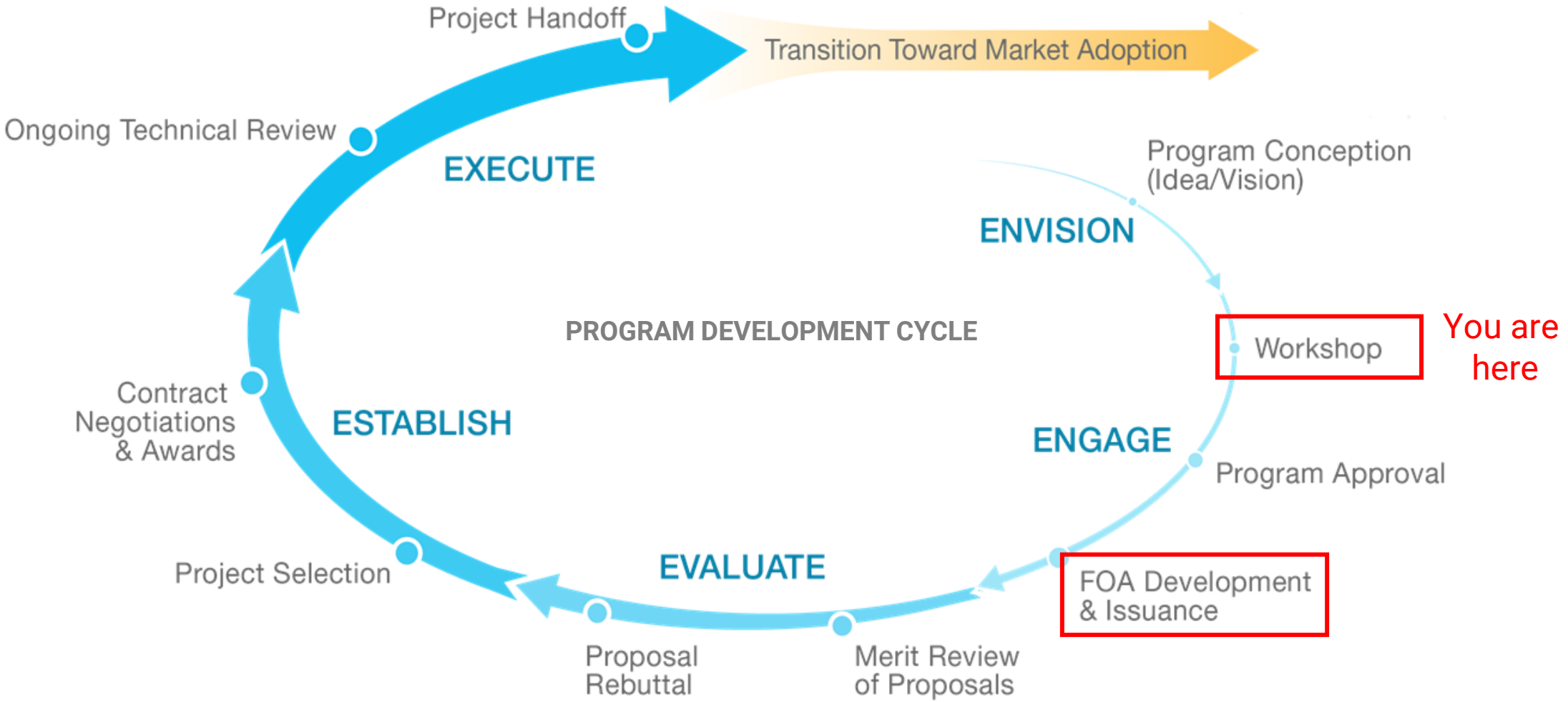


2023

1,468+ Awards
69+ Programs

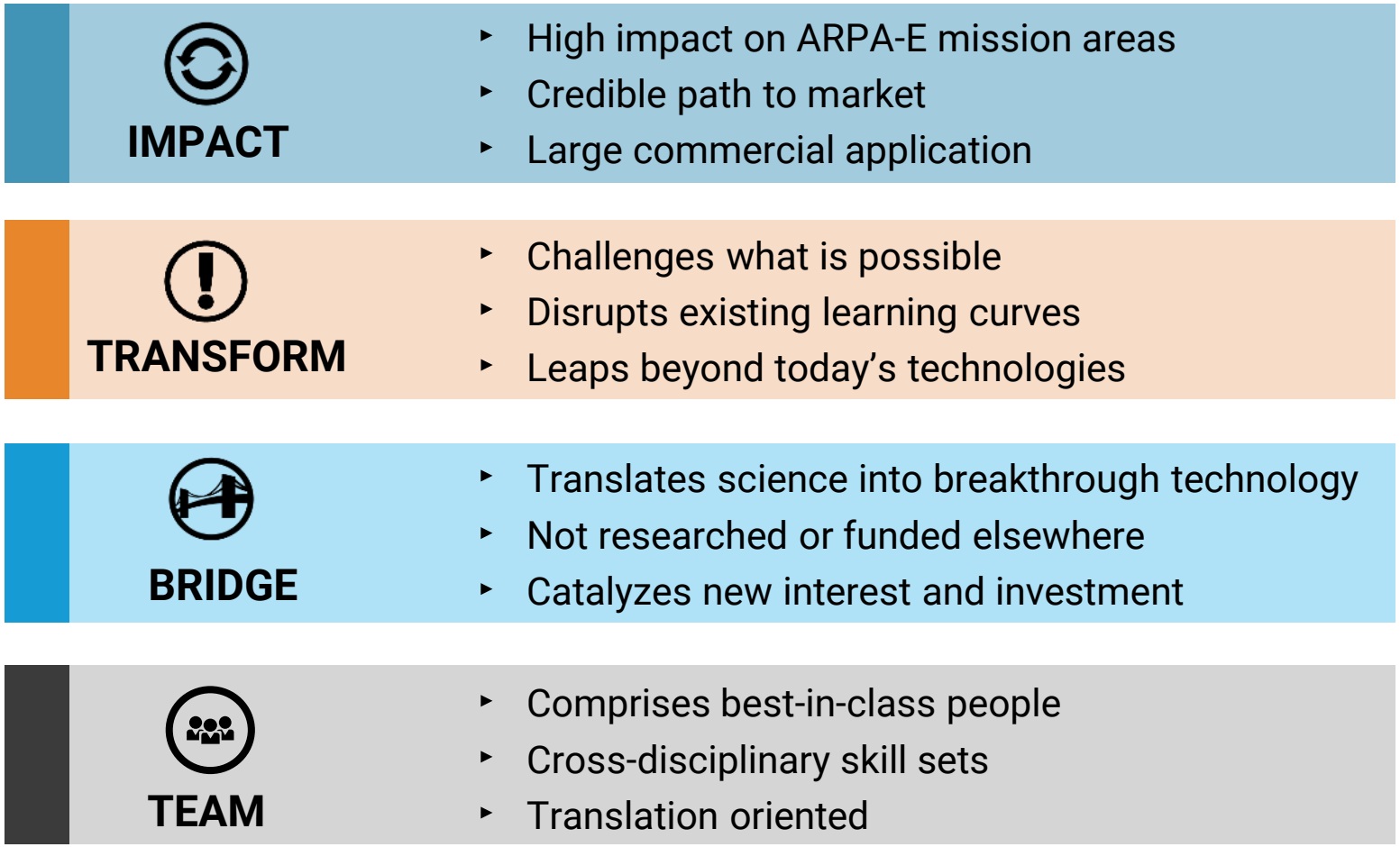
Current Funding:
$470M
(FY23)

Technology Acceleration Model



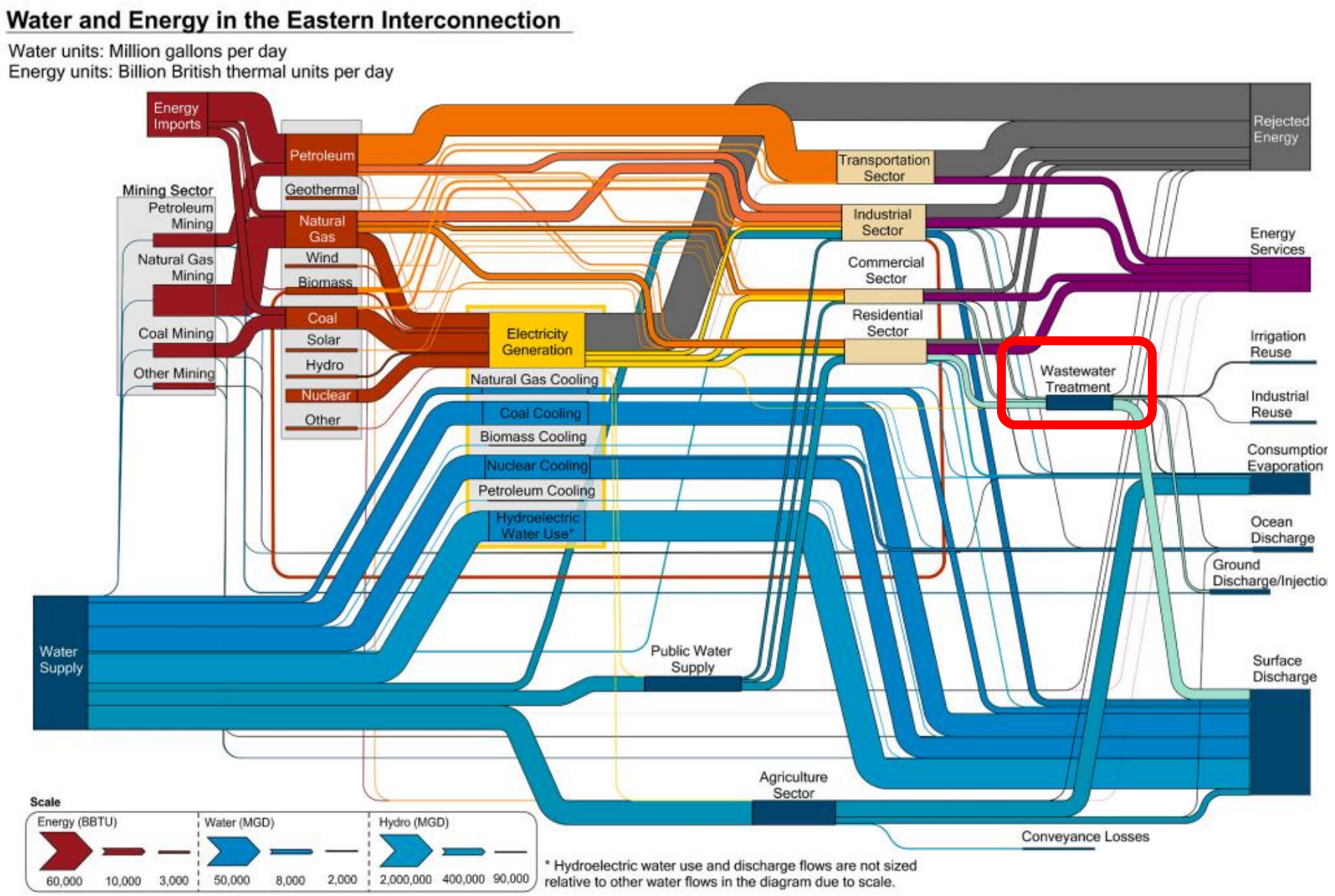
USEPA, 2024; American Public Power Association, 2024

What Makes A Strong ARPA-E Project?



The Water-Energy Nexus Provides A Prime Opportunity To Further ARPA-E's Mission

- Water and wastewater systems account for ~2% of US energy demand
- U.S. electricity generation requires ~47 trillion gallons of water per year



USEPA, 2024; American Public Power Association, 2024

Vision: Recover High Energy-Valuable Materials from Aqueous Waste Streams

Ammonia (e.g., NH_3, NH_4^+)
Base Metals (e.g., Cu, Pb, Zn)
Precious Metals (e.g., Au, Ag, Pd, Pd, Rh)
Rare Earths (e.g., La, Eu, Yb)

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Two Primary Categories

Ammonia Recovery

Critical Minerals (CM) Recovery

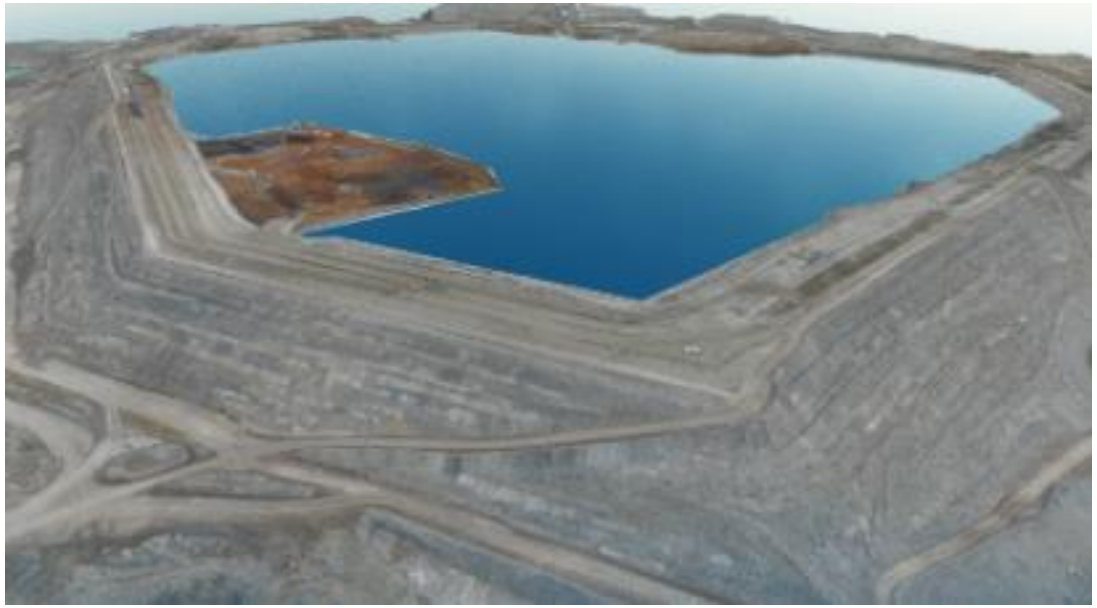
With Common Proposed Goals:

1. Displace up to 30% conventional ammonia and critical mineral supplies
2. Beat traditional energy demands for concentrating target molecule or atom (e.g. Beat Haber-Bosch or conventional mining)
3. Recover market-valuable product at a competitive price

Aqueous Waste Streams Represent an Untapped Cache of High Energy-Value Materials

- Municipal and animal feedlot waste streams contain almost half of the ammonia applied as fertilizer to crops

- Produced waters, mining wastewater, reverse osmosis (RO) concentrate, and other waste streams can provide the entire U.S. demand for some critical minerals



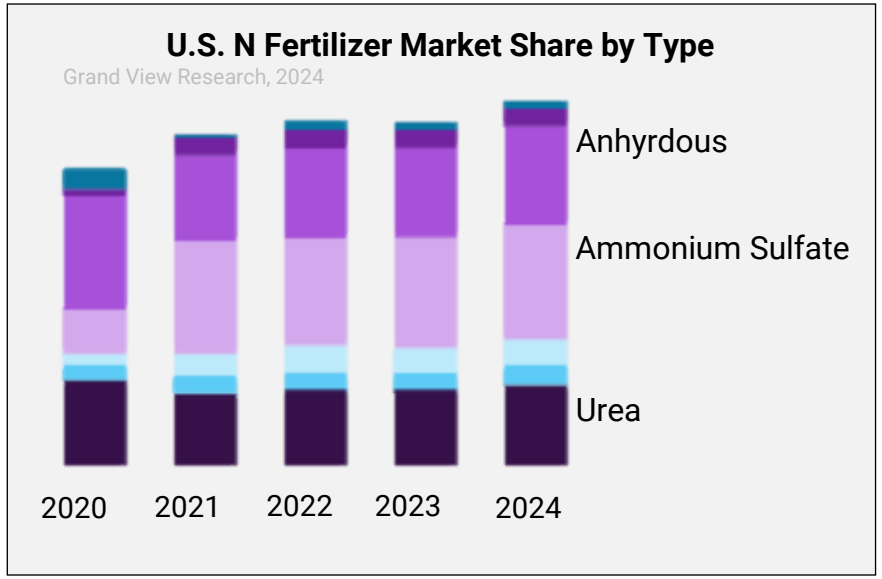
https://platepolitics.wordpress.com/2013/11/23/aerial-photos-of-feedlots-apocalyptic/

https://sustainability.newgold.com

More Than 15 MmT of Ammonia Are Produced Each Year Using the Haber-Bosch Process, Mainly for Fertilizer to Feed The World

- Haber-Bosch consumes 1% of world's energy
- Haber-Bosch emits 2% of world CO_2eq

US N-Fertilizer Market ~ $23B Annually

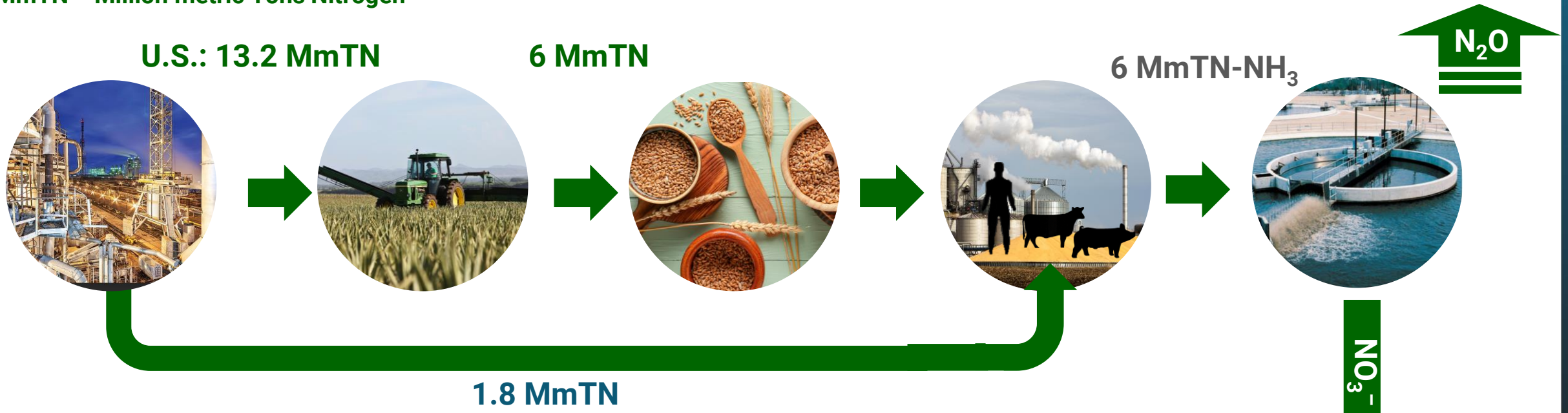


- Fertilizers are necessary for high crop yields

https://extension.okstate.edu/fact-sheets/pre-plant-nitrogen-response-in-irrigated-corn.html

Ammonia Lost in Wastewater Treatment Plants Represents >4 Quads Per Year of Energy, and 400 MMT CO_2eq Emissions Worldwide

MmTN = Million metric Tons Nitrogen



There is the Opportunity to Displace ~40% of Ammonia Production from the Haber-Bosch Process

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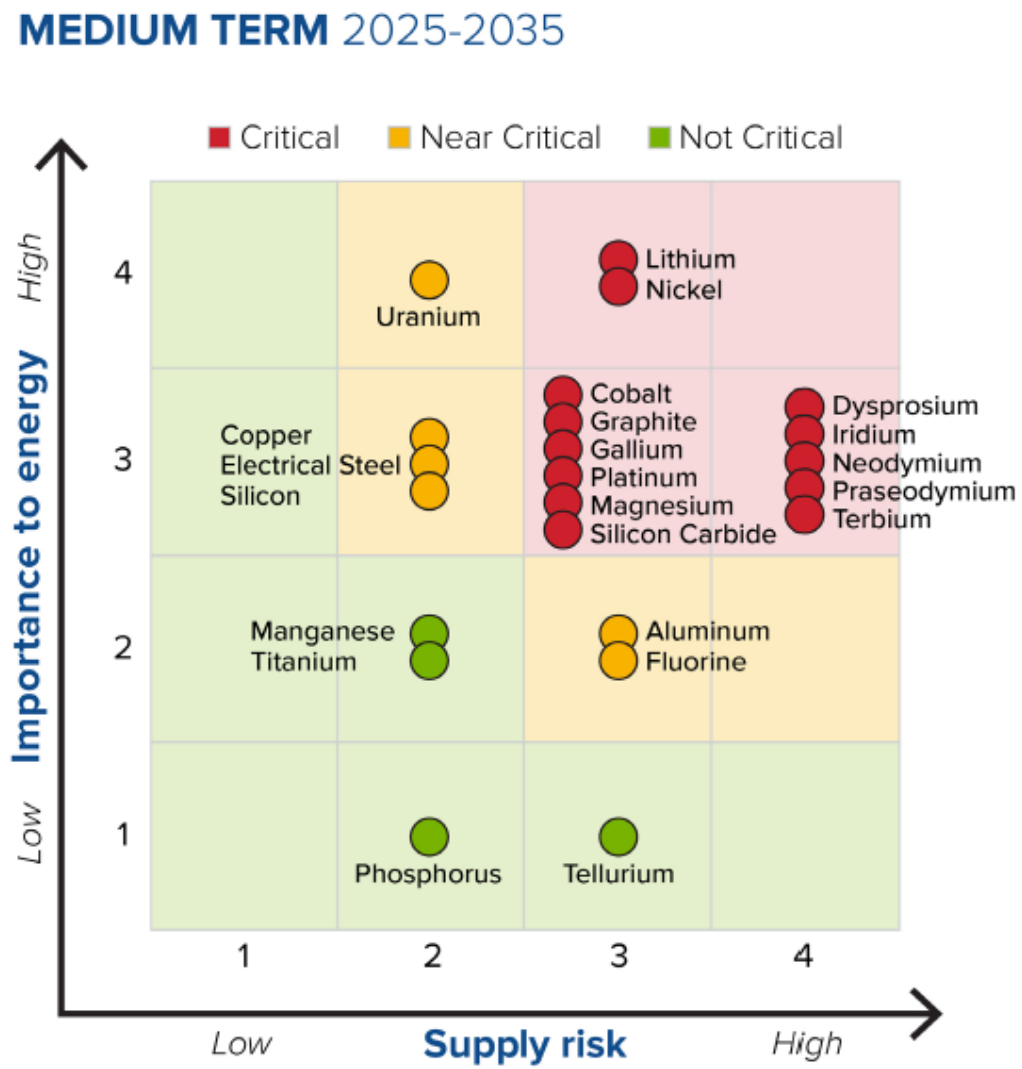
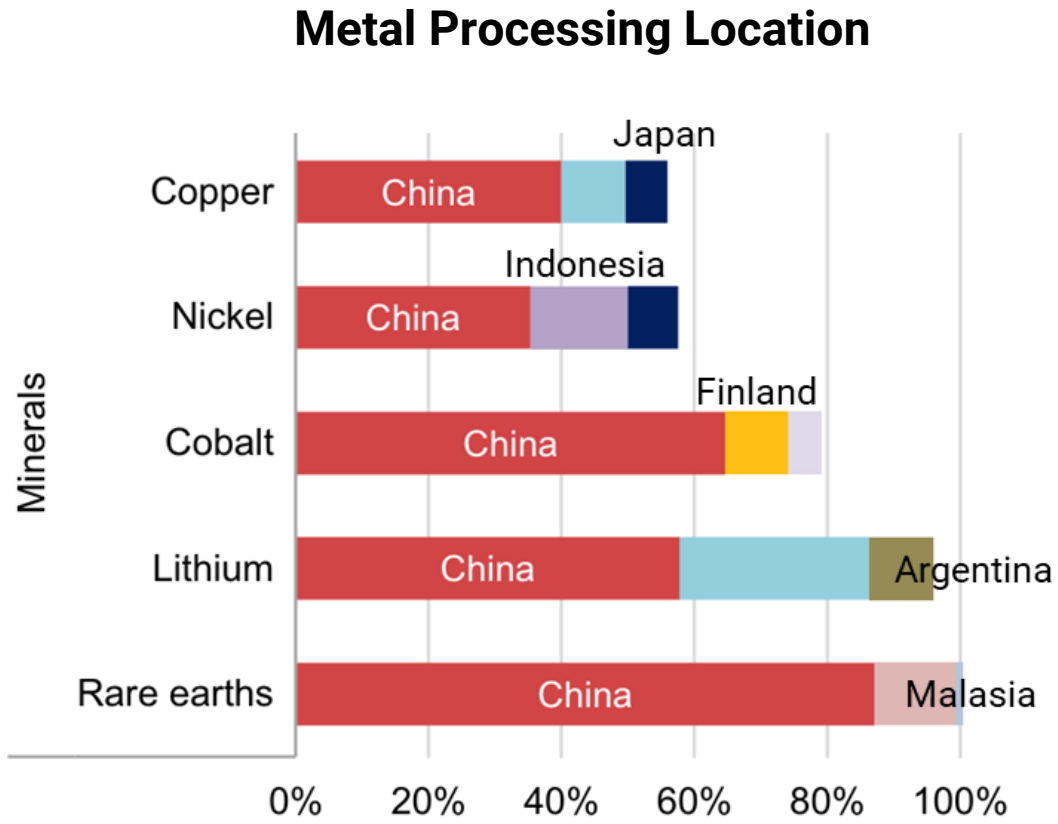
USGS, Miner. Comm. Summ., 2024; NaturalNews.com; USEPA, 2024; Gilbert, Biogeochem., 2020; GetDrawings.com

Critical Minerals Are Vital to U.S. Energy Technologies, and Supply Chain Diversification Is Needed

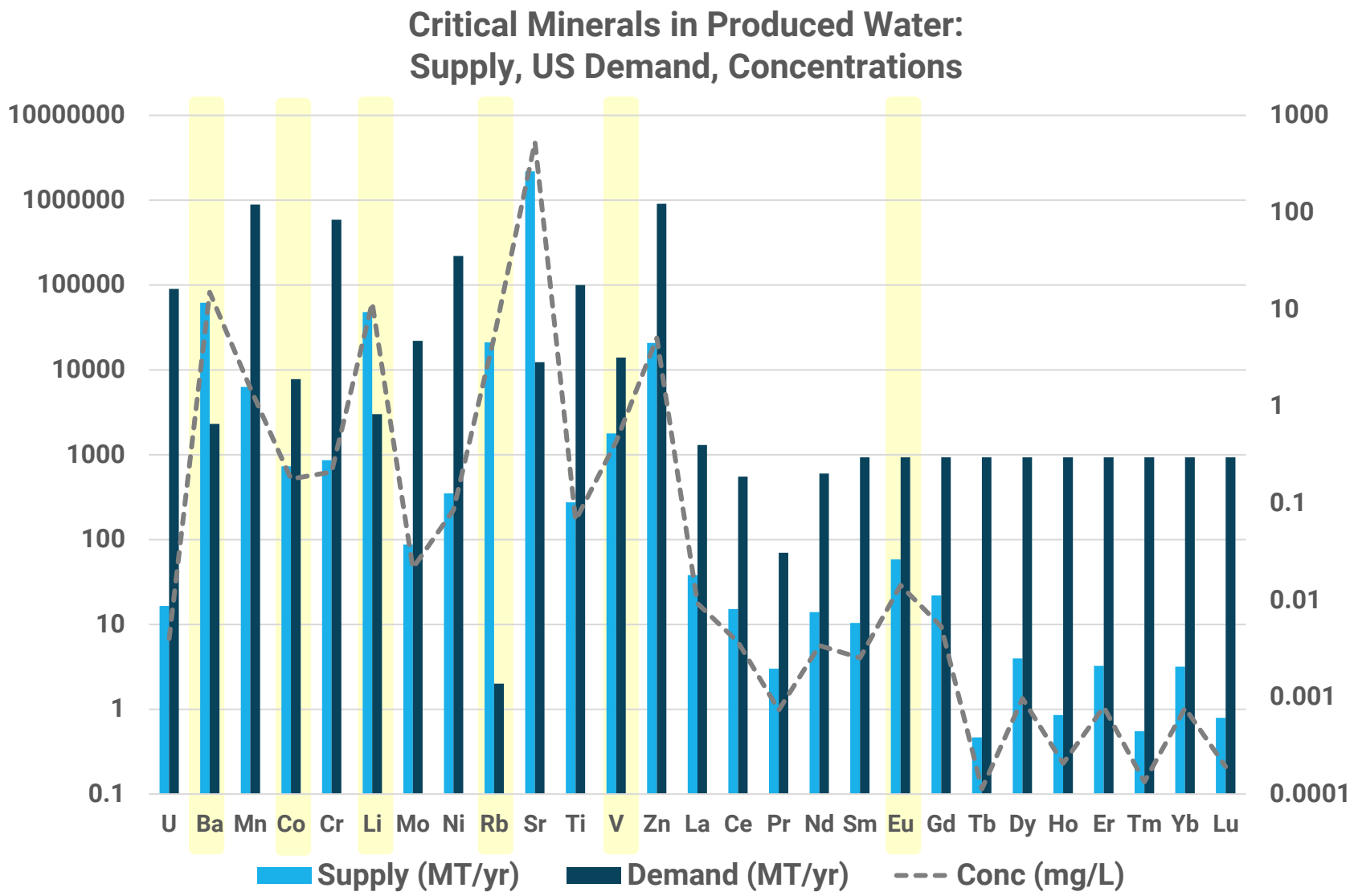




Eia, The role of critical minerals in clean energy transitions, 2022

In Produced Water Alone, There is Sufficient Ba, Co, Li, Rb, V, and Eu to Significantly Displace Overseas Sources*

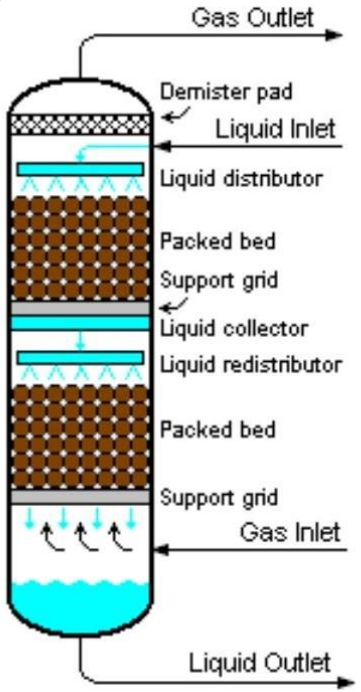
*(Based on average USGS Values)

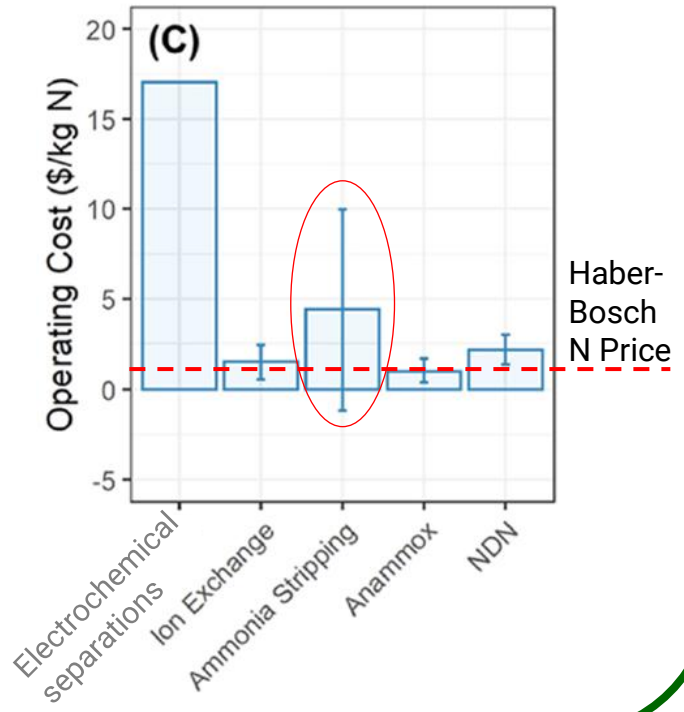


https://www.gwpc.org/wp-content/uploads/2021/09/2021_Produced_Water_Volumes.pdf
Lithium Statistics and Information | U.S. Geological Survey (usgs.gov)
Bern et al., Environ. Science: Processes Impacts, 23, 1198, 2021.

Emerging Recovery Technologies Cannot Yet Economically Recover Ammonia or Critical Minerals from Aqueous Waste Streams

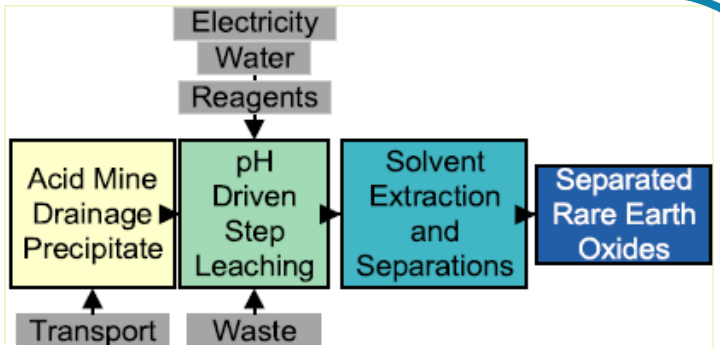
Ammonia Recovery

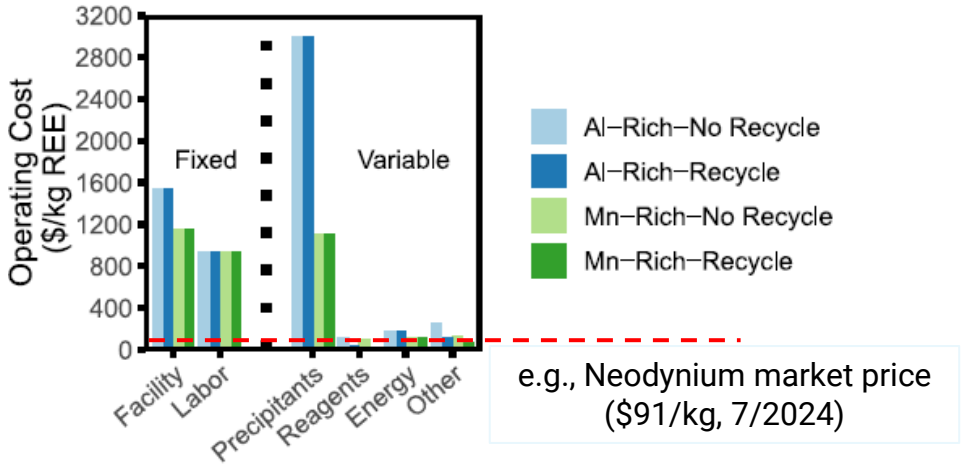




Critical Mineral Recovery

REE Recovery from Acid Mine Drainage





e.g., Neodynium market price ($91/kg, 7/2024)

Friztz et al., ACS Sust. Chem Eng., 9(28), 2021
Kogler et al., ACS Environ. Au, 2024, 4, 2, 89–105

Encouragingly, RFI Responses Highlight Many Exciting New Technology Possibilities That Can Improve Recovery

- **Technology Solutions**
  - **Ion selective adsorption** and membranes followed by **electrochemical separations** are most common approaches
  - Critical mineral recovery primarily **lithium** focused
  - Claims of **> 95% removal** for both NH_3 or Li
- **Major Challenges**:
  - Separation between similar ions
  - Simultaneous separations
  - Fouling (e.g., contaminants, pH sensitivity)
  - Poor stability
  - Additional chemicals/energy input for higher selectivity
  - Concentration steps

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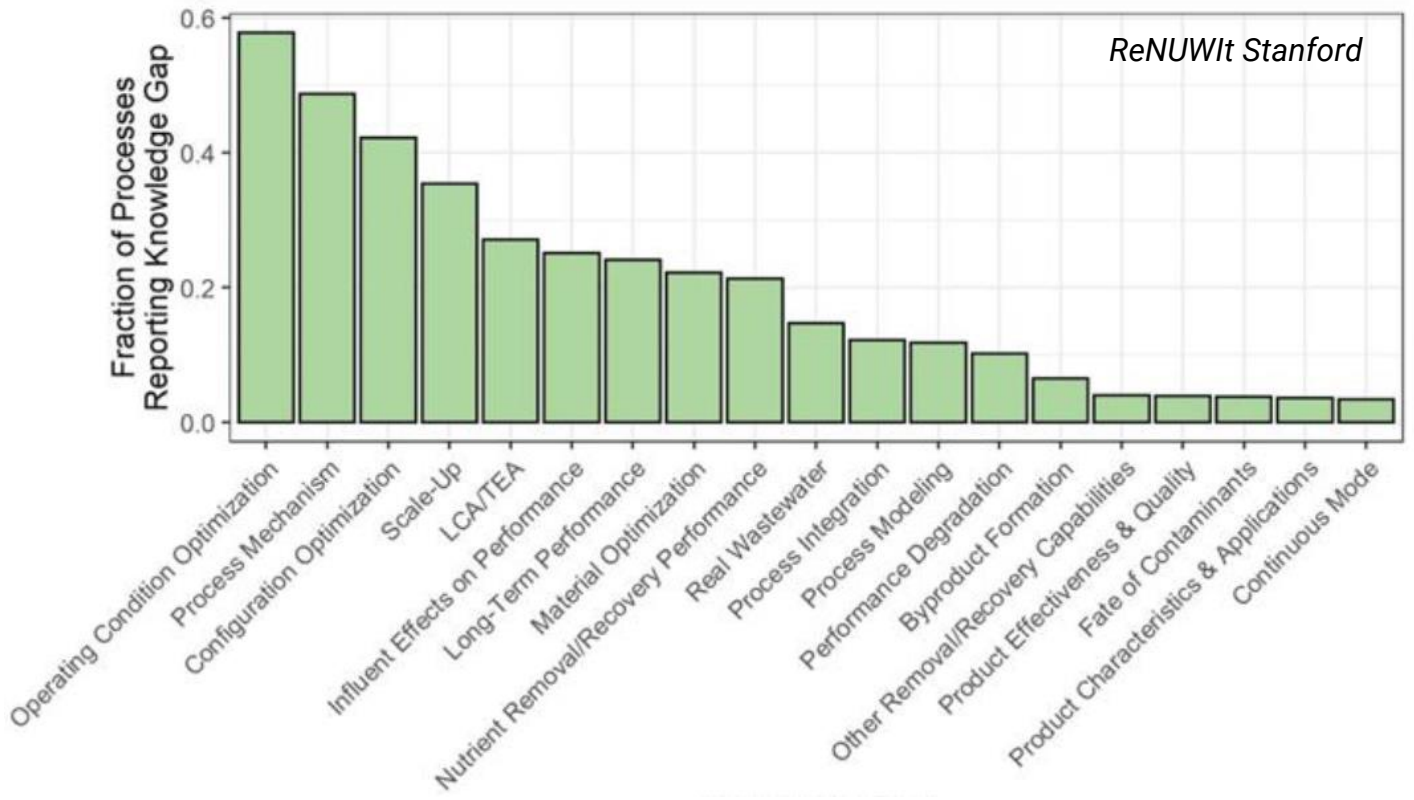
RFI Responses Also Highlight Programmatic White Space That Needs Further Development

Takeaways:

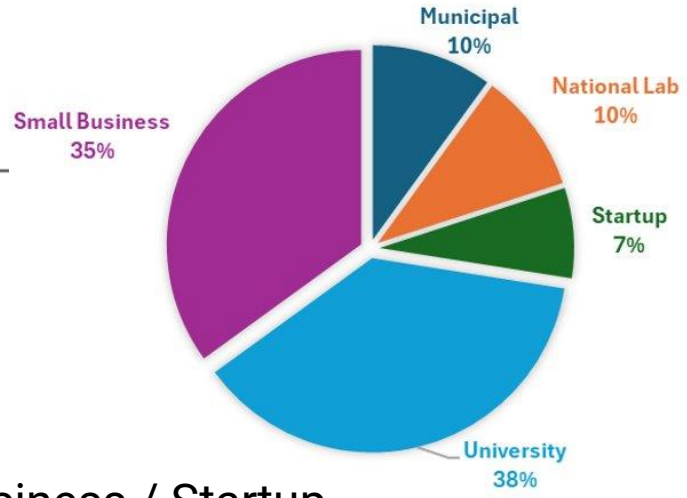
- Need to gain a better understanding of NH_3 and critical mineral value chains from various water sources.
- Technical advancements are necessary to fully build the value chain.
- Performance metrics are needed to develop technologies for commercialization.
- Domestic customers of the recovered product need to be identified.

WW Nutrient Recovery Academic vs Industry Knowledge Gaps



https://doi.org/10.1021/acsestengg.0c00253

Thank You RFI Responders!



Municipal

ORO LOMA SANITARY DISTRICT
San Francisco Public Utilities Commission
CITY UTILITIES WATER THAT WORKS
SUSTAINING FORT WAYNE FOR TODAY AND TOMORROW

National Lab

NATIONAL ENERGY TECHNOLOGY LABORATORY
SRNL SAVANNAH RIVER NATIONAL LABORATORY
NREL NATIONAL RENEWABLE ENERGY LABORATORY
Lawrence Livermore National Laboratory

University

THE GEORGE WASHINGTON UNIVERSITY WASHINGTON, DC
PRINCETON UNIVERSITY
UIC
APL JOHNS HOPKINS APPLIED PHYSICS LABORATORY
TEXAS The University of Texas at Austin
Stanford University
UNIVERSITY OF SOUTH CAROLINA
NORTHWESTERN UNIVERSITY
NORTHEASTERN UNIVERSITY
Northeastern University
Amarillo College
JOHNS HOPKINS UNIVERSITY
UNIVERSITY OF MINNESOTA
THE UNIVERSITY of WISCONSIN MADISON

Business / Startup

FORAGER STATION
Searles Valley Minerals
SRI
COUNTER TRACE
OLOKUN MINERALS
aepnus TECHNOLOGY
MEMBRION
BARYON
SPG SUSTAINABLE PROJECTS GROUP
GEOLITHIUM POWER THE WORLD
REEgen
SUNCHEM
Purammon
YOKOGAWA
VANDSTROM
SiTration
Roca Materials
FISHERH2O, LLC
ChemFinity TECHNOLOGIES

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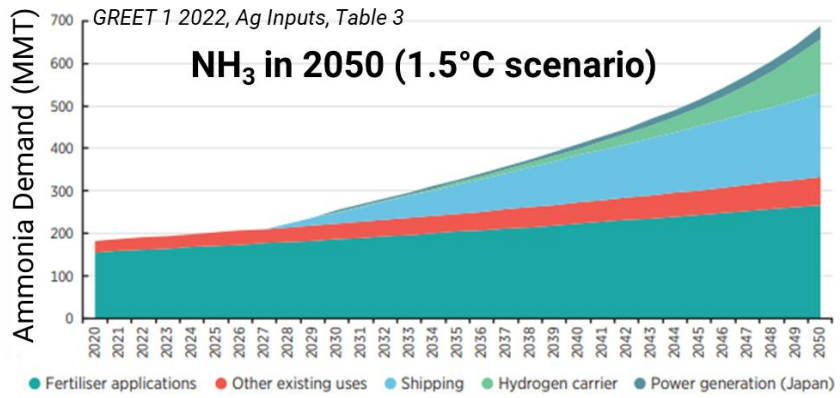
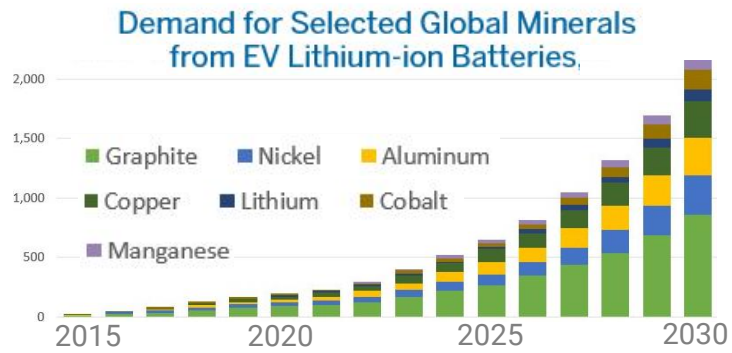
The Time Is Right To Focus On Recovery of Ammonia and Critical Minerals From Waste Streams

Driver	Ammonia	Critical Minerals
Rapid growth in demand for decarbonization		 Bloomberg Energy Finance
Regulatory incentives due to climate, pollution, & supply chain concerns	IRA (2022) tax credit for new biogas facilities, and funds for Rural Energy for America Program California Senate Bill-1383 (2016): Regulation of methane emissions from dairy/livestock ops Illinois property tax incentives for pollution control facilities	U.S. H.R. 2849: Rare Earth Magnet Manufacturing Production Tax Credit Bill of 2023 Inflation Reduction Act (2022) 10% tax credit for costs to domestically produce critical minerals
Rapid scientific advancements	Molecular-level design and tailoring of functional groups for selective adsorbents, membranes, and electrodes	

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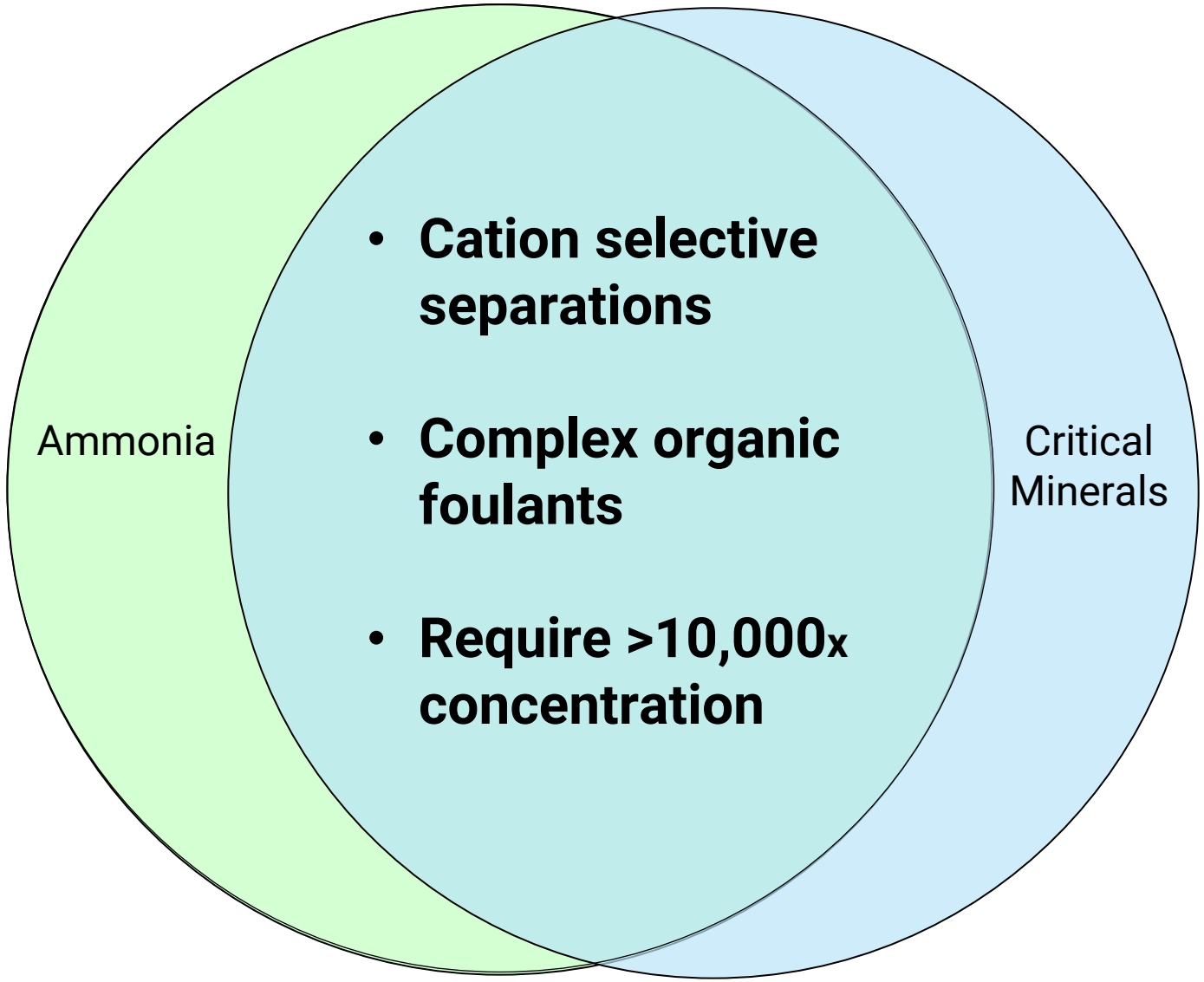
There is Synergy Between Ammonia and Critical Mineral Recovery

- Both ammonia and critical minerals have common technology challenges:
- Federal funding and government priorities have created more investment interest in critical minerals, and this can benefit technology development and investment in ammonia recovery



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Our Workshop Has Ambitious Goals

- Inform ARPA-E on technologies needed to recover high energy-value materials from aqueous waste streams
  - Identify market opportunities, needs, impacts, and obstacles
  - Present emerging and relevant technologies
  - Identify technological opportunities and obstacles
  - Define ambitious metrics to assess technologies

- Build a community focused on high energy-value materials recovery
  - Be engaged in all technical conversations: talks, panels, breakout sessions
  - Share your technical expertise and opinions
  - Listen and learn
  - Network and find partners that complement your strengths
  - Enjoy!

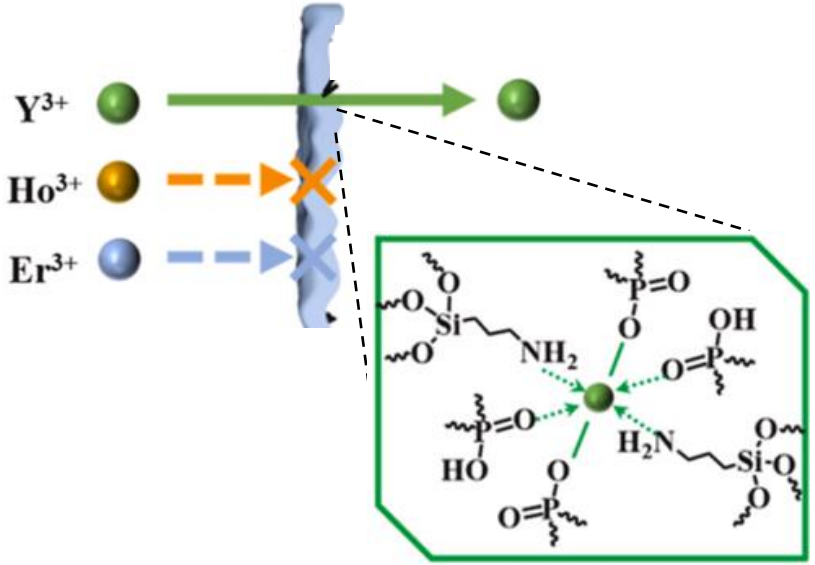
There Are A Number of Key Questions That Will Come Up

- What technology white space should ARPA-E focus on?
- What aqueous waste streams should be targeted for recovery to impact ammonia or critical mineral(s) supply chains?
- What form and concentration of ammonia or critical mineral(s) should be recovered, who will purchase, and at what price?
- What are the opportunities, barriers, and/or risks to integrating new recovery technologies into existing waste stream management systems?
- What tools are available to assess cost, energy demand, and carbon footprint?

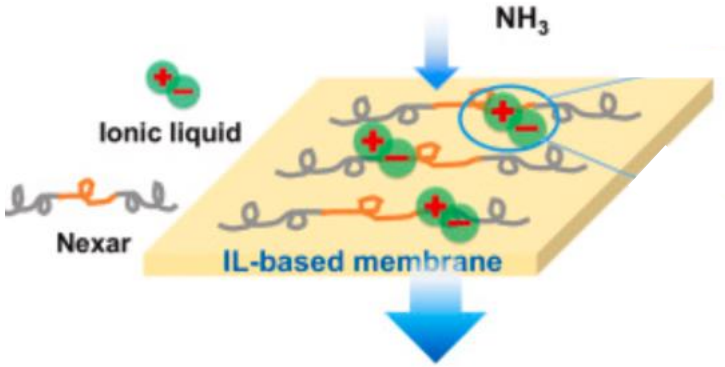
Identifying the Technology White Space Is Particularly Important

- Some representative examples:

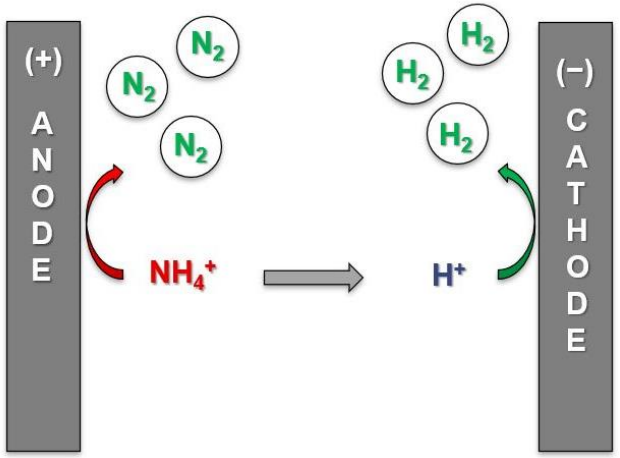
Improved Cation Separations (e.g., NH_4^+, Ni^{2+}, La^{3+})



Improved Gas Separations (e.g., NH_3)



More Energy Efficient Electrochemical Reactions (e.g., $NH_4^+ \rightarrow H_2$, $Ni^{2+} \rightarrow Ni^0$)



- **Greater Resilience To Fouling**
- **Component or Systems Integration**
- **Other...**

Lu Liu, Qi Wu, Shunli Wang, Wei Lai, Peijun Zheng, Can Wang, Xin Wei, and Shuangjiang Luo*, I&EC Research*
Weiguo Pan, Li Chen, Yitan Wang, Yongsheng Yan, Journal of Membrane Science.
Daniel V. Esposito, Membraneless Electrolyzers for Low-Cost Hydrogen Production in a Renewable Energy Future
Yang et al., J. Membrane Sci.

Technology Performance Metrics

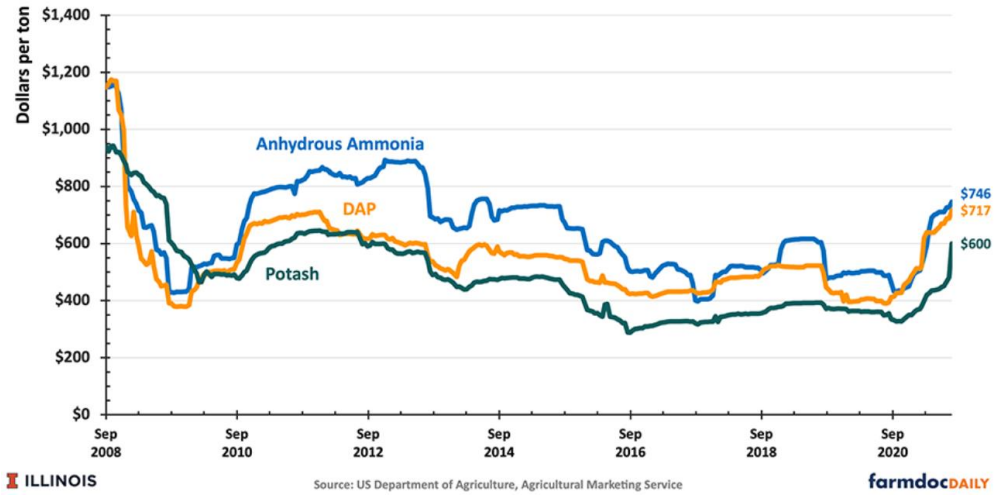
Proposed Metric	Rationale
Recover **>90% of target** constituent from waste stream	Needed to impact conventional supply chain
Target for recovery: **1) 5 wt%** N or M aqueous stream **2) 10wt%** N or M precipitate 3) For NH_3, **80 vol%** NH_3 or H_2	Minimum concentration for market valuable product
Continuous treatment of real waste stream for **1 month at ≥1 L/hour**	Necessary to assess technology performance under realistic treatment conditions (i.e., with fouling mitigation)
Path to **meet target cost**, **energy, and CO_2eq emissions** for a given resource determined from market conditions (e.g., Haber-Bosch, Hard Rock Mining)	Targets represent current practices that new technologies must meet to be competitive

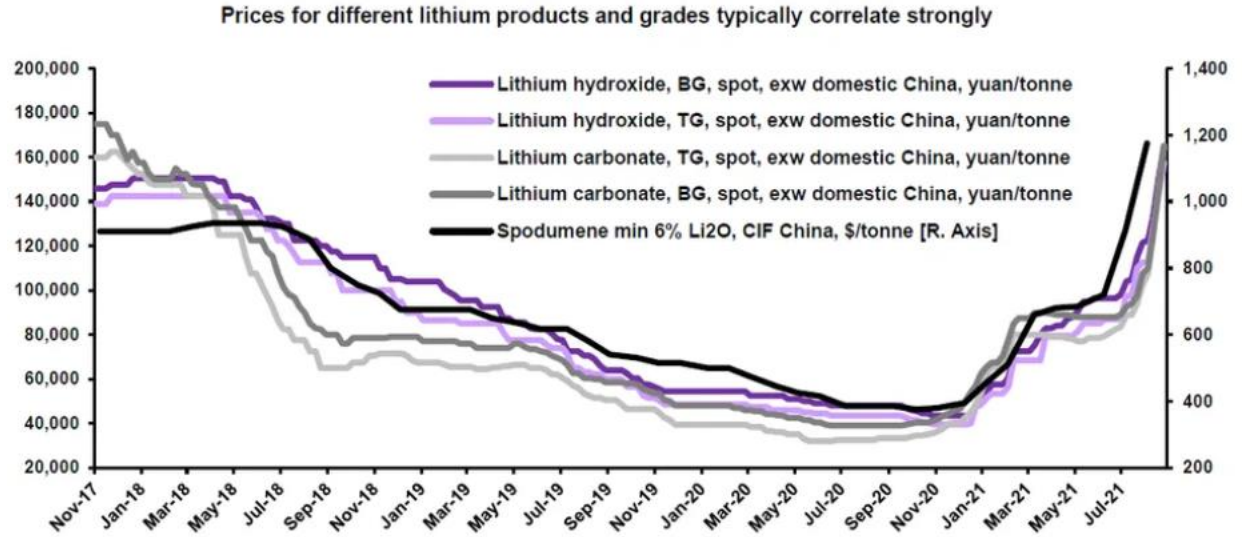
N = Nitrogen, M=Metal

Better Define The Market For Recovered Products

Identifying the market price for a commodity is fairly straight forward

Figure 2. Fertilizer Prices in Illinois From 2008 To 2021
September 2008 to July 2021





- How is the price of off-spec products determined?
  - Based on $/kg-N or $/kg-M in a product plus or minus a premium
  - Adjusted for tax breaks or other market incentives

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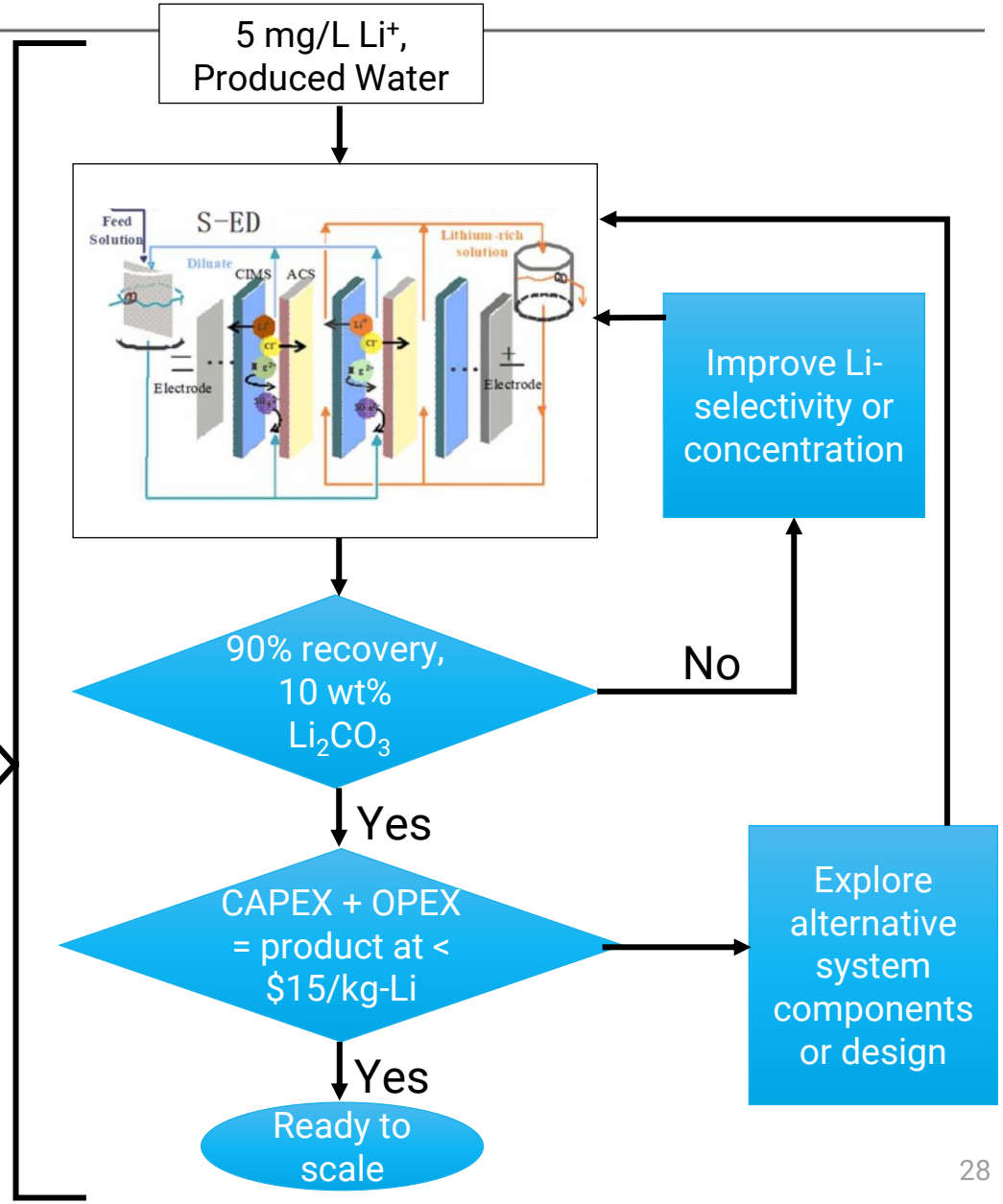
2021 Fertilizer Price Increases in Perspective, with Implications for 2022 Costs - farmdoc daily (illinois.edu)
https://www.fastmarkets.com/insights/why-the-lithium-market-needs-to-take-a-leap-of-faith-on-pricing/

A Common Approach To Assess (and Improve) Impact is By Coupling Technology Performance With TEA/LCA

Steps	Description	Example
1	Target molecule or element, and waste stream, of interest	Lithium, Li, Produced water
2	Target concentration & waste stream volumetric flow rate	C=5 mg/L, Q=1 B L/day
3	Target ion recovery opportunity	5 mT/day
4	Anticipated recovery efficiency	90%
5	Anticipated form and purity of recovered target	10wt% Li_2CO_3 precipitate
6	Potential buyer and price point (considering incentives)	XYZ Battery Corp. $15/kg-Li



Zhang, Xiao-Chai et al., J. Environ. Chem. Eng. ***2021,*** *9 (6), 106635. DOI: 1016.j.jece.2021.106635*

Ground Rules

- Burning questions wait to Q&A and Networking
- This is working session not a conference
- Take your cell phone calls outside if you must
- Push past the edges – new hypotheses
- Try to stay as punctual as possible
- Participate! Participate! Participate!
- Take “rabbit hole” discussions off-line or over dinner – keep focused!
- One speaker at a time and respect perspectives even if you disagree
- Respect the CONFIDENTIALITY of your colleagues

Look Around, You Have a Lot of Smart People To Learn From Or Collaborate With…

Ammonia Recovery

Critical Minerals Recovery

Self-identify Your Expertise with Respective Sticker(s)

Ammonia Wastewater Management

- Wastewater engineers
- Producer or storage of NH_3 waste streams
- Seeking solutions for enhance NH_3 recovery

Critical Minerals Wastewater Management

- Wastewater engineers
- Producer or storage of CM waste streams
- Seeking solutions for enhance CM recovery

Materials Development

- Developing new separation materials: adsorbents, anodes, cathodes, membranes, etc.
- Studying material separation physics or chemistry.

Reactor Design

- Designing reactors or separations systems

System Assessment

- TEA or LCA analysis
- CapEx and OpEx management
- Market analysis

System Integration & Optimization

- Integration and of sequential processes
- Scaling and implementing new technologies
- Pilot plants

Contribute to a Potential New Funding Space For Water in ARPA-E

Agenda

DAY ONE

- **Introductions**
  - **ARPA-E**
  - **Workshop**
- **Resource Recovery Opportunity Talks**
- Lunch
- **Breakout Session**
- **Innovative Technology Talks**
  - Lightning Pitches
- **Breakout Session**
- **Adjourn**

DAY TWO

- **Turbo Teaming & Networking**
- **System Assessment & Integration Talks**
- Lunch
- **Breakout Session**
- **Adjourn**
  - Individual Meetings with Charlie

Final Instructions

Sit with someone different each session

Make plans to visit each other

Eat every meal with a different crowd

Get inspired to unlock the future

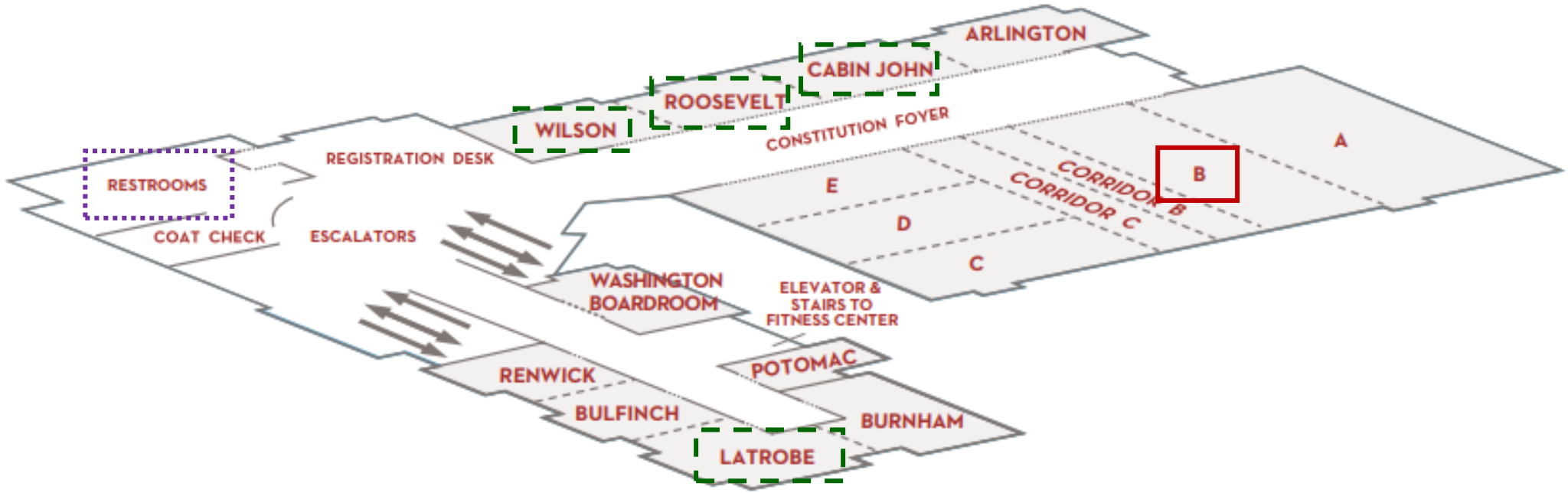
Hotel Map

General Session – *B*
- Presentations
- Networking
- Meals

Breakout Sessions
- Wilson
- Roosevelt
- Cabin John
- Latrobe (also individual meetings)

Restrooms

Constitution Level (3B)



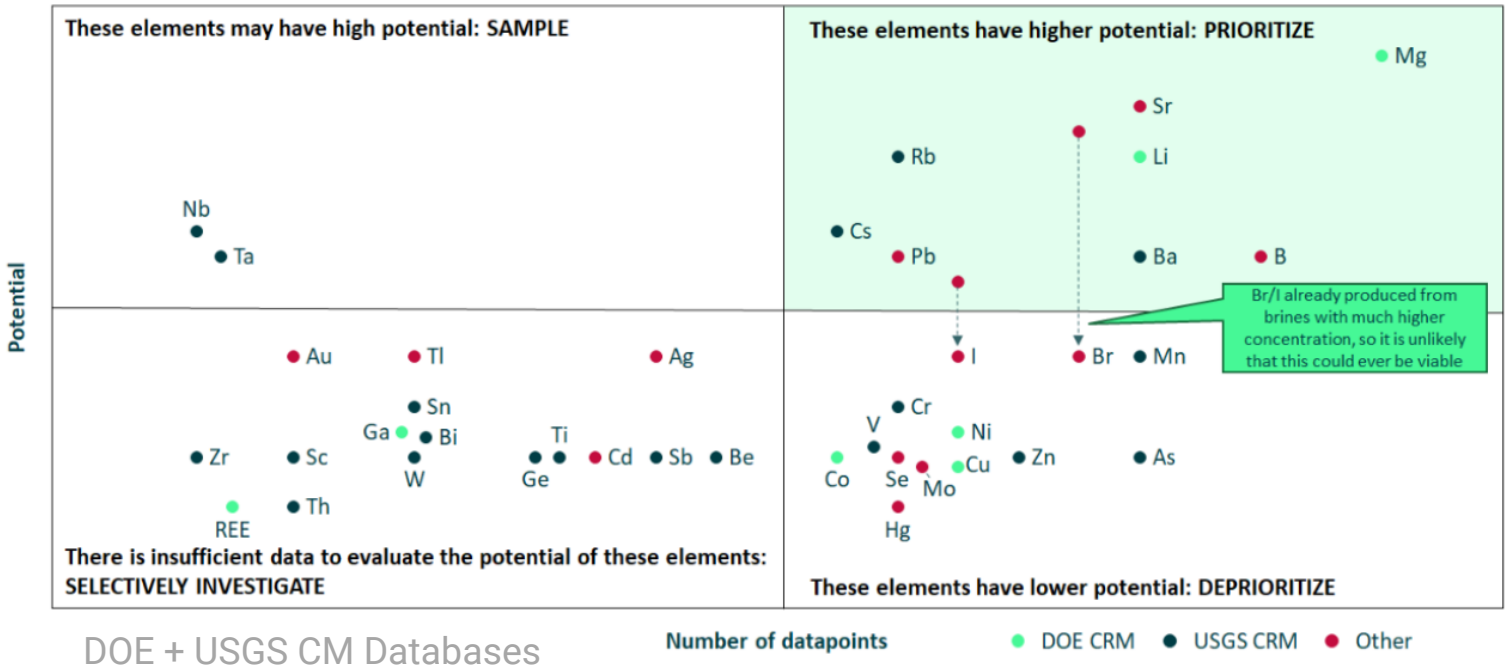
QUESTIONS?

This is to schedule a brief session with Charlie Werth and team.

Part 2: Technology End Users, Assessors, and/or Beneficiaries

Produced Water Critical Mineral Market Potential

Sustainable Projects Group Inc. / Lithium Harvest



DOE + USGS CM Databases

#1 Priority : Li + Mg

#2 Priority : Ba, Rb, + Cs

End Market : Battery Materials

Tech-to-Market

Small wells = small water volumes = need to centralize streams

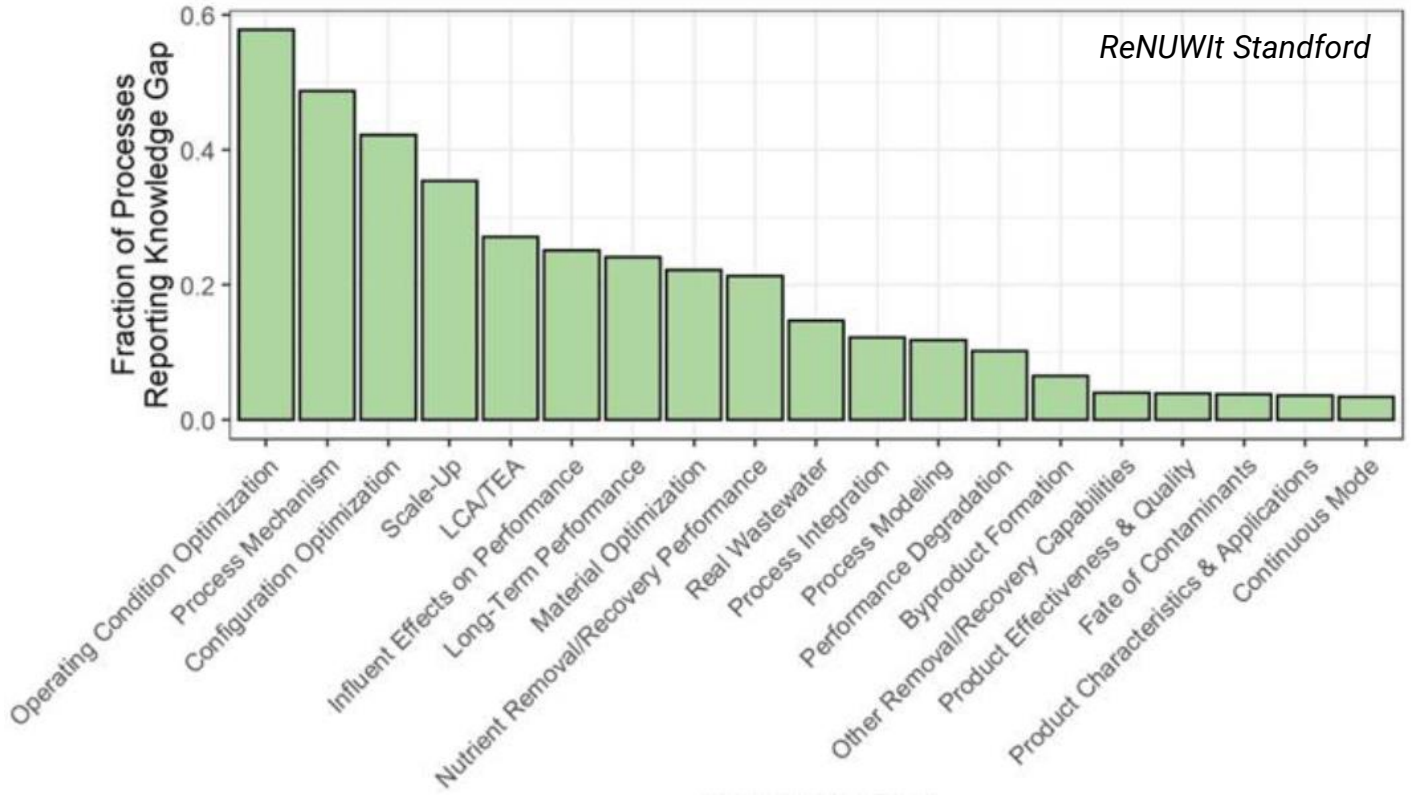
Integration with existing systems is primary concern

Focus technology on maximizing CM extraction.

Will likely need an intermediate to further refine and process for commercial use.

Part 2: Technology End Users, Assessors, and/or Beneficiaries

WW Nutrient Recovery
Academic vs Industry Knowledge Gaps



Tech-to-Market

1. Operating Condition Optimization
2. Process Mechanism
3. Configuration Optimization
4. Scale-up

5. LCA / TEA
6. Influent Effects on Performance
7. Long-term Performance
8. Material Optimization
9. Nutrient Recovery Performance

https://doi.org/10.1021/acsestengg.0c00253

Encouragingly, Your RFI Responses Highlight Many Exciting New Technology Possibilities That Can Improve Recovery