Energy & Environmental Research Center (EERC)

TODAY'S CRITICAL MINERAL TECHNOLOGIES AND HOW TO MOVE FORWARD

November 30, 2022

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PRESENTERS

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Emissions and Carbon Capture, EERC

Nolan Theaker, Technical Group Manager
Critical Minerals, Institute for Energy Studies

Webinar Series Events

Critical Minerals: What, How, Why All the Hype?
September 21, 2022

Today's Critical Mineral Technologies and How to Move Forward
November 30, 2022

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Our Strengths, Our Assets, Our Needs
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Securing the Williston Basin's Critical Mineral Future:
Findings and Next Steps
March 2023

Defining Critical Minerals

Critical Minerals

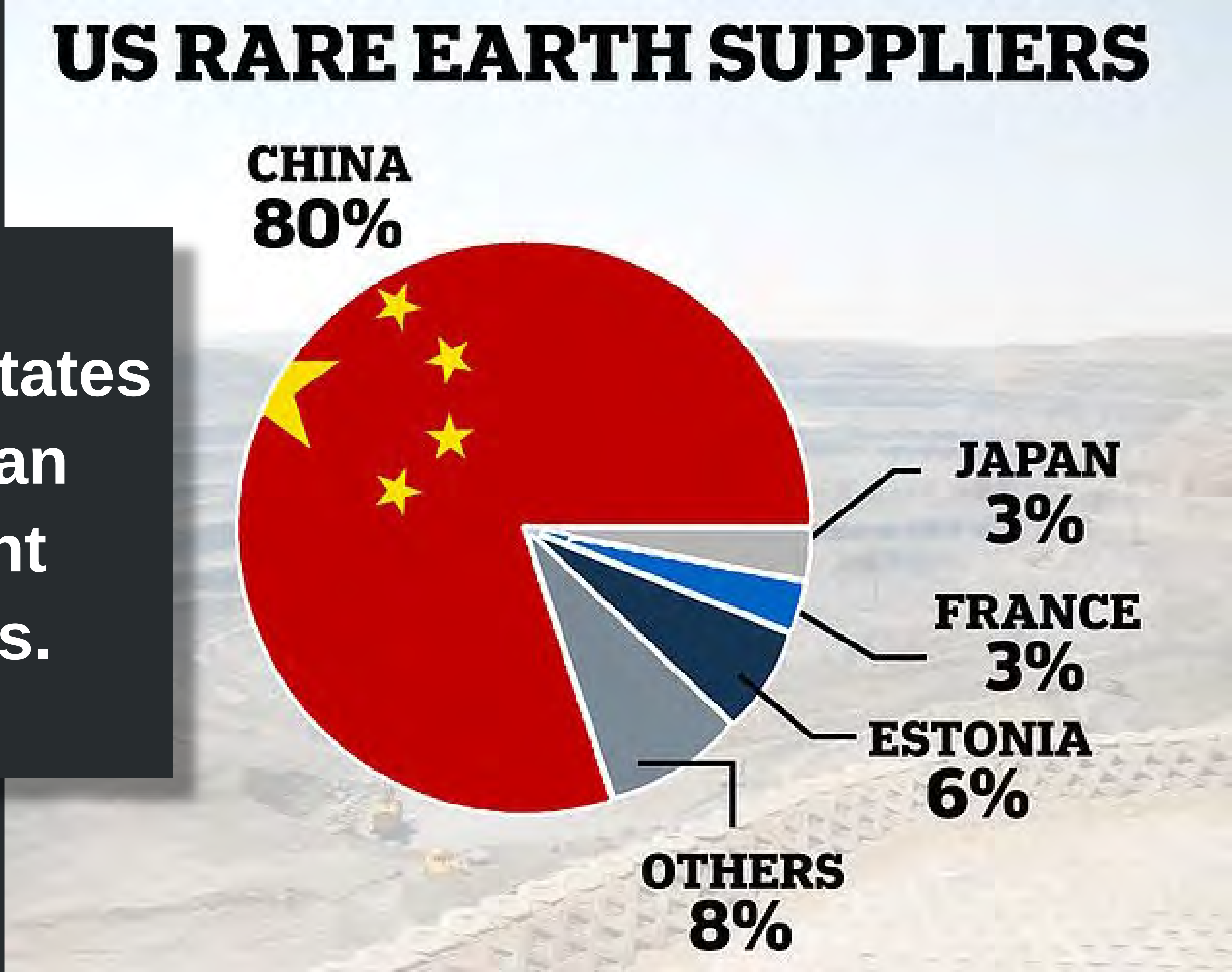
Rare-Earth Elements (REEs)

- Not rare but found together.
- Chemically similar and difficult to separate.
- Each has a different use.

Critical Minerals (CMs)

- Catch-all term for the critical minerals that are not REEs.
- No other common factor.

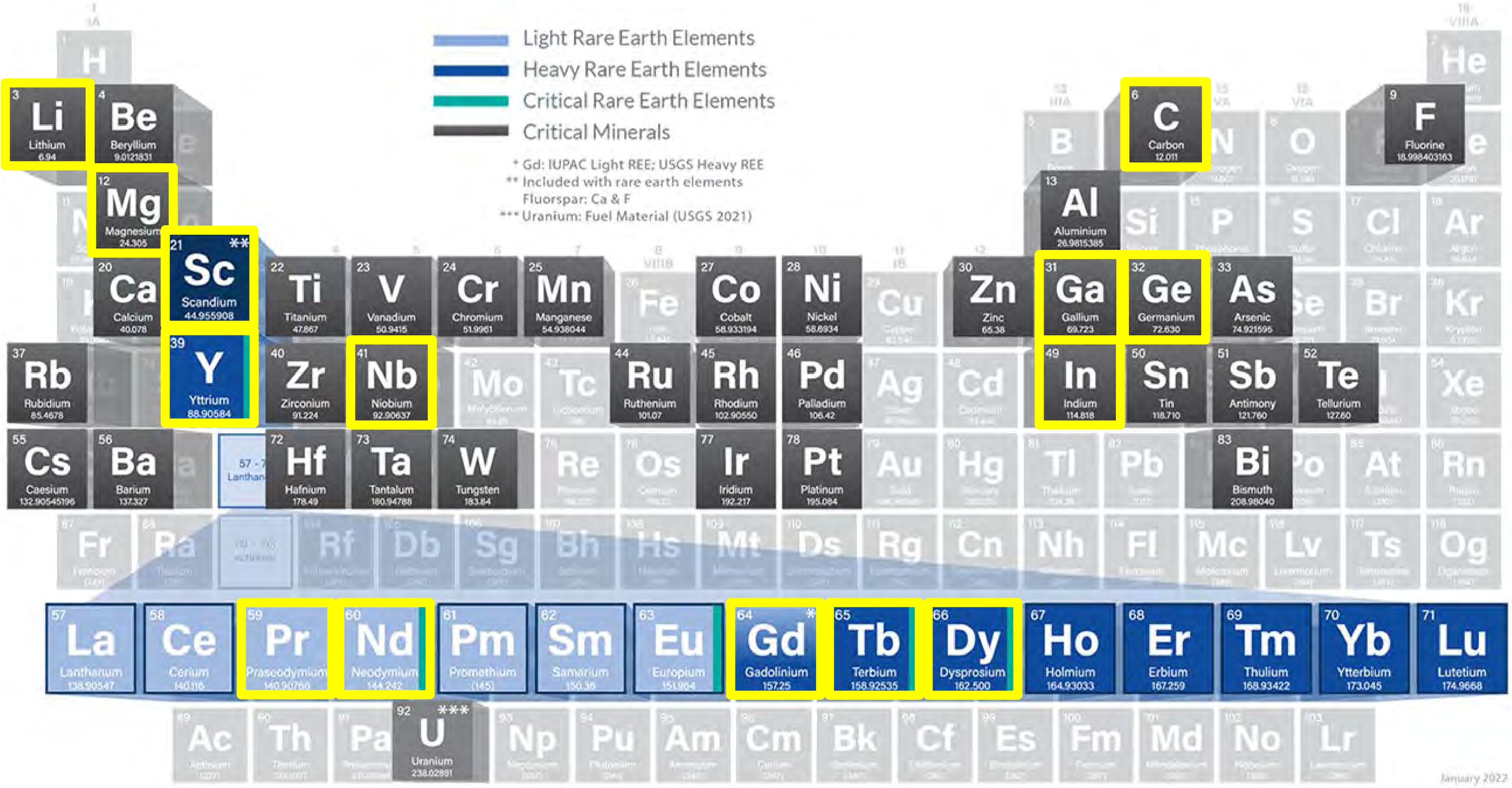
Critical Minerals Play a Vital Role in Our Modern Economy and National Security



The United States is more than 80% reliant on imports.

Williston Basin Business Region

Elements with Greatest Potential to Contribute to the Williston Basin Market

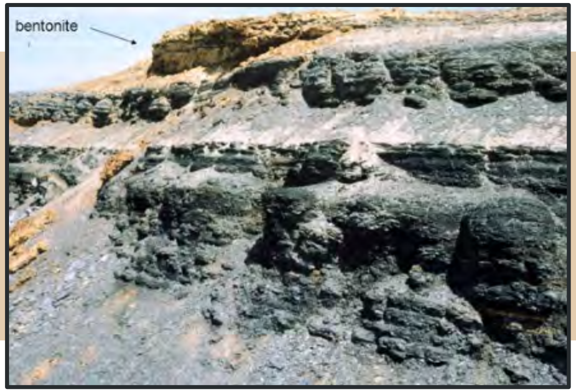


Developing New Sources and Innovative Ways to Extract CMs and REEs

Existing Lignite Coal Mines

Produced Water

ND Shales: Pierre, Niobrara, Upper and Lower Bakken



Deep Unminable Coal Seams by In Situ Extraction

Energy & Environmental Research Center (EERC)

Technologies for CM Extraction and Use

Nolan Theaker

Technical Group Manager, Critical Minerals

Institute for Energy Studies

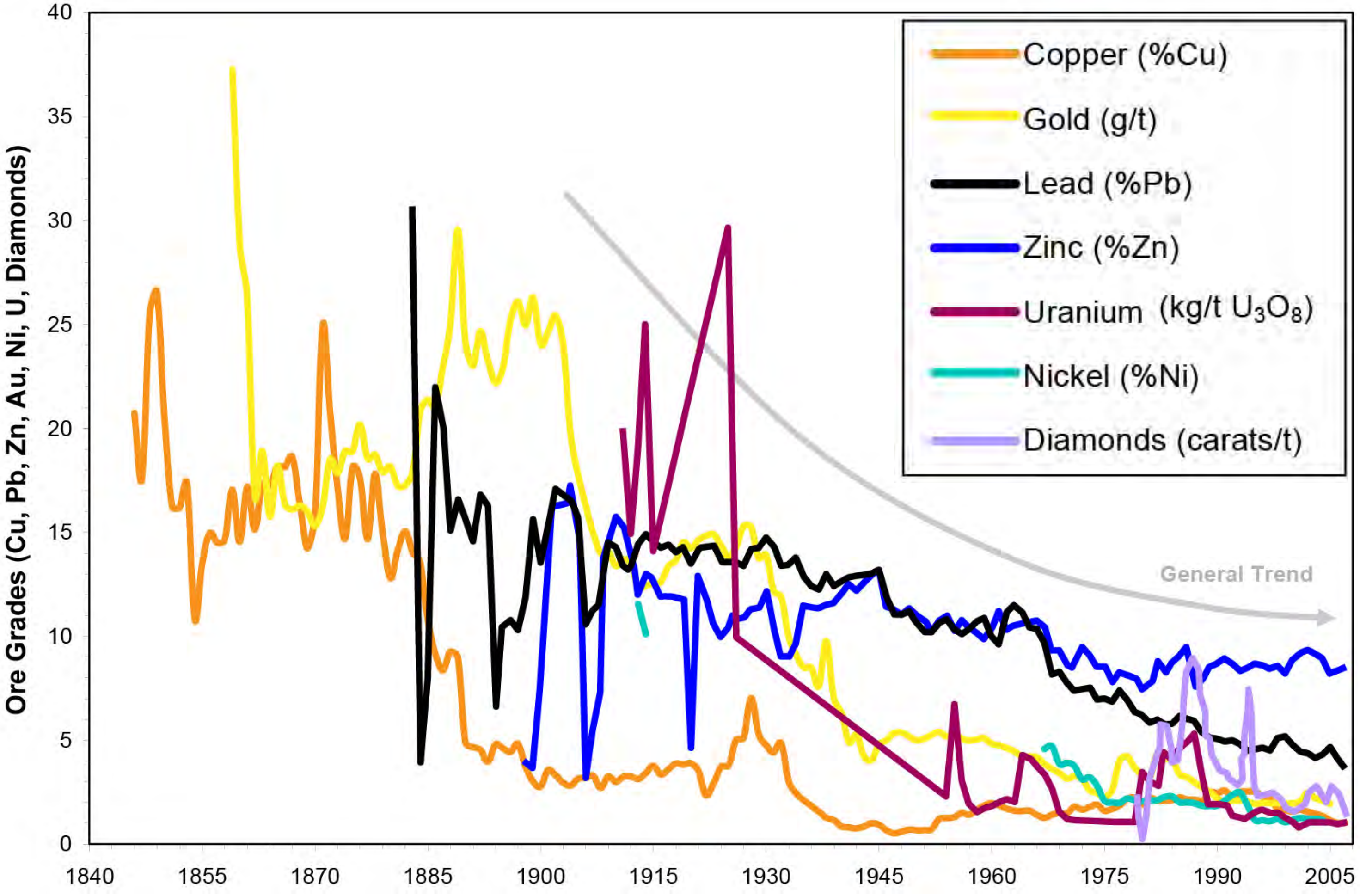
Questions to Answer

- Why do we need new technology?
- How can we extract CMs?
  - Coextraction
  - Metallurgy
- What technologies do we use in the supply chain?
  - Case study: REEs from lignite
- How do we move forward with CMs?

Why Do We Need New Technologies?

- Ore grade (how rich a source is) usually goes down.
  - *If processing cost linearly increased with grade, no mining would occur.*

- Production rates dictate a scalable process for mining and extraction.
  - Rates of CM use are increasing.



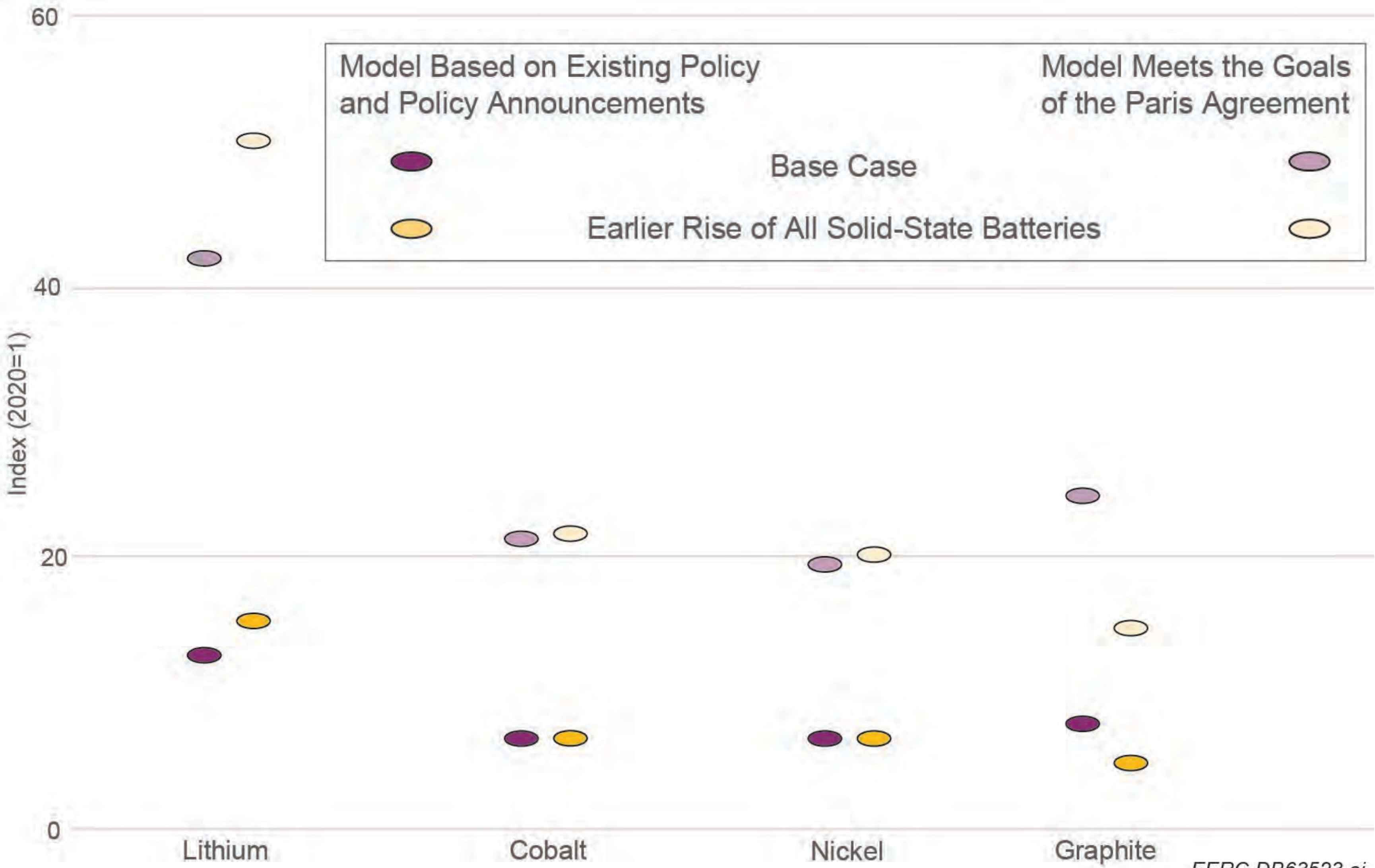
New Technologies for More Production

Production increasing

- Meet climate goals
- Meet computer and electrification needs

Production for some elements will need to increase by many times the current rate.

IEA 2040 Demand Scenarios



EERC DB63523.ai

New Technologies to Reduce Environmental Impact

- Making value from wastes:
  - Coal ash
  - Produced water
  - Acid mine drainage

- Use more benign processes:
  - Less chemicals = less spill risks.
  - Less toxic chemicals = less safety risk.

- Use more energy-conscience methods:
  - Lower power/fuel requirements

New Technologies to Use Unconventional Ore

Can access new ores previously unexplored:

- May have lower content but be in a more accessible form.
- Coproduct options and/or reducing environmental impacts of other resources.

May generate business benefits to using unconventional (reduced permitting).

Examples:

- REEs/CMs from coal – built-in by-product
- Lithium and magnesium from produced water – reducing an environmental burden and paying for it

Goals of Extraction Dictate Technologies to Employ

- Form of the ore matters:
  - Easier/harder to extract
  - More/less harmful impurities

- Also important: whether the CM is the **dominant economic interest:**
  - Most CMs are by-products from other processes.
  - Benefits from joint processing.

Image from Collins Dictionary

Image from Minerals.net

How Does Coproduction Make CMs Possible?

- Many CMs are too rare/dilute to recover individually.
  - On the order of a teaspoon per ton
- If the CM exists with another mineral you can extract, it reduces cost.
  - Done with copper, aluminum, and iron
    - World's largest producer of REEs comes from an iron mine: Bayan Obo

Image from Bruker

Case Study: Gallium (Ga)

- Used in solar cells, LEDs
  - Market isn't going down; more is needed.
- Average content of 18 parts per million
  - Very difficult to extract economically alone.
    - ♦ Teaspoon per ton – (actually ¾ teaspoon)
- Aluminum (Al) processing concentrates Ga
  - 10x more concentrated.
  - In a solution form due to dissolving Al.
  - Essentially all of Ga in the world comes as a by-product from aluminum processing.

Image from GeologyIn

Extractive Metallurgy

Mineral Processing
Physical processing of minerals

Pyrometallurgical
Use of temperature/pressure to separate minerals

Hydrometallurgical
Use of liquid solvents to extract and separate the CM of interest

Electrometallurgical
Use of electricity for separation and/or processing

Image from IOM3

Mineral Processing

Physical processing and handling of the constituent minerals

- Size classification
  - Crushing
  - Grinding
  - Screening
- Use of physical parameters for separation
  - Density
  - Ability to grind (hardness)
  - Wettability

RP-4 Shaker Table for Gold

Examples of Mineral Processing

- Gold panning: a form of crushing, screening, and density separation
- Pulverizing coal for combustion
- Mineral-concentrating spirals
- Not applicable to solution ores such as produced water or brines

Image from Shore Excursions Group

Coal pulverizers from Babcock and Wilcox

Hydrometallurgy

Image from Hydrometallurgy Section

Use of solvents, acids, and bases to separate CMs from other materials

Pros

- Liquids can be moved around easily.
- Many separation methods exist in liquids.

Cons

- Environmental effects of water use.
- Costly/hazardous chemical use.
- Essentially impossible to form metals.

Examples of Hydrometallurgy

- Nature uses hydrometallurgy to make minerals.
  - Calcite → Limestone
  - Pyrite formation
  - Capture of REE ions by lignite (theory)

- 70 elements made possible by hydrometallurgy.
  - Leaching of copper started in the 1200s.

Image from I-Optia

Pyrometallurgy

Use of thermal and pressure processes to separate materials.

- Using heat to chemically or physically alter a material.

Pros

- Little to no dependence on a chemical.
- Many possible sources of heat available.

Cons

- Not a robust separation method.
- Moving hot, molten metal is difficult.

Image from Gerri-Germany

Examples of Pyrometallurgy in CMs

- Iron/steelmaking – Mixing coke (carbon-rich coal) with iron ore to form pure iron metal.

- Germanium, gallium, and titanium all use a chlorine-based pyrometallurgy process for purification.
  - Mix ore with Cl_2 gas, heat, then boil the CM-chloride.

Image from: American Iron and Steel Institute

Electrometallurgy

Use of electrical potential to chemically alter and/or separate materials

- Very often is, but does not need to be direct electric use.

Pros

- Can and is used to metallize virtually all metals.
- Little to no environmental impact.

Cons

- Very susceptible to certain impurities.
- Can be very high electric demand.

Image from Goldgenie

Examples of Electrometallurgy in CMs

- Silver and gold plating on silverware
  - Electrodeposit precious metal on a metallic, conductive base (typically brass/copper)

- Act of making metals for over 30 elements
  - REEs included
  - Aqueous metallization for a select few
  - Molten salt metallization for most

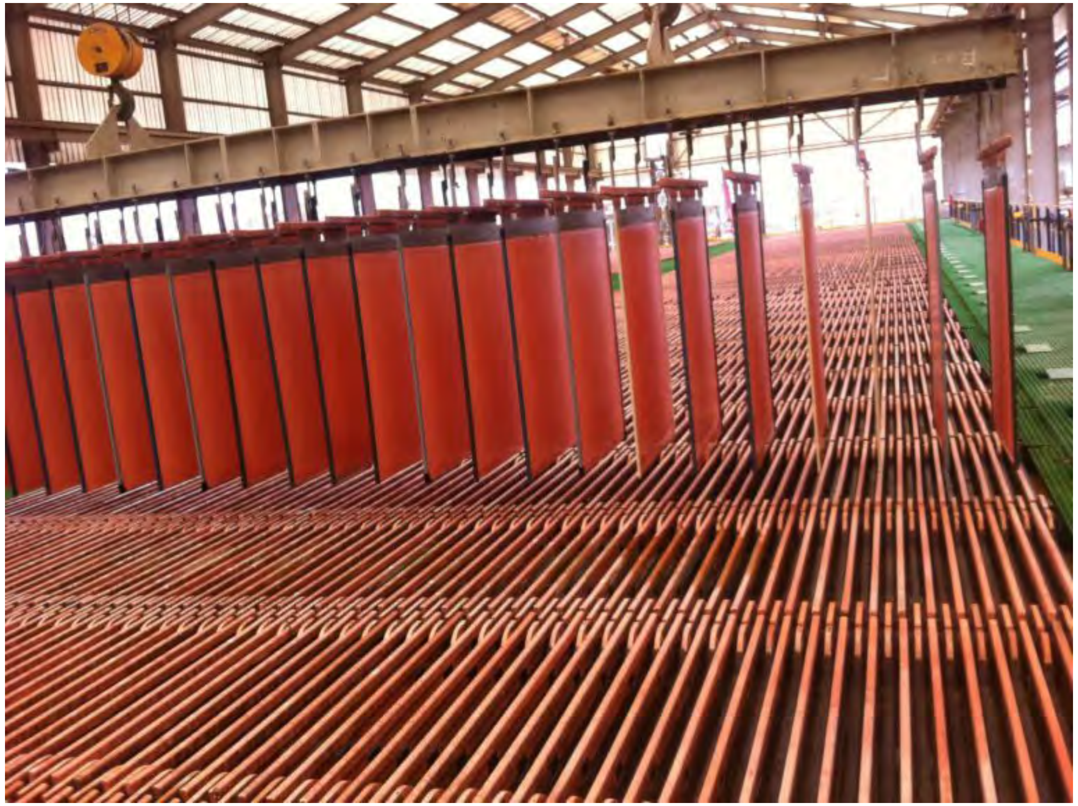


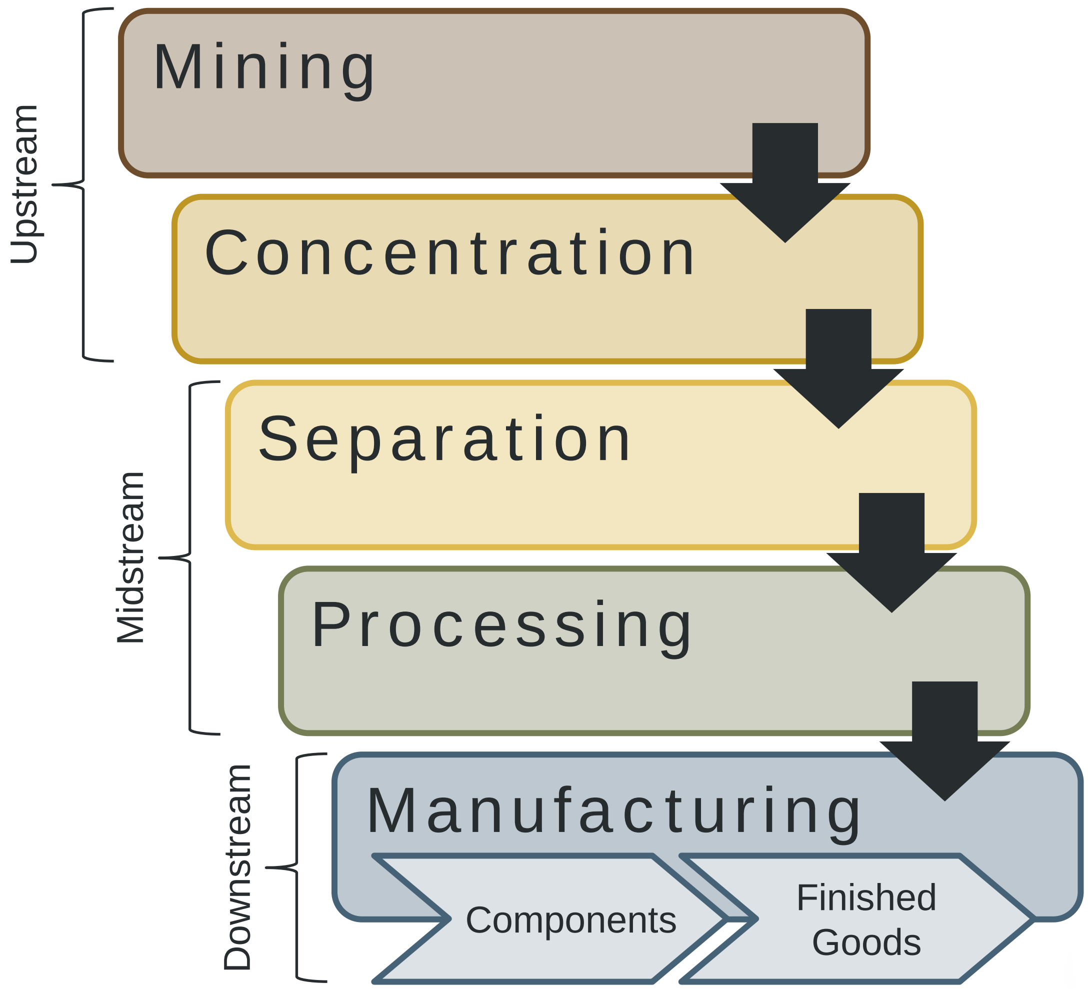
Image from UT Electrode

Definitions

Supply Chain

- *Merriam Webster* – “The chain of processes, businesses, etc., by which a commodity is produced and distributed.”
- *Investopedia* – “a network of companies and people that are involved in the production and delivery of a product or service.”

- For mineral processing, this doesn’t typically include distributors in the equation, more so the processes required.



Mining Technologies

Process of getting high-value ore to surface including:

- Exploration technologies
- Ore extraction technologies/methods
- Online/belt analysis/sorting technologies

Image Credit: Lignite Energy Council – Falkirk Mine

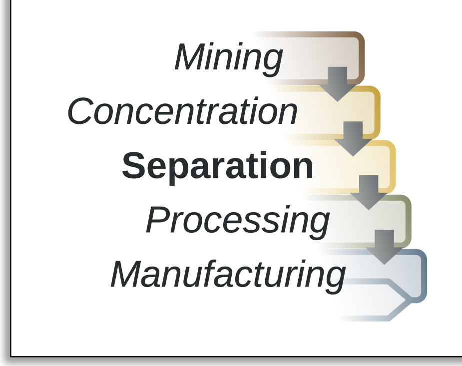
Image Credit: Energy Technologies Inc.

Mining
Concentration
Separation
Processing
Manufacturing

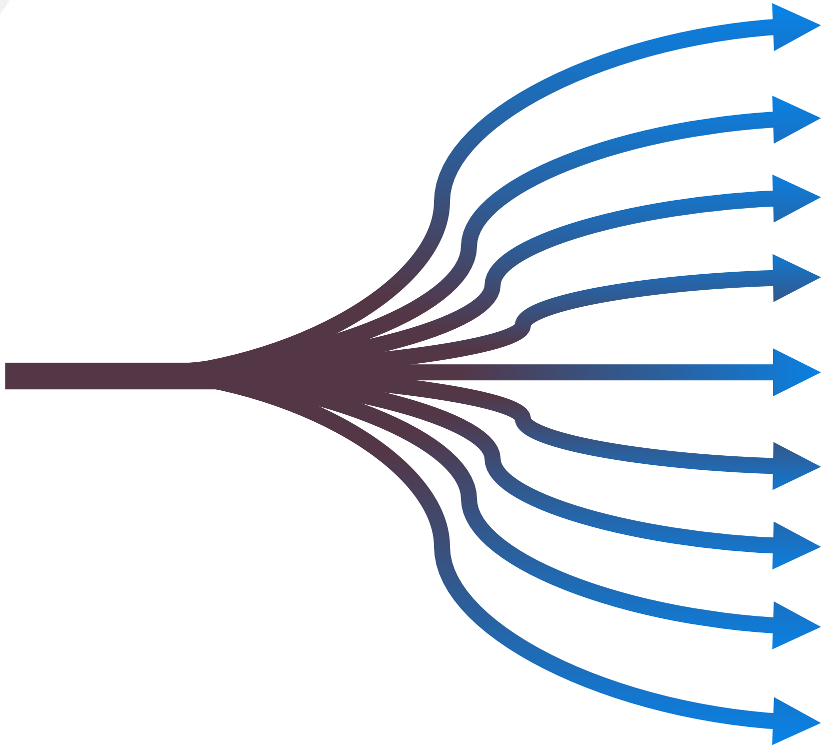
Ore Concentration

Image Credit: Mineral Technologies

- Making a valuable component in a dilute ore more pure
  – Product not purity or form of final product
  – <5% ore to >90% concentrate
  – Removing impurities that are challenging to refine
- Physical and chemical means of ore concentration
  – Commonly both methods combined for a single processing method
  – Process designed for the feedstock



Separation



- Separating: Generating a high-purity material (may not be in the right form):
  - Example: separating mixed REEs into individually pure forms
    - ♦ Many separation approaches exist.
- Ore feedstock only somewhat affects the processing technology.
  - Certain impurities not amenable with certain technologies.

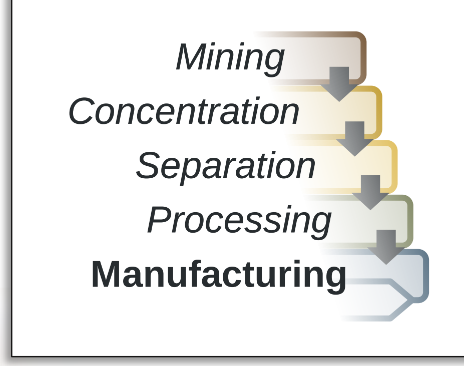
Processing

Mining
Concentration
Separation
Processing
Manufacturing

- Processing – Converting the high-purity material into a usable form:
  - Example: Making metals from oxides or salts, or carbon fibers from pitch
  - Typically, does not involve substantive purification.
- Typically, ore-feedstock-agnostic.
  - Purity set by downstream, met by upstream.

Image credit: Atlantic Copper/Mining Journal

Manufacturing



Making the products that we use and need

- Generally marketable products
  - Products that are salable in many industries/final products
  - Magnets and electrical components
  - Graphite, carbon fibers, etc.
- Process may become feedstock-conscious again:
  - Nontechnical but for business
  - Buy American, ESG

Image Credit: NETL – REE/CM Website

Case Study: REEs from Lignite (mines)

- REEs typically concentrated at the tops/bottoms of seams
  - Explore for REEs throughout the mine area
  - Remove during the current mining plan
  - Remove with surface miners for thin seams/layers

- Separate from the combined coal stream
  - Analyze and separate using on-belt sorting

Image Credit: Lignite Energy Council – Falkirk Mine

Case Study: REEs from Lignite

- Ore concentration – hydrometallurgy
  - Extracting the REE from an ore using an acid
    - ♦ Concentrated – conventional ores
      - Monazite in coals
    - ♦ Dilute – unconventional ores
      - Organic-bound in lignites
  - Precipitating REEs as a solid
    - ♦ Some form of REE-salt
- Calcining – pyrometallurgy
  - Converting the salt to an oxide

Image Credit: UND Institute for Energy Studies

Case Study: REE Separation

Two main paths:

- Hydrometallurgy
  - Solvent extraction with organics
  - Ion-exchange extraction
  - Impurities must be constant but can generally tolerate most.
- Electrometallurgy
  - Electrowinning of individual REEs
  - Impurities can vary, but some may be process-killing.

Image Credit: SoS Rare Metals

Case Study: REE Metallization and Alloying

Two main paths:

- Electrometallurgy – current global leader in producing
  - Major environmental controls needed
- Pyrometallurgy
  - Metallothermic reduction with another, more easily electrically formed metal
    - Separating the metals can be tricky.

Image Credit: Less Common Metals

How Do We Move Forward?

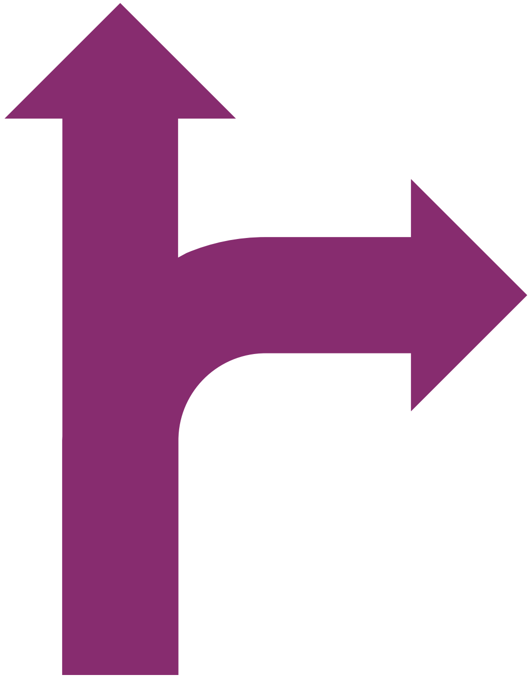
Evaluate technologies with:

- Ore and reserve in mind
  - Type, impurities, grade, size
  - Is coproduction possible?
- Current technology scale
  - Is this commercial and trusted?
  - Is this a decade away, but could make impacts?
- Market needs
  - Does this produce the products the market demands (now/future)?

How Do We Move Forward – Really?

Business questions – risk/benefit analysis

- Do we take a $1B risk on a new technology that could be better?
- Do I simplify my process to make one to two products instead of many?
  - Will those products always make me money? (REEs)
  - Which product is the primary?
  - Which product comes first?
  - Who is my buyer and what do they want?



Summary/Takeaways

Why do we need new technology?

- Ore grade and production rates

How can we extract CMs?

- Coextraction with a major
- Review of extractive metallurgy

What technologies do we use in the supply chain?

- Mining → Manufacturing techs
- Case study – REEs from lignite

How do we move forward with CMs?

- New techs and business challenges

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Carbon Ore, Rare Earth, and Critical Minerals Initiative (CORE-CM)

U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL)-Led Program

- Catalyze economic growth.
- Job creation in energy communities.
- Energy communities not to be left behind.
- Domestic production of REEs and CMs.
- Strengthen our national economy and security.

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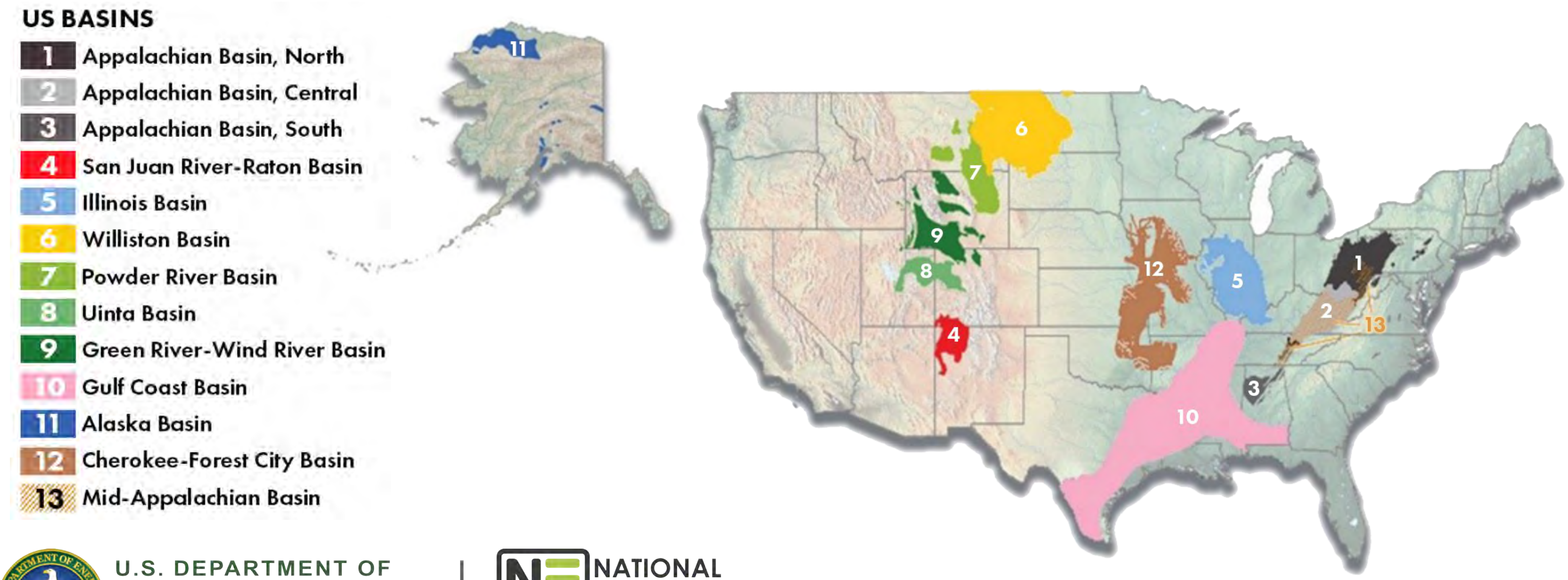
13 CORE-CM Initiative Teams



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Source: NETL

Williston Basin CORE-CM Project Team

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UND Institute for Energy Studies
UND Nistler College of Business & Public Administration
Pacific Northwest National Laboratory
North Dakota State University
Montana Tech University
Critical Materials Institute (Ames)
Basin Electric Cooperative
BNI Energy
Current Lighting Solutions
General Atomics
Illinois Geological Survey CORE-CM Team
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Western Dakota Energy Association
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