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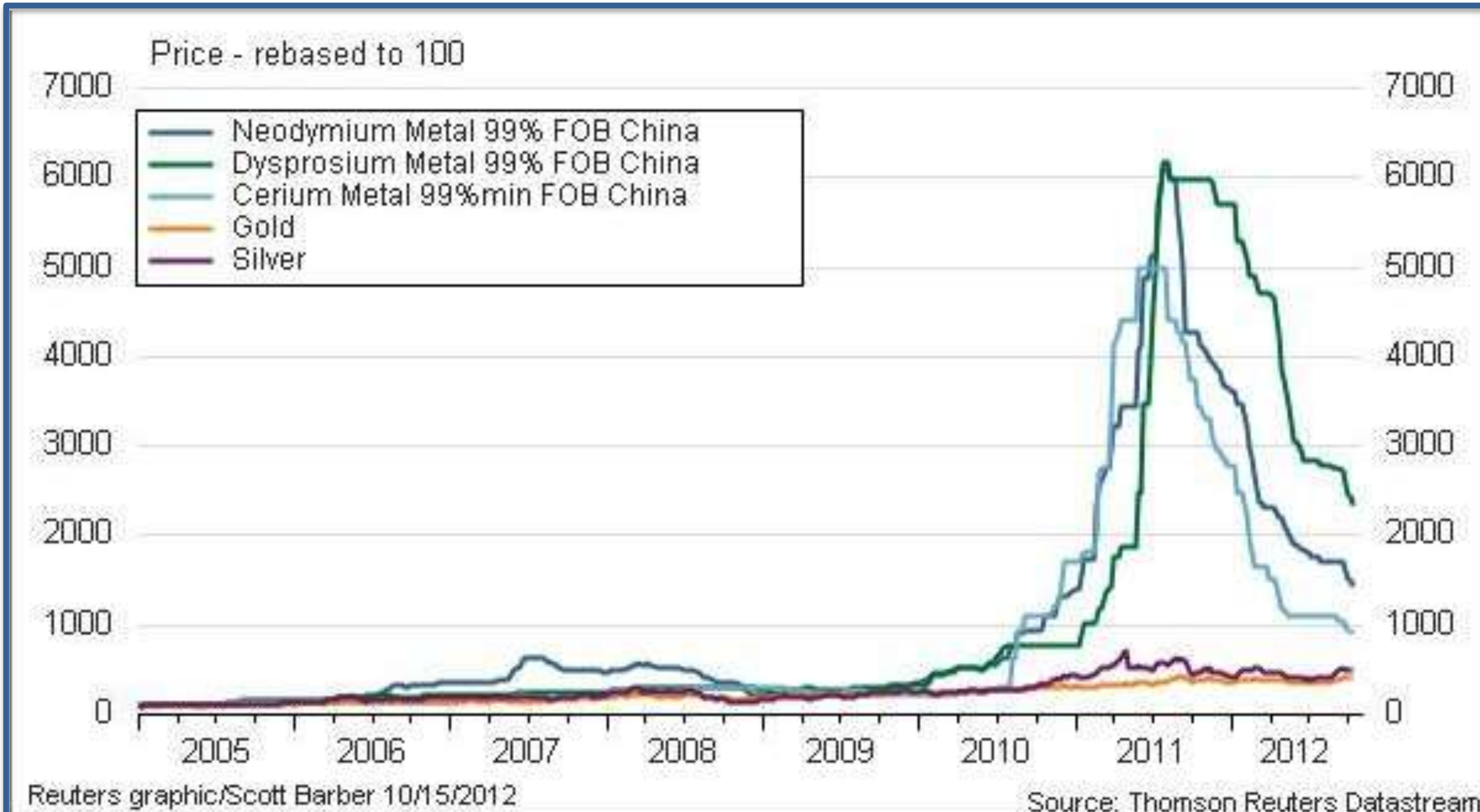
CMI | Accelerating Energy Innovations

U.S. DEPARTMENT OF ENERGY

Rare Earth Prices compared to Gold & Silver



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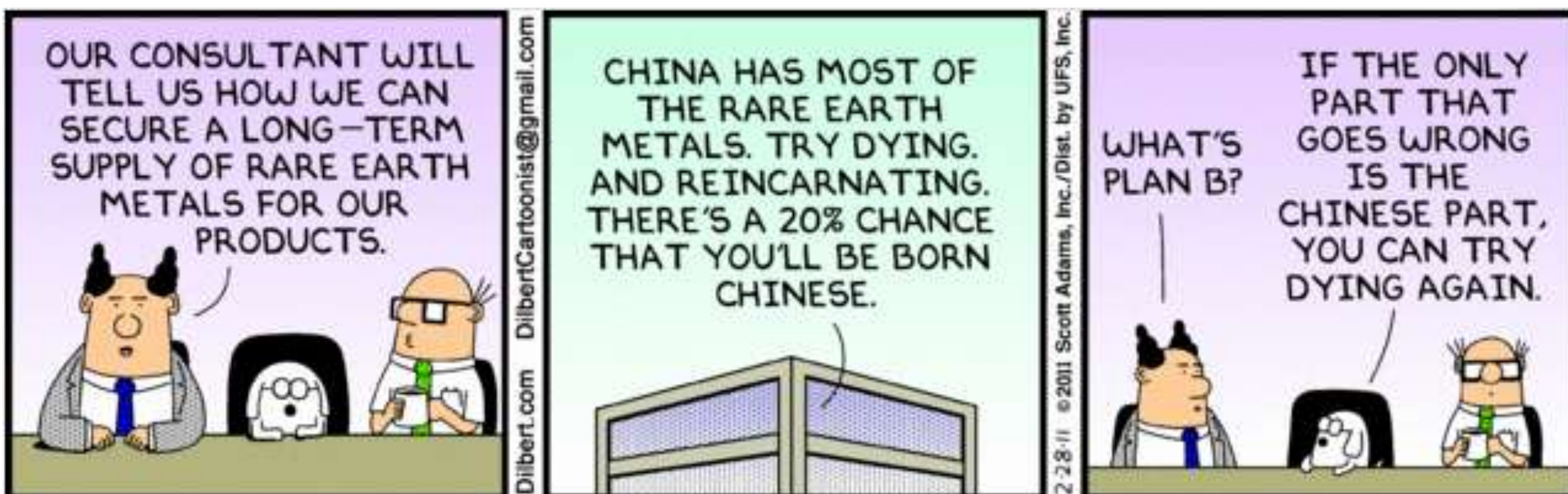
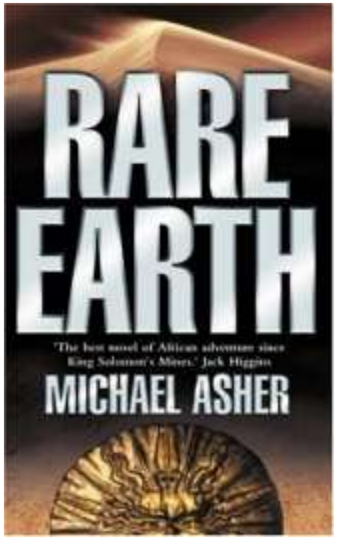
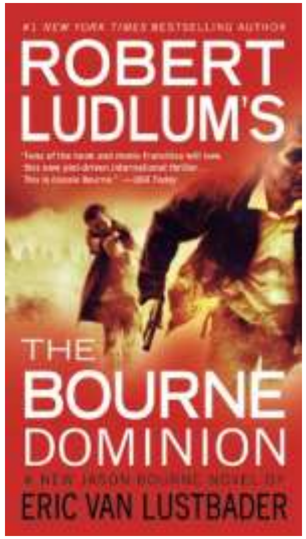
Cul de Sac, August 7, 2010

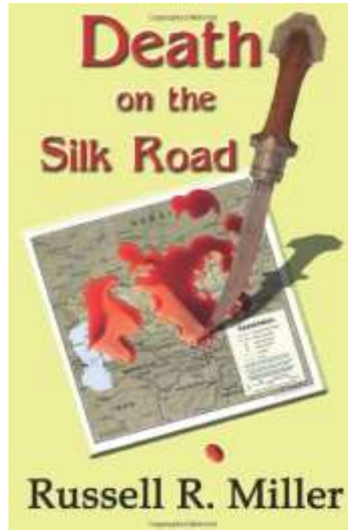


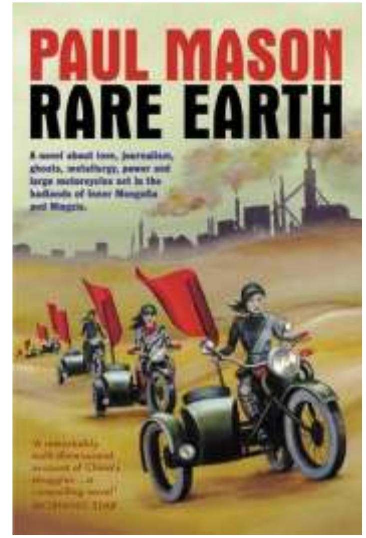
Dilbert, February 28, 2011

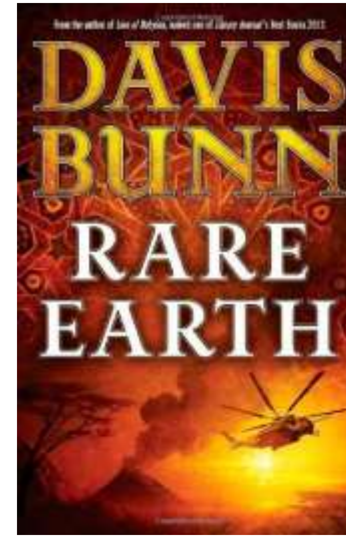
The hottest new literary sub-genre?

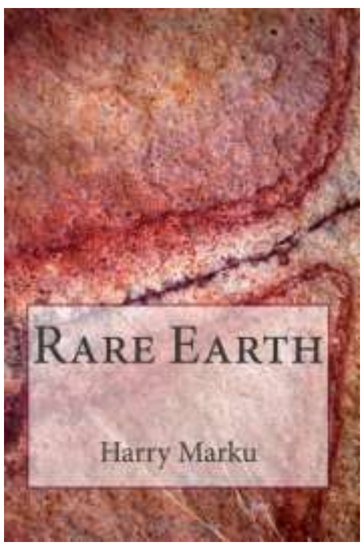


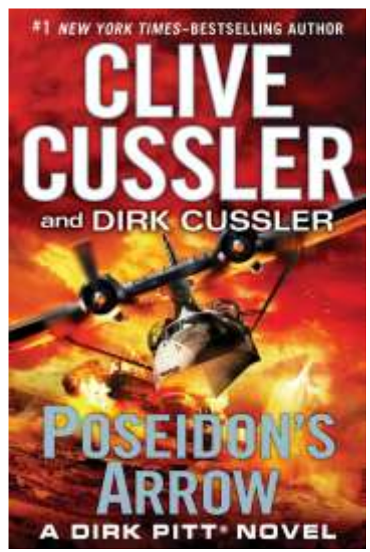


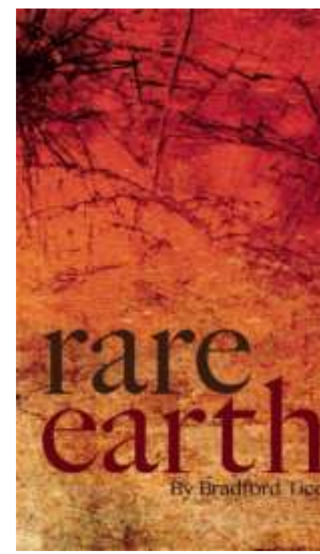




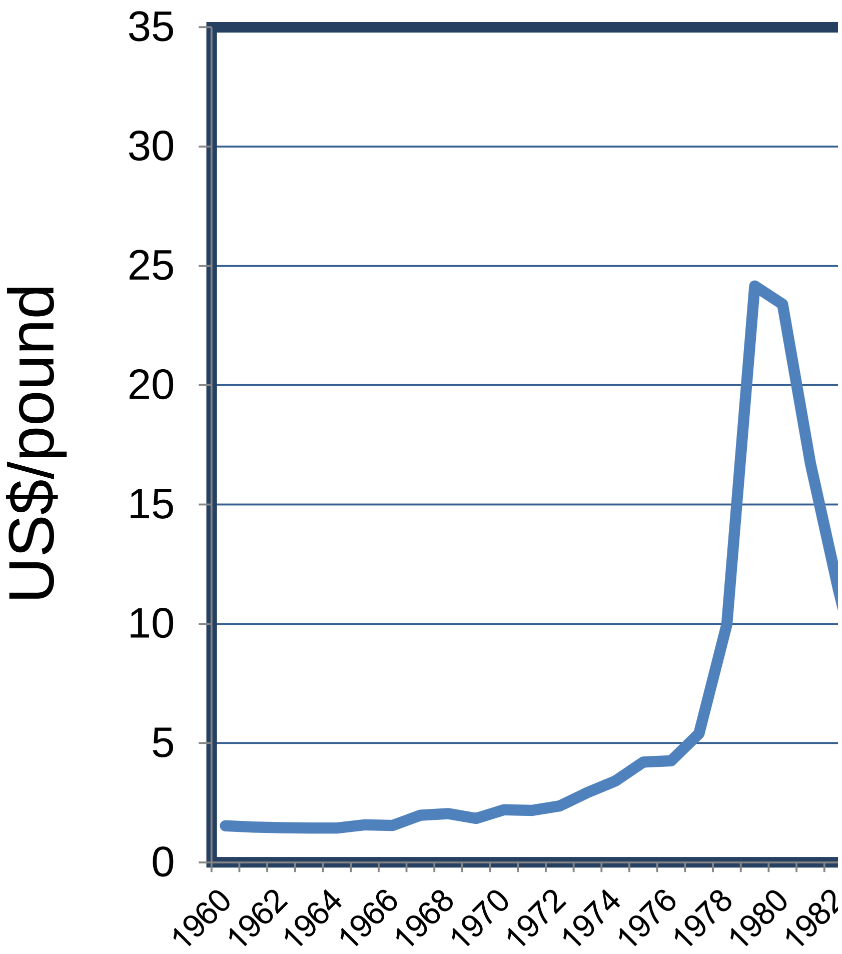








Annual Average Cobalt Prices



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Critical Materials are Not New

- "The stone age did not end because we ran out of stones" – Steven Chu.

- The copper age replaced the stone age because copper was better for some things.

- The bronze age replaced the copper age because bronze was better than copper.

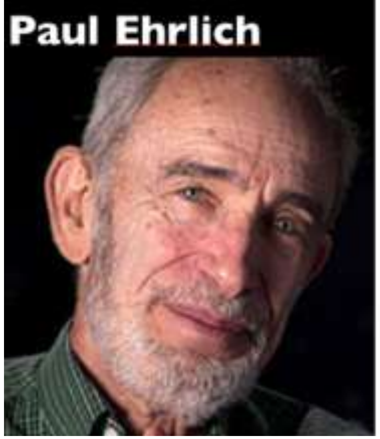
- But the bronze age was not replaced by the iron age. It ended because copper became unavailable.

The Bronze Age Collapse

~1200 BC

- Bronze becomes unavailable
  - Possibly because Cyprus is overtaken by war, making copper inaccessible.
- Responses include
  - Recycling
  - Source Diversification
  - Materials Substitution
- Results
  - Collapse of trade; collapse of civilization
  - Strengthening of Egypt, which found alternative sources in Africa
  - Eventual emergence of the iron age

The Ehrlich-Simon Bet
1980

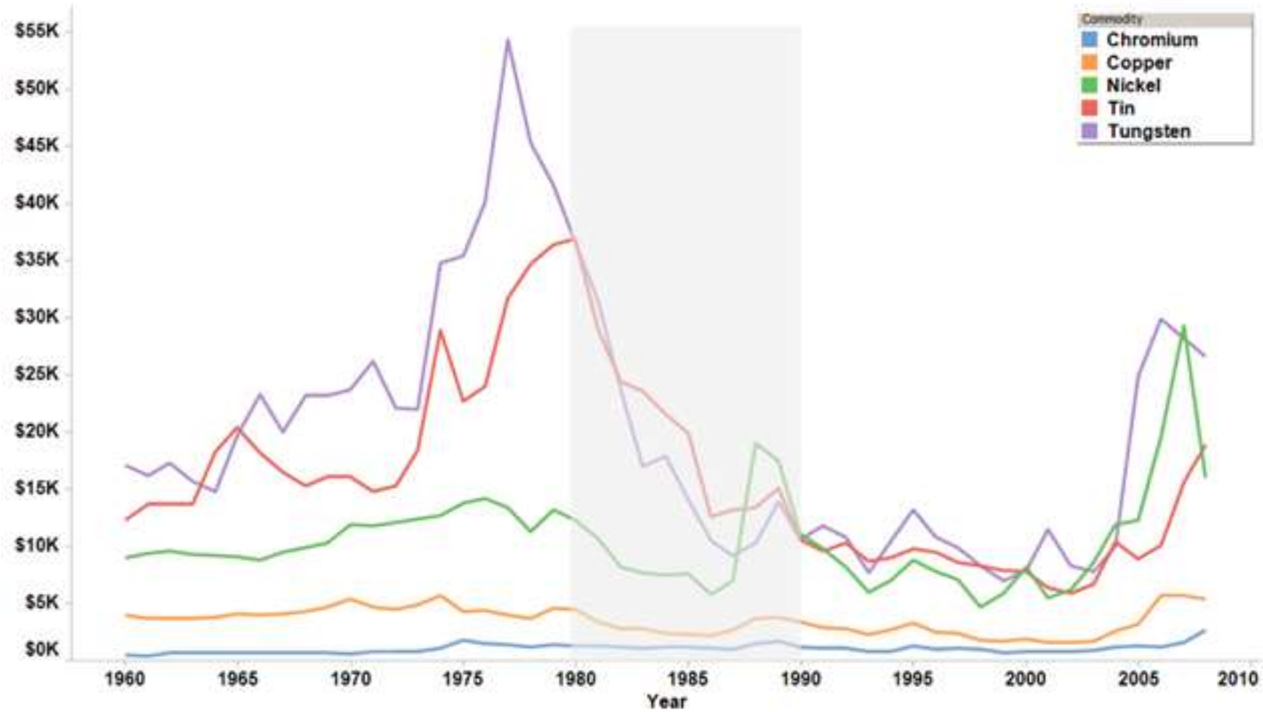


- Paul Ehrlich (prof. of Population Studies at Stanford University)
  - Metal prices will be higher in 10 years because of ever-increasing demand driven by relentless population growth.

- Julian Simon (prof. of Business Administration at the U. of Maryland)
  - Prices will be lower because technology will make the extraction of the metals cheaper, or we will find alternatives for those that are really running out.

Who won?

- Ehrlich and his colleagues selected a $1000 “market basket” comprising $200-worth of each of five different metals, at 1980 prices.



- In 1990, Ehrlich gave Simon a check for $576.07, representing the decline in value of the basket.

Long-term trends

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Is there a "hockey-stick" effect?

Source: McKinsey Global Institute

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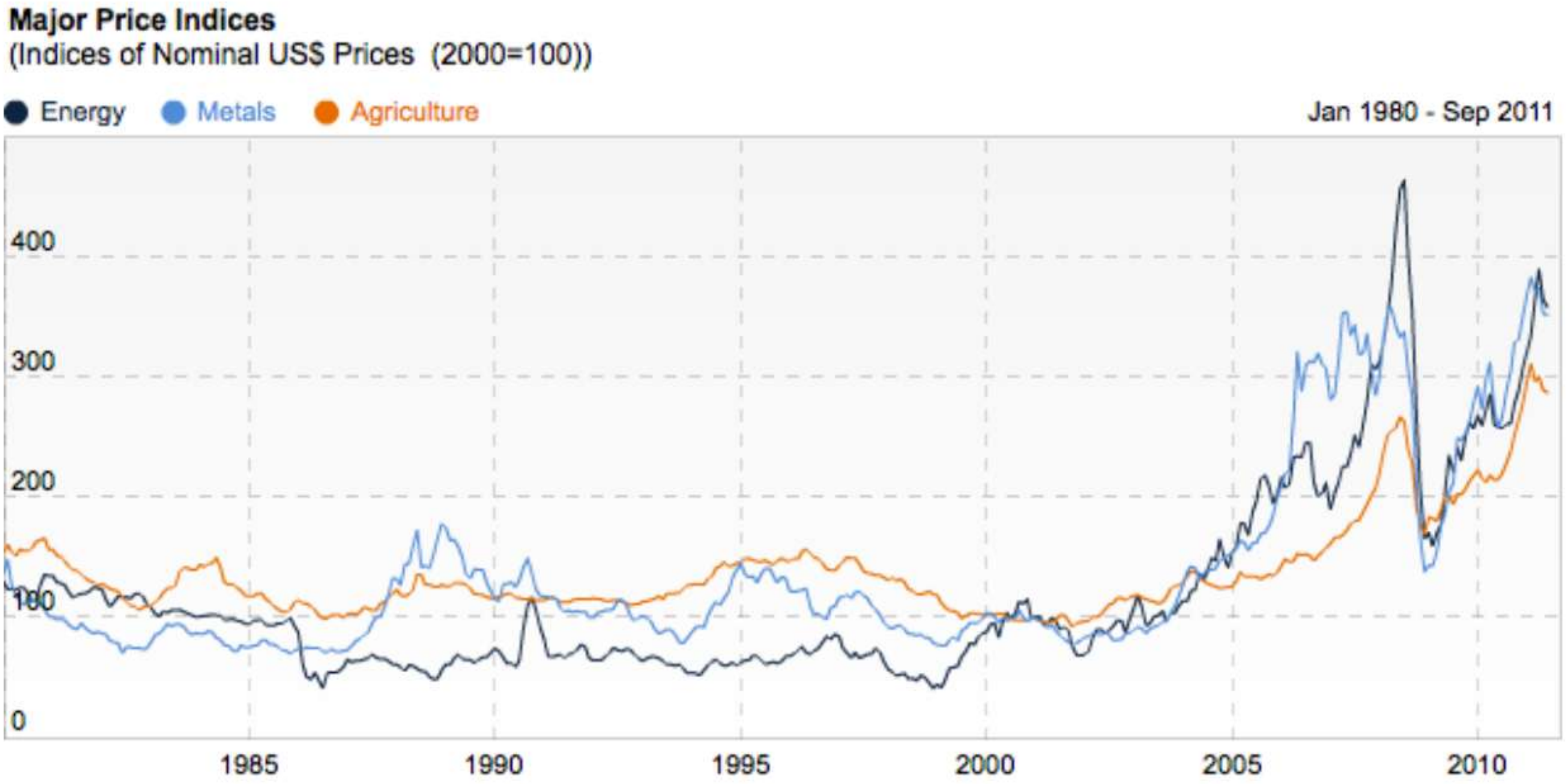
Is there a “hockey-stick” effect?



Source: World Bank

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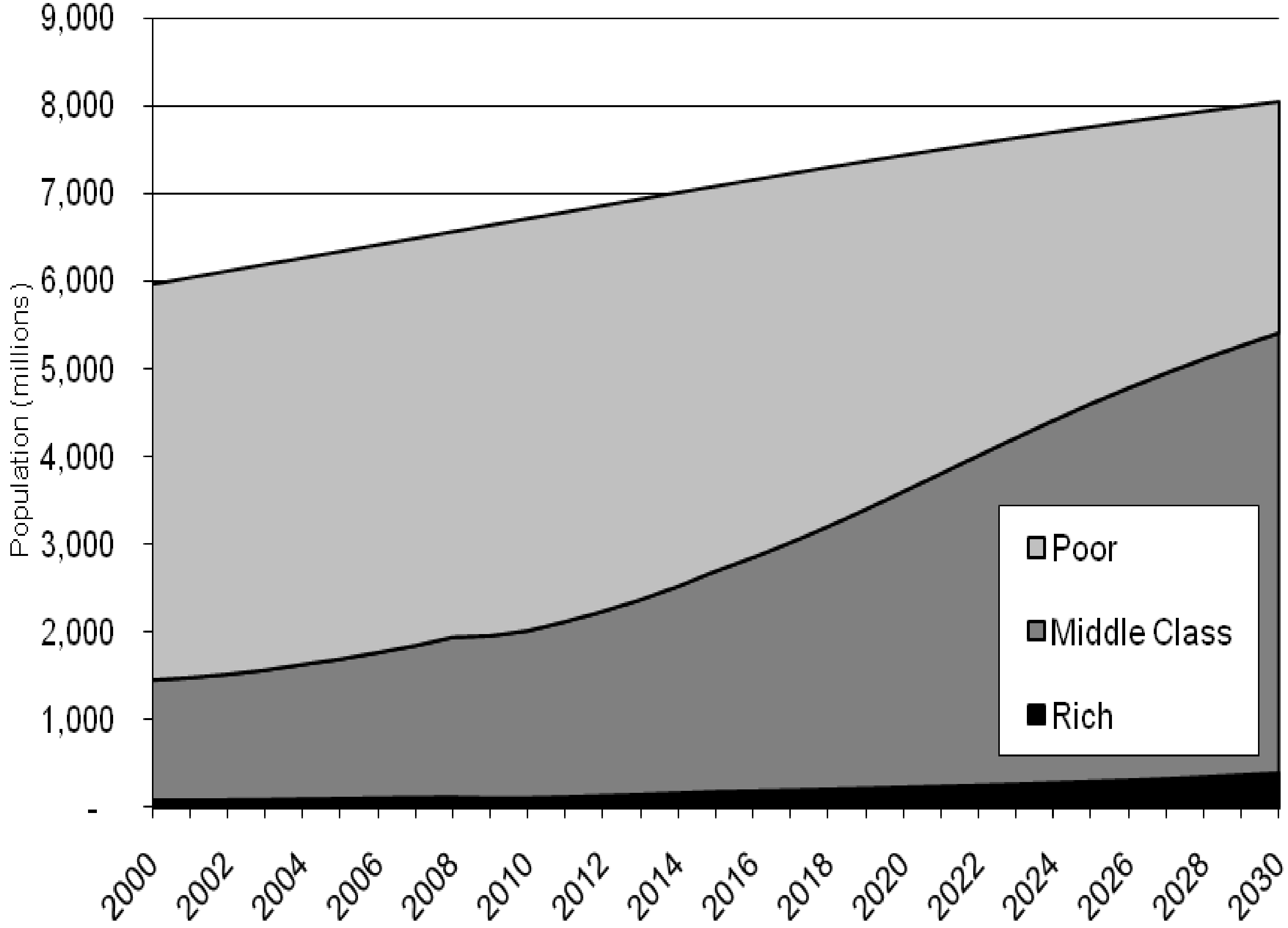
Middle class growth

OECD expects the world's middle class to grow -

from1.8 billion people, in 2012,

to 4.9 billion in 2030.



Source: Wolfensohn Center for Development, at Brookings

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Materials criticality is affecting us today

- The target date for transition to high-output T5 fluorescent lamps has been delayed by two years because manufacturers claim that there is a shortage of Eu and Tb for the phosphors.

- Utility-scale wind turbine installations are overwhelmingly gearbox-driven units, despite the high failure-rate of the gearboxes, because of the cost and unavailability of Nd and Dy required for direct-drive units.

Most solutions take effect "tomorrow"

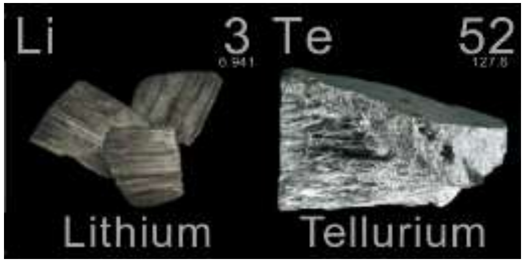
- Mine development, *where there is a known resource*, takes at least 10 years.

- Deployment of substitute materials, *when there is an existing option*, takes an average of 4 years.

- Development and deployment of *new* substitute materials takes an average of 18 years.

The Mission of CMI

Eliminate materials criticality as an impediment to the commercialization of clean energy technologies for today and tomorrow.



Four CMI Outcomes

Workers at Acciona Wind Power in West Branch, Iowa assemble a casing around the nacelle of a wind turbine. *Credit Clay Masters / IPR*

- Materials supply chains assured for clean energy manufacturing in the US
  - Current critical materials issues solved
  - Future criticality issues identified and averted
- Supplies of technical talent and expertise assured
- Critical materials information provided to researchers, producers & OEMs
- Federal critical materials research efforts coordinated for maximum impact

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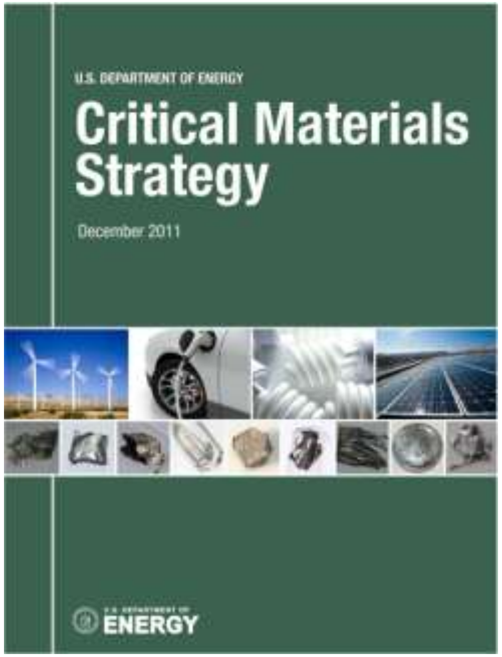
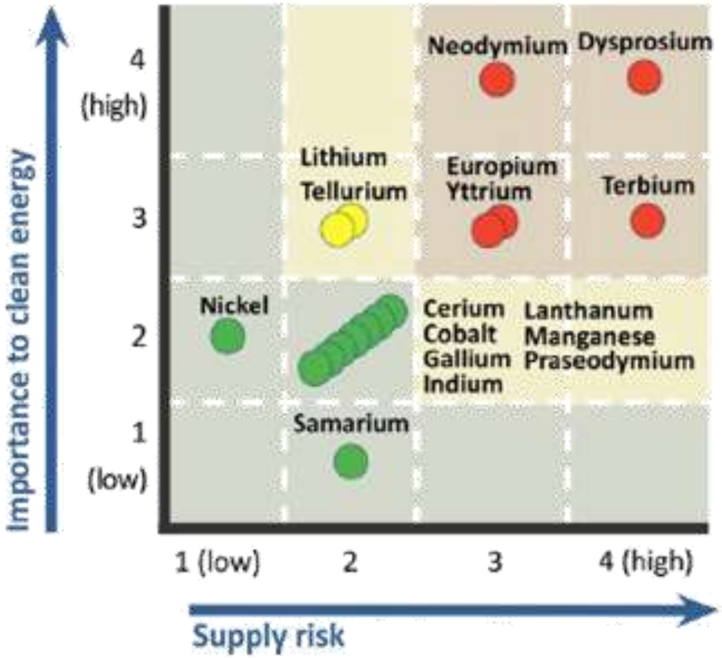
Three-D Approach

- Diversify supply
- Develop substitutes
- Drive reuse, recycling, and efficient use of materials in manufacturing



Essentially following DOE's Critical Materials Strategy, but applying it very selectively



Medium Term Outlooks: 2015 – 2025

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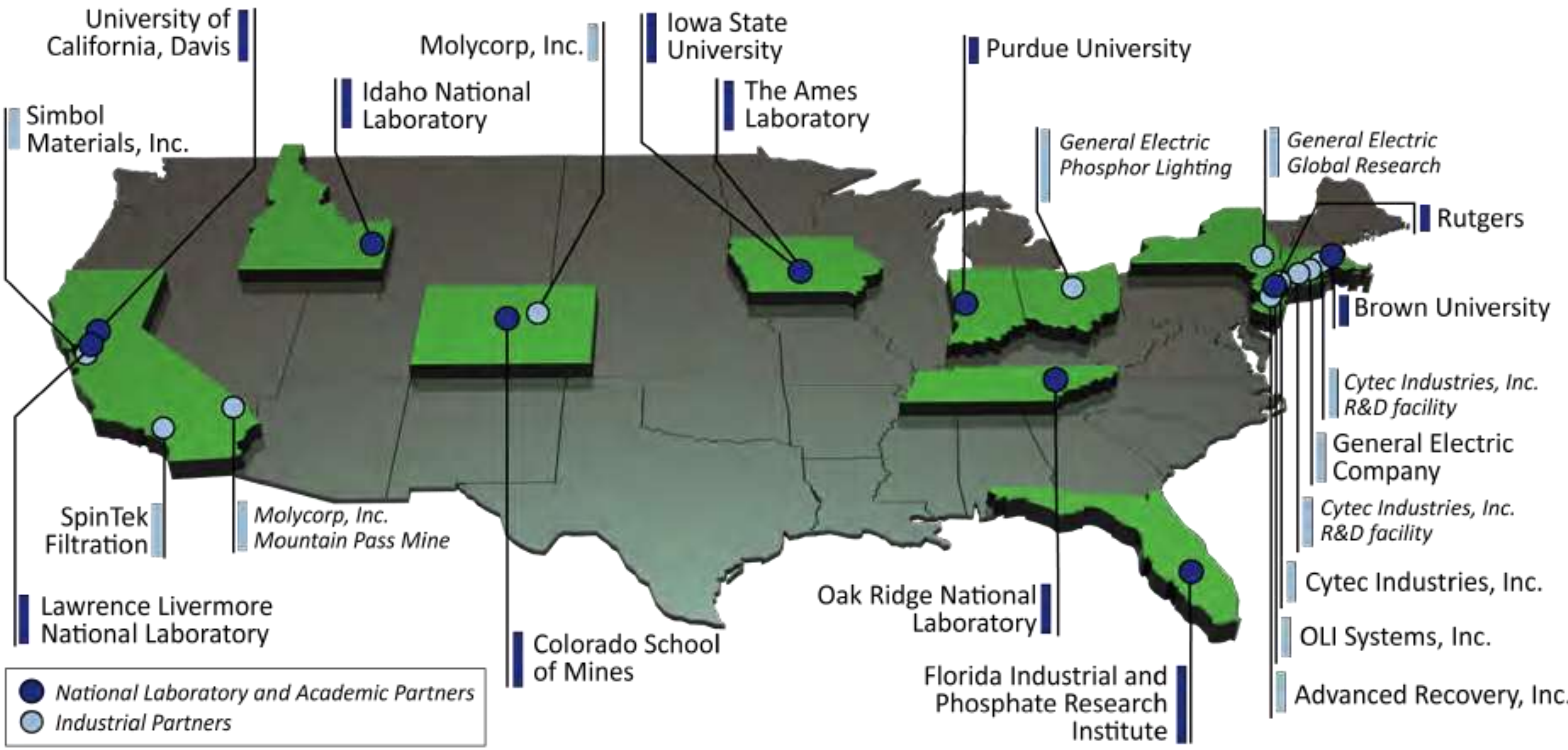
Two Guiding Principles

- Produce more

- Use less

- We have to address the entire materials lifecycle, going from birth through death, and beyond, to include resurrection.

One Integrated Team

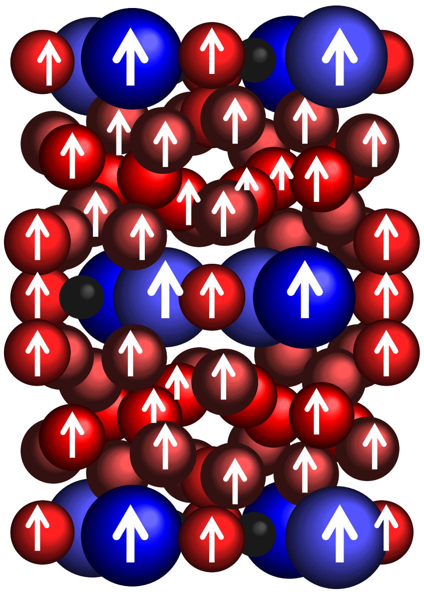


CMI Project Selection and Design

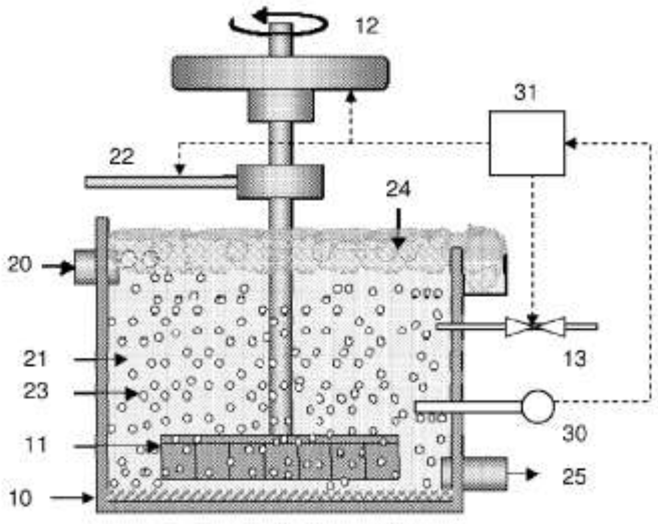
- CMI addresses 7 critical or near-critical chemical elements.
- 35 initial projects, selected for several criteria
  - Potential for impact at a key point in the materials lifecycle, in a realistic timeframe.
  - Integration of strengths and capabilities across the Hub. (No project is carried out by a single partner institution.)
  - Clear path to deployment. Commercialization plan in place on day one.
  - Annual evaluation addresses continued adherence to the timeline and each of the above criteria.
- As the world changes, we expect to terminate projects and start new ones.

Neodymium

- Used for high-performance magnets
- Traditional uses:
  - Hard disk drive spindle motors
  - Portable electronics - loudspeakers & microphones
  - Small motors in vehicles
- Emerging uses:
  - Traction motors in electric vehicles
  - Wind turbine generators



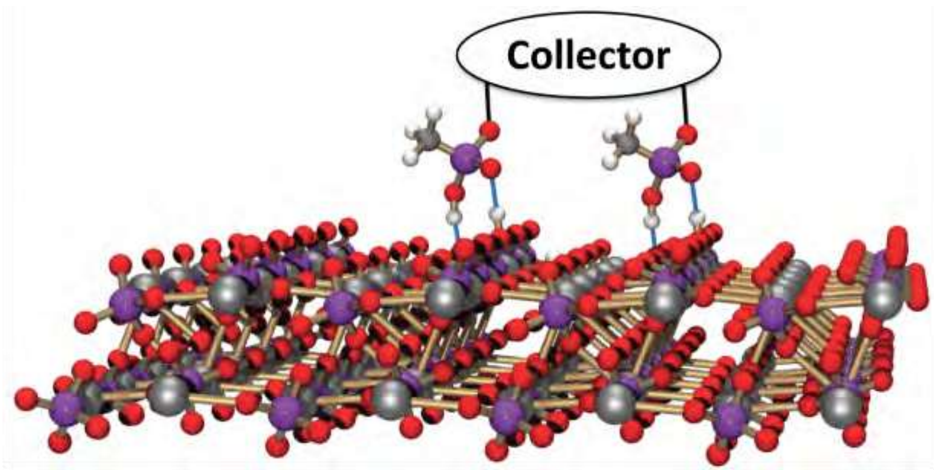
Classical Froth Flotation

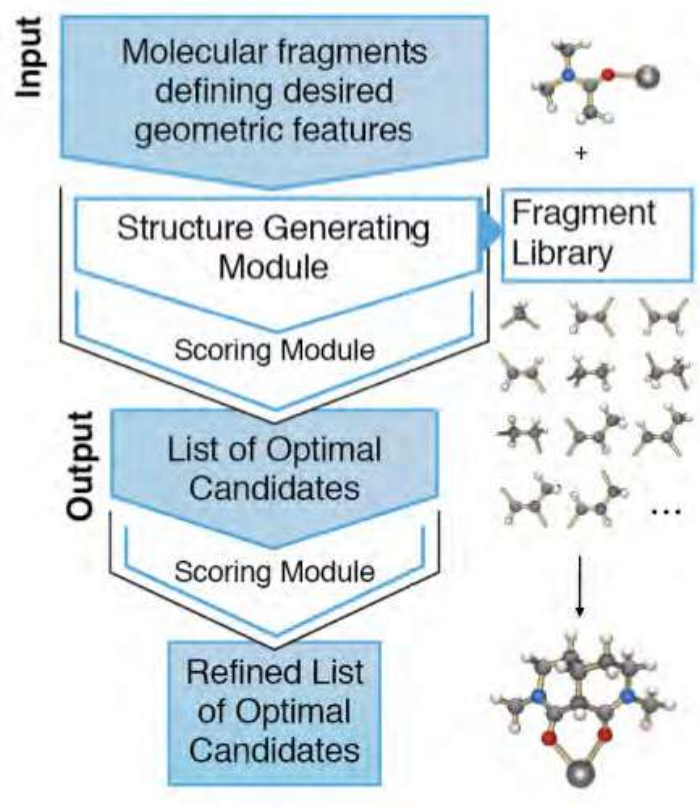


- Separates valuable ore from the associated gangue.
- Concentrates bastnaesite, but not monazite.
- Monazite contains more of the higher-value heavy rare earths, but currently goes to the tailings heap.

Quantum Froth Flotation

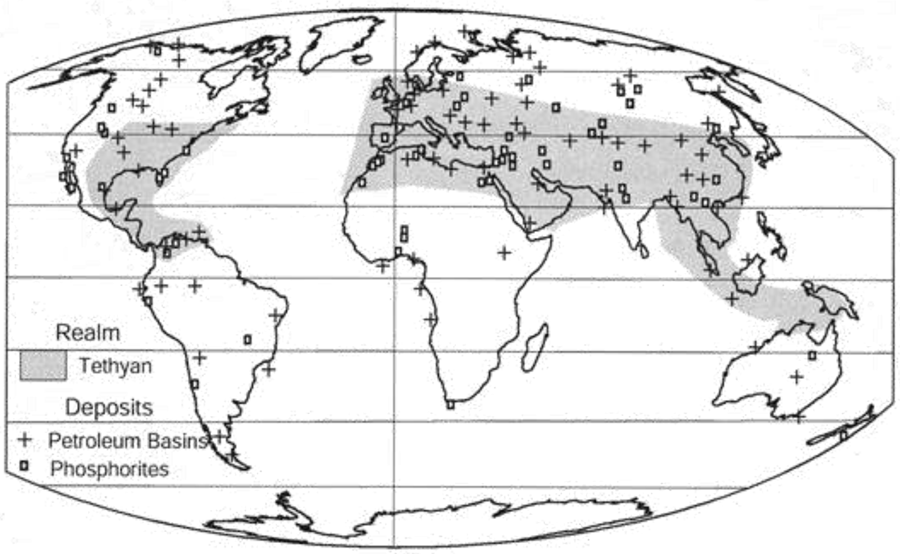
- Solution: find collector molecules that bind monazite to air bubbles.
- Quantum chemistry computations at Ames and Oak Ridge.
- Pilot-scale testing at Idaho.
- US-based chemical manufacturers.
- Deployment to US mines.





REEs in the Phosphate Deposits of the Tethys

- Average of 300 ppm REE
- Contains 2.7×10^{7} tons of REE resources
- Represents ~200 years of current world demand



Source: USGS

Phosphate Production

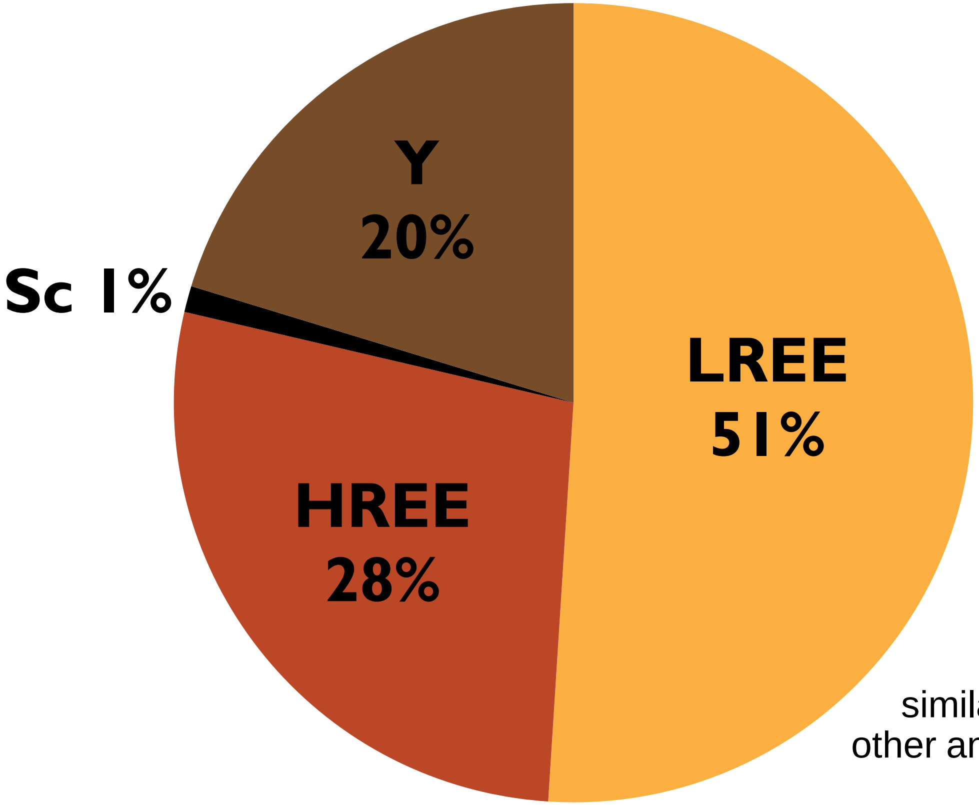
- About 220 million tonnes of phosphate rock is processed annually, worldwide, (USGS, 2013)
  - China – 89 million MT
  - United States – 29 million MT
  - Morocco and Western Sahara – 28 million MT
  - Russia – 11 million MT

- Primary use is for agricultural fertilizers
- The large-scale processes are attractive for recovery of other valuable materials
  - mining and significant portion of processing infrastructure exist, and costs are borne by current economical processes
- Uranium concentration in phosphate rock ranges from 50 to 200 ppm, averaging greater than 100 ppm
- Rare earths constitute 0.01 to 0.1% of the apatite, averaging 0.05% REO

REE in Florida Phosphate – recent data

2011 FIPR Characterization Study

REE Distribution in sand flotation tailings



similar distribution in
other analyzed streams

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How to win the co-products?

Phosphates offer several options for extracting critical materials

Sand tailings (~10% of REE)

Waste clay (~40% of REE)

Phosphate ore

Sulfuric acid → Dissolution

$Ca_{10}F_2(PO_4)_6 + 10H_2SO_4 + 10nH_2O \rightarrow 10CaSO_4 \cdot nH_2O + 6H_3PO_4 + 2HF$

Di-hydrate process, n = 2; Hemi-hydrate process, n = 1/2; Anhydrite, n = 0

Filtration → **Phosphogypsum** (~38% of REE)

Wet-Process Phosphoric Acid (~12% of REE)

Extraction → **U / Th** co-product

Evaporation → **Fertilizer** Production

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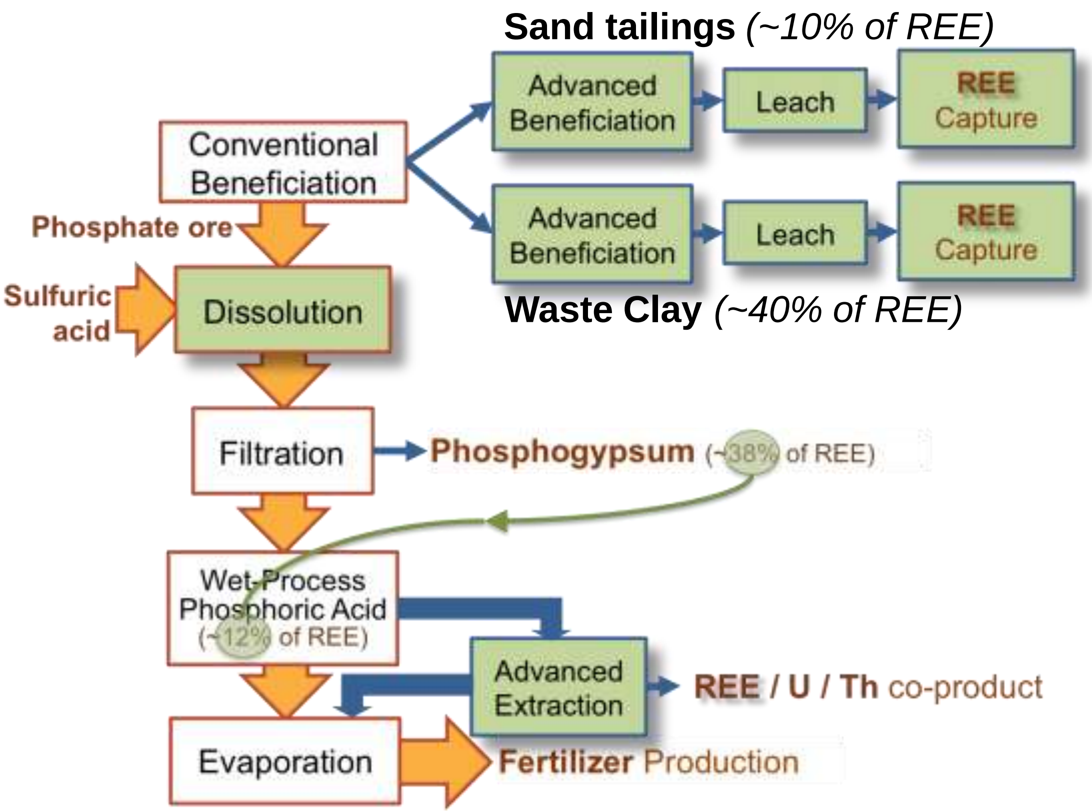
Addressing the barriers to economic production of REE from phosphate



Improving Recovery

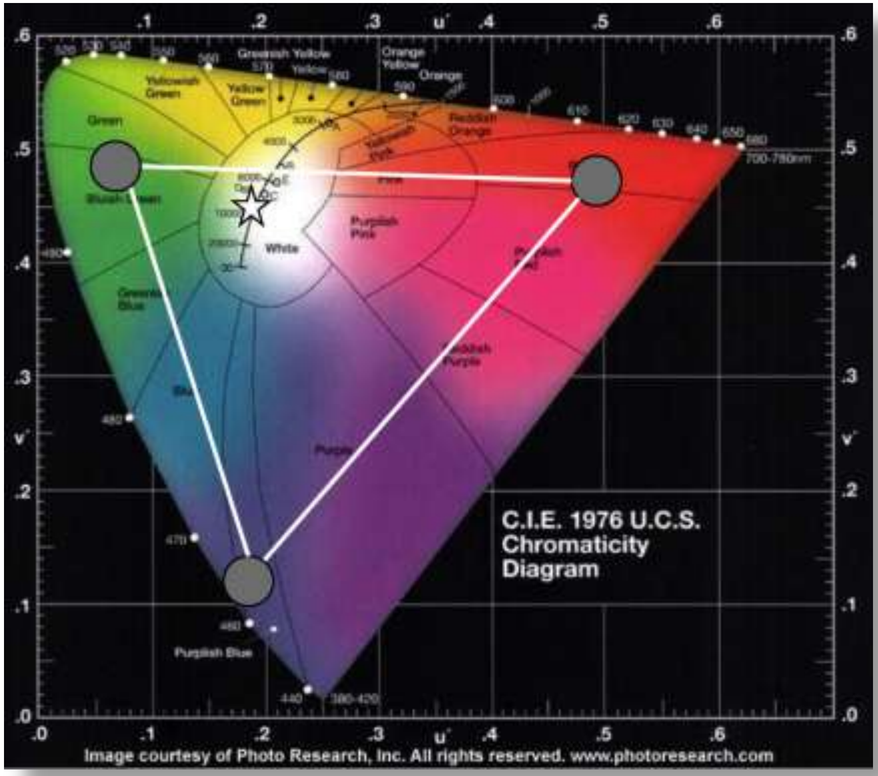
- Concentrate REE-containing material from flotation tailings by gravity separation, followed by acid leaching
- Concentrate REE in waste clay by removing clay minerals, followed by acid leaching
- Modify dihydrate dissolution process to increase REE fraction in the acid phase

Enhancing Extraction

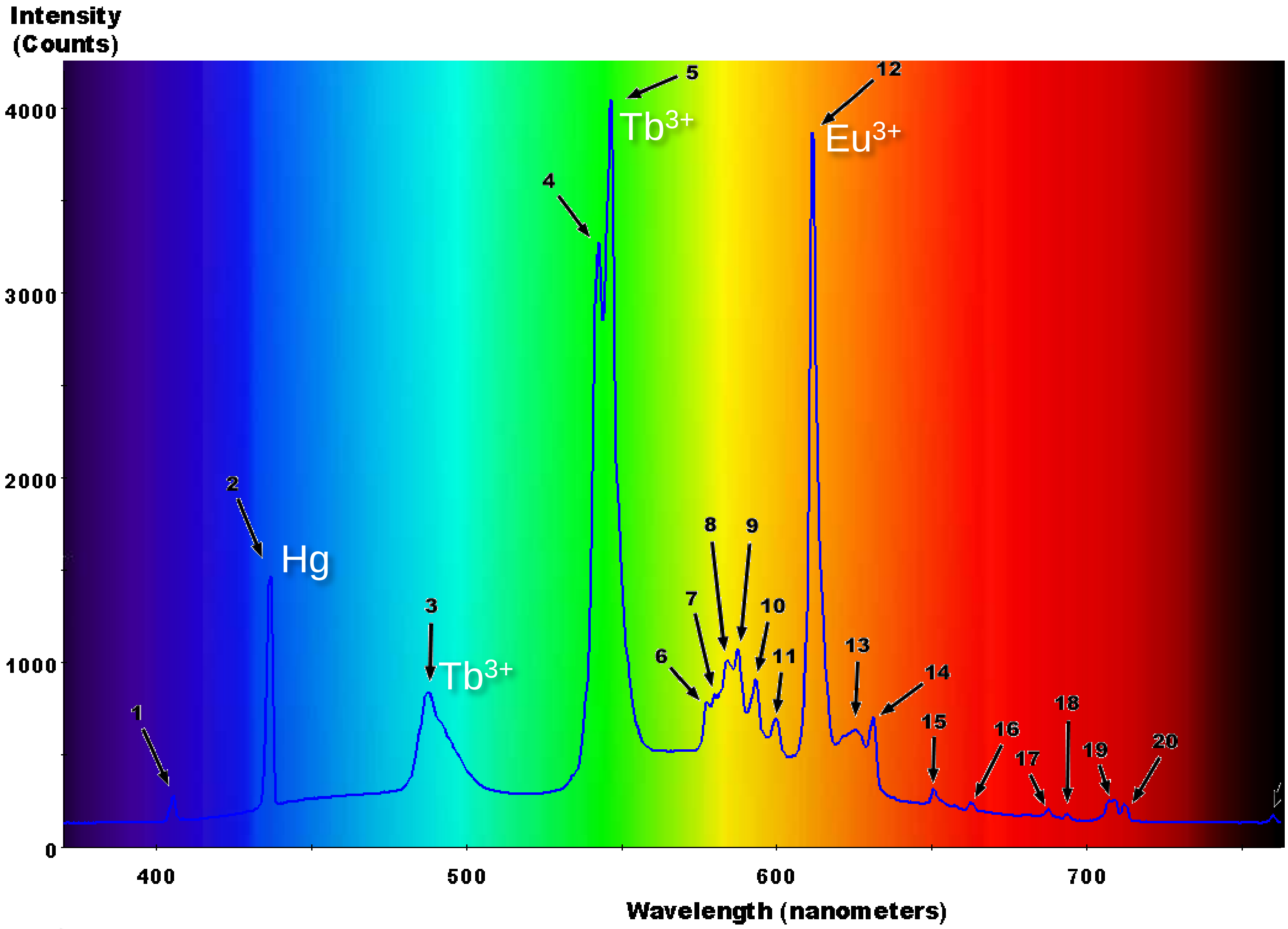
- Employ synergistic systems to enhance REE extraction at high acid concentrations
- Investigate capabilities of advanced sorbents and lanthanide-selective extractants identified through molecular design

Terbium & Europium

- Provide green and red light emission
- Traditional uses:
  - CRTs
  - Long-tube fluorescent lamps
  - Flat panel color displays and TVs
- Current uses:
  - Compact fluorescent lamps
  - Personal electronics
- Future uses:
  - LED lighting
  - OLED displays



Phosphor design



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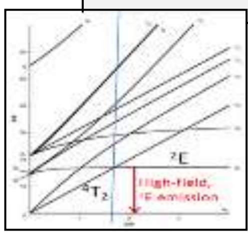
Substitution efforts address four key areas

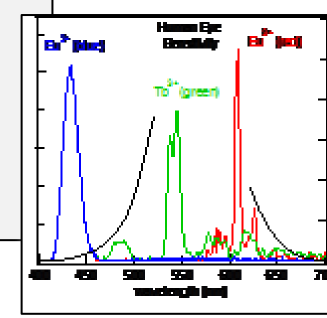
Candidate Selection
- Literature & databases
- Classic models: Judd-Ofelt; Tanabe-Sugano; Crystal field
- Advanced quantum models



Synthesis
- Combustion
- Precipitation (e.g. urea)
- Solid state reaction
- Flame synthesis
- Vapor doping
- Post-treatments

New phosphor meeting all specifications

Characterization
- Emission (CIE)
- Absorption
- Decay time
- Photo-stability
- Structure
- Composition



Lamp Performance
- Mercury resistance
- Water insensitivity
- Firing stability
- Radiation resistance
- Protective coatings
- *Long-term stability*

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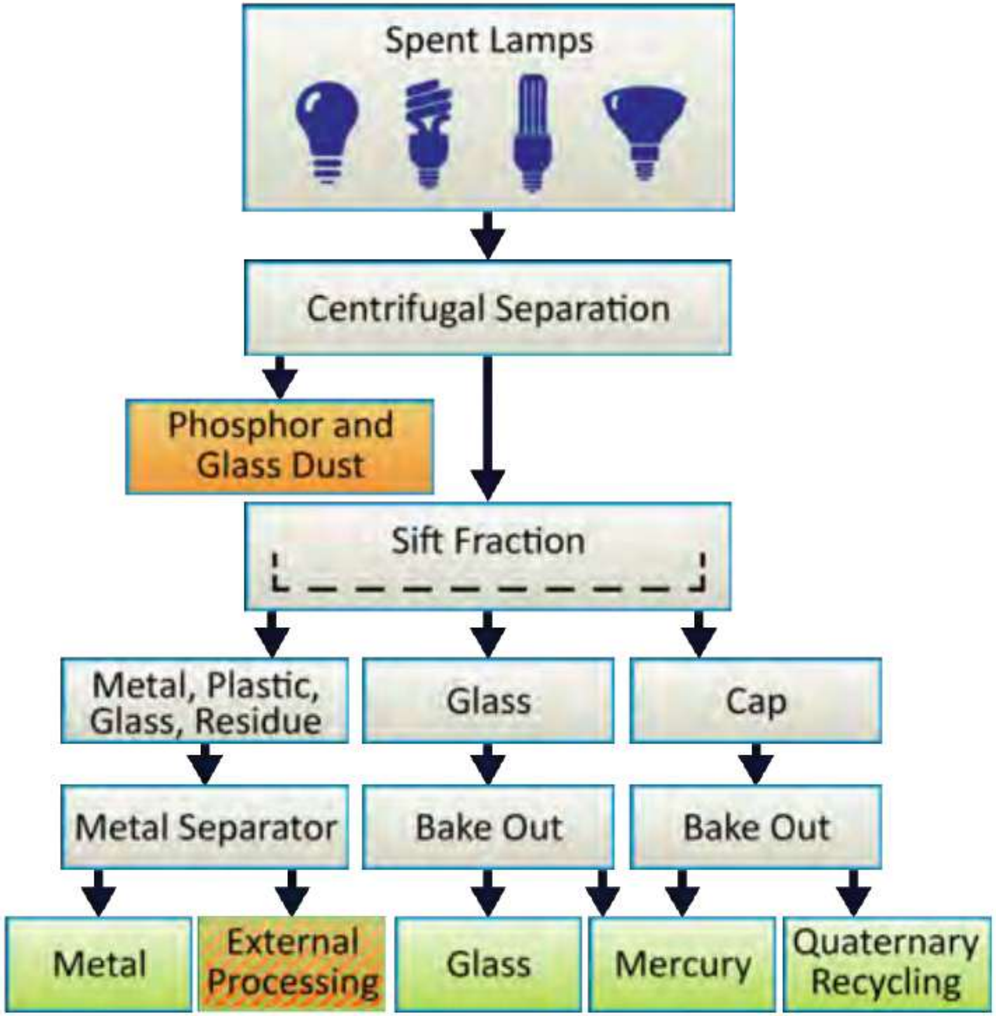
Fluorescent lamp recycling

- Long-tube and compact fluorescent lamps are already collected for recycling, primarily as a means of controlling mercury release into the environment.
- Fluorescent lamps represent about 7% of the total usage of Eu and Tb.
- Phosphors, however, are not typically recycled although they contain highly valuable Eu and Tb.



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Phosphor recycling research agenda

- Veolia collects about 1,200,000 lbs of phosphor every year.
- This contains 9-12.5% of high-value REO.
- CMI will assess the physical and chemical character of this phosphor.
- Three different approaches to separating the REO will be assessed:
  - Physical beneficiation
  - Hydrometallurgical leaching and precipitation
  - Pyrometallurgical processing
- Open Questions:
  - Phosphor re-use?
  - Phosphor separation by type?

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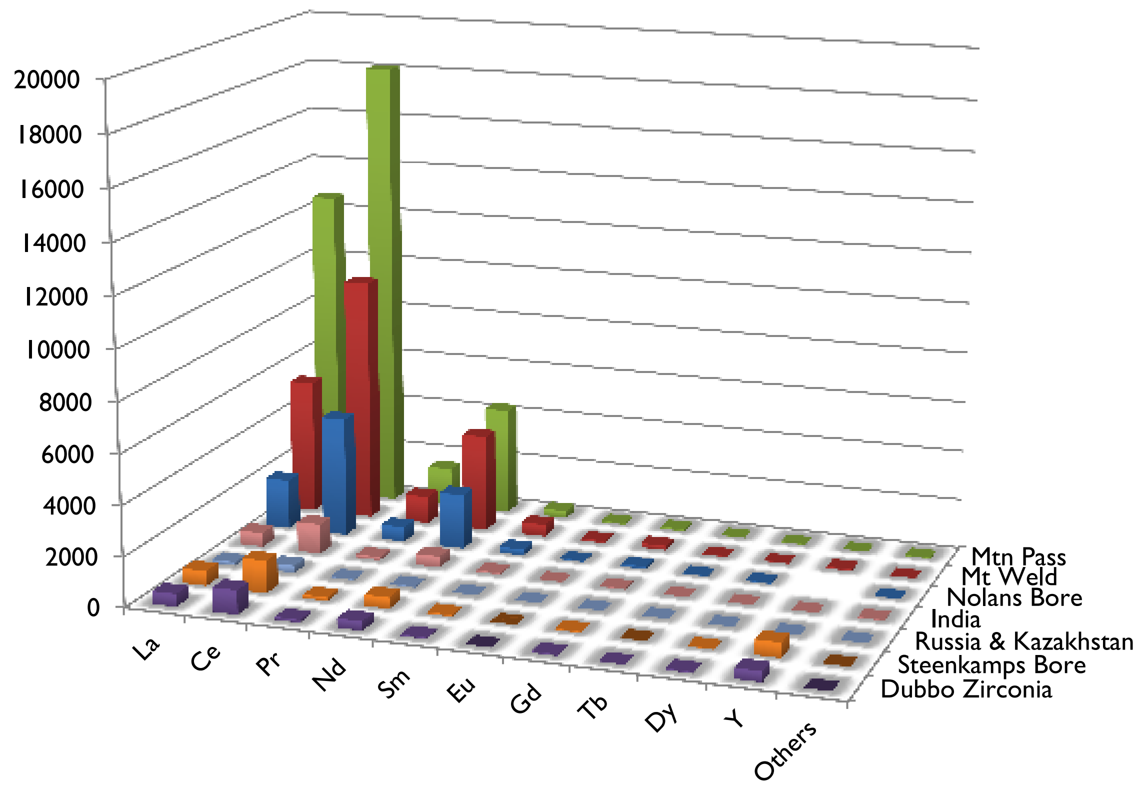
Projected Annual Production of Emerging Mines

tonnes of REO

Separating these elements is costly, time-consuming and potentially highly polluting.

Some ore bodies also contain radioactive elements.

Not all of the elements can be absorbed by the market.

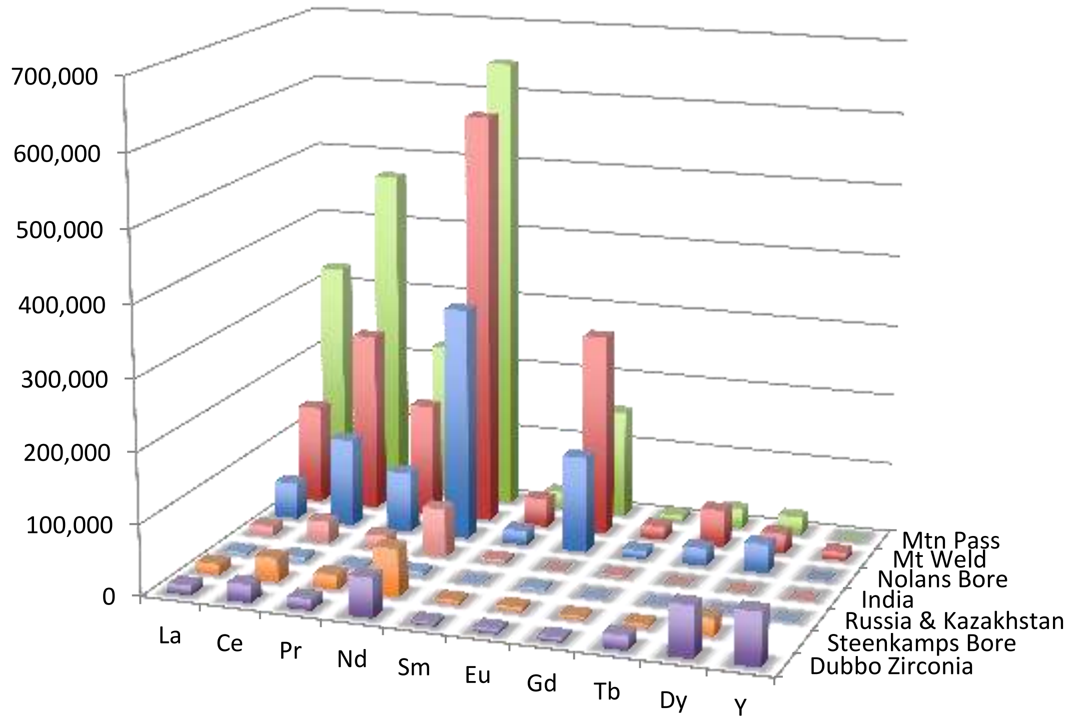


Data extracted from US Department of Energy: Critical Materials Strategy, 2011.

Potential Annual Revenue, USk$/yr
at April 2008 prices

Not all of this revenue is realizable, because some elements are overproduced relative to demand – notably Ce.

If we succeed in inventing a substitute for Nd, then its price will drop. This will reduce mine revenues and challenge the sustainability of supply for other rare earths.



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Challenges

- Incommensurate timescales of criticality development and research projects
- Emergence of alternative solutions
- Co-production complications
- Lack of predictive tools for supply and demand
- Persistent lack of control at key points of the supply chain

Research is not always the answer!!

Thank You!

Questions?