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Commodities, Commotion, Complexity and Competition:

Interesting Times in the Rare Earth Business

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U.S. DEPARTMENT OF ENERGY

Commodities

- In economics, a commodity is a marketable item produced to satisfy wants or needs.

- Sometimes the item is fungible:
  - One ounce of pure gold is equivalent to any other ounce of pure gold.
  - This relies on agreed standards.

- If the item is fungible, it might be traded on a commodity exchange.
  - If there is an exchange, then price and stock information are openly available.

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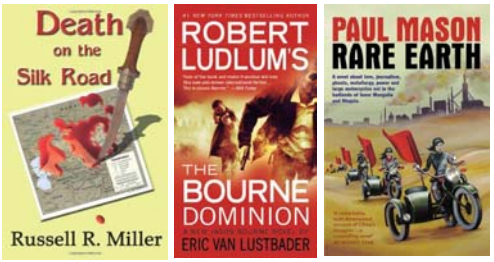
Commotion

2011



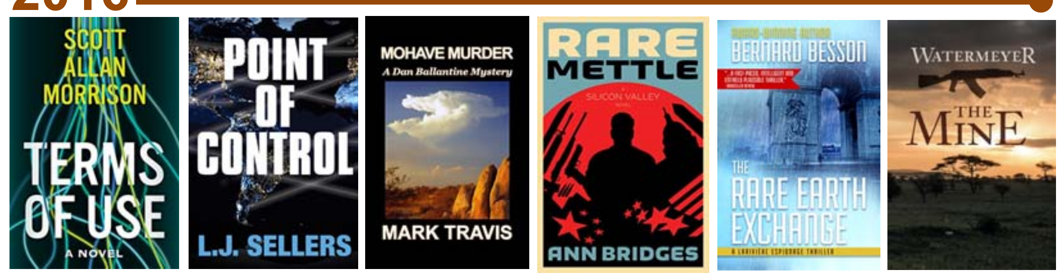
2012

2013

2014

2015

2016



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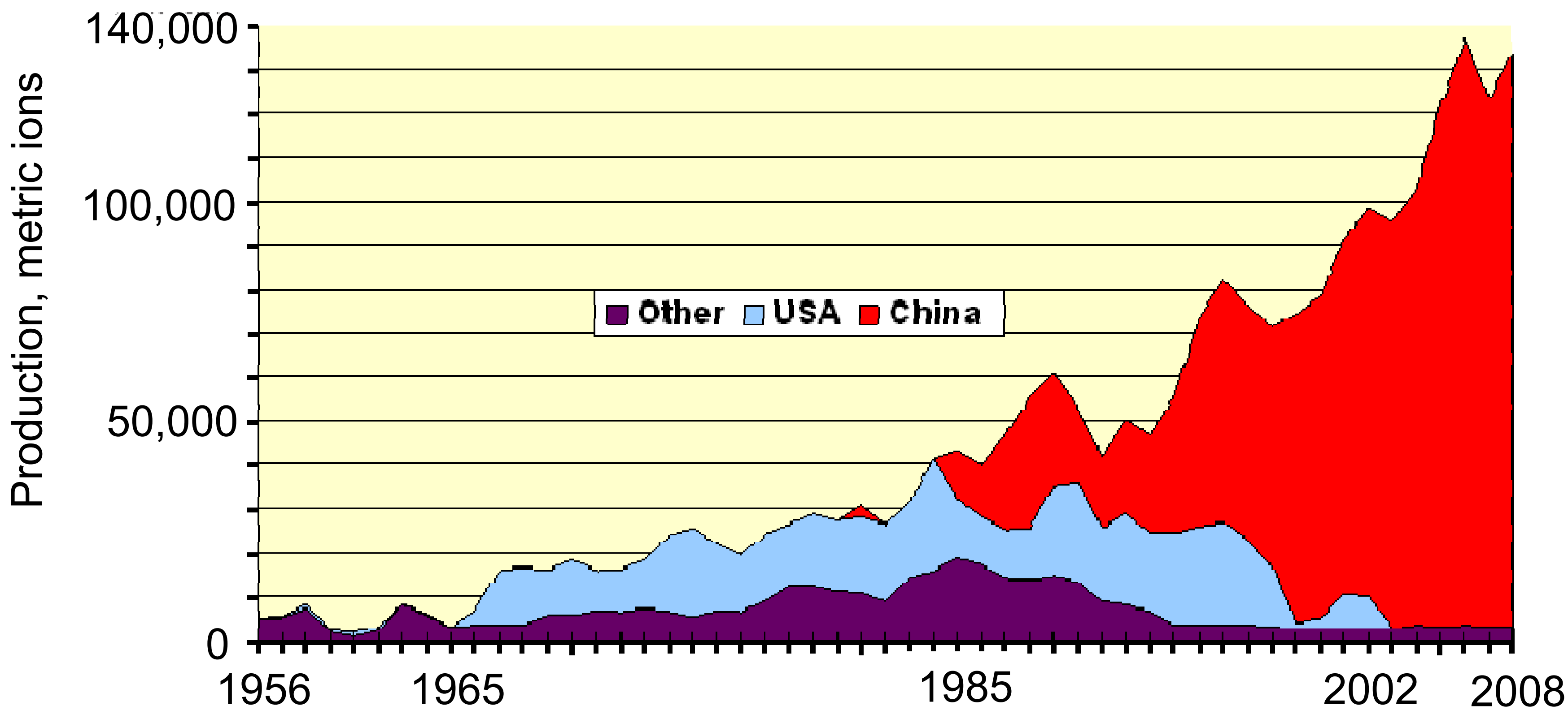
REE production trends



Monazite-placer era | **Mountain Pass era** | **Chinese era → ?**

Source: USGS Fact Sheet 087-02 updated with recent USGS Minerals Yearbook

Deng Xiaoping

Paramount Leader of the People's
Republic of China, 1978 – '89.

The Middle East has oil; China has rare earths.

From a speech given in Jiangxi, PRC
January 1992

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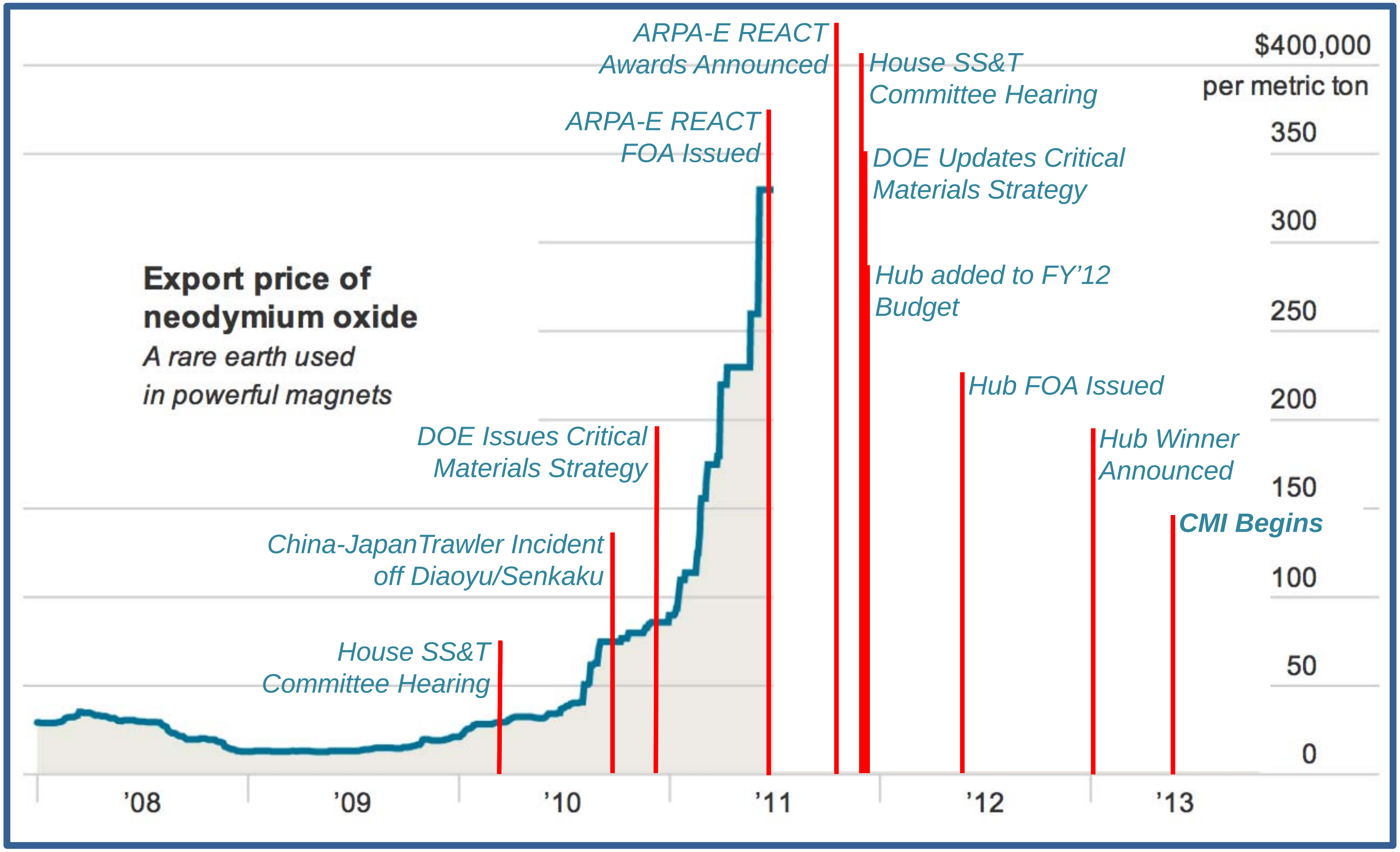
A highly selective timeline of the "rare earth crisis"



Price Graphic: *New York Times*, 10-22-2013

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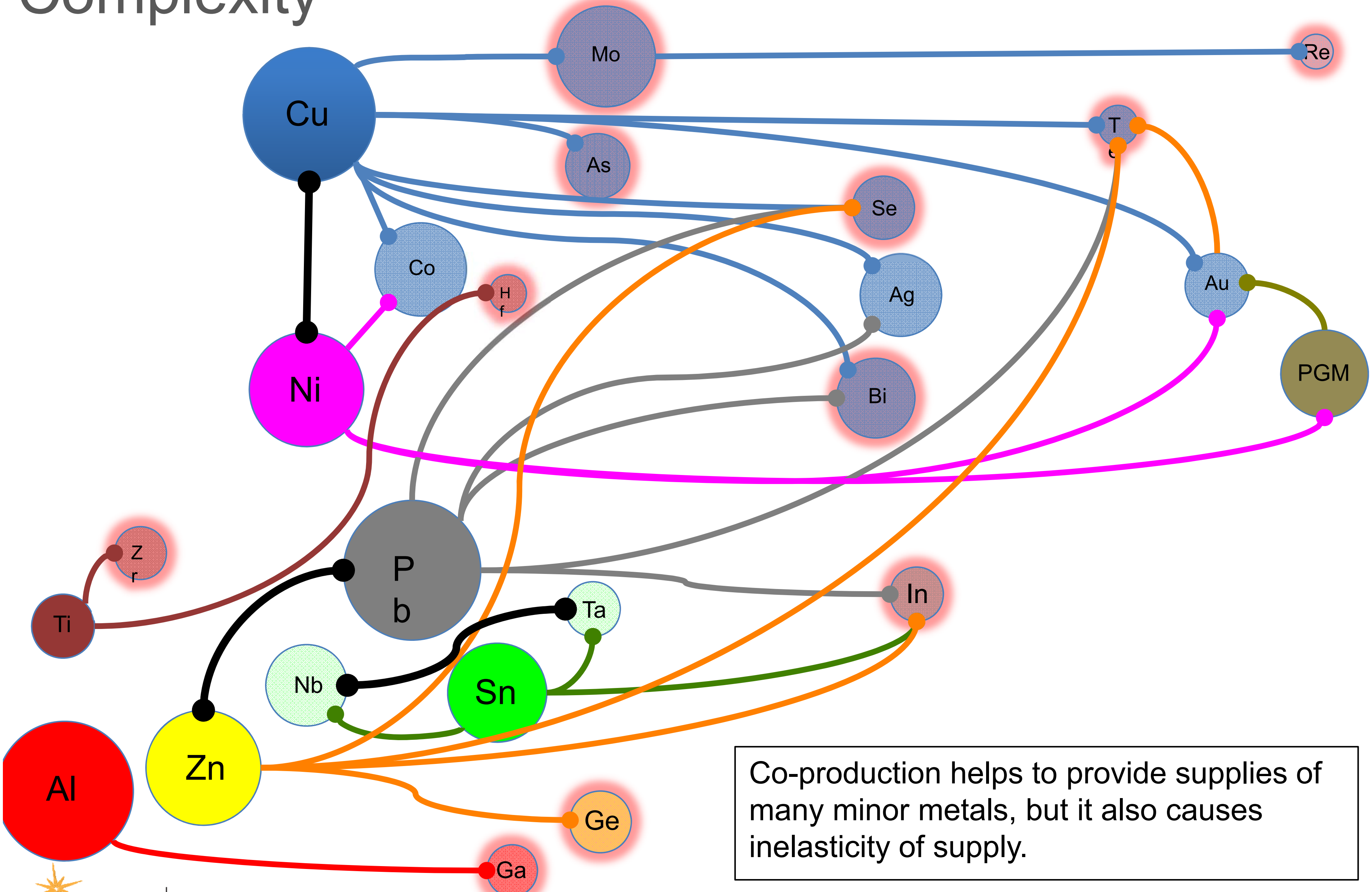
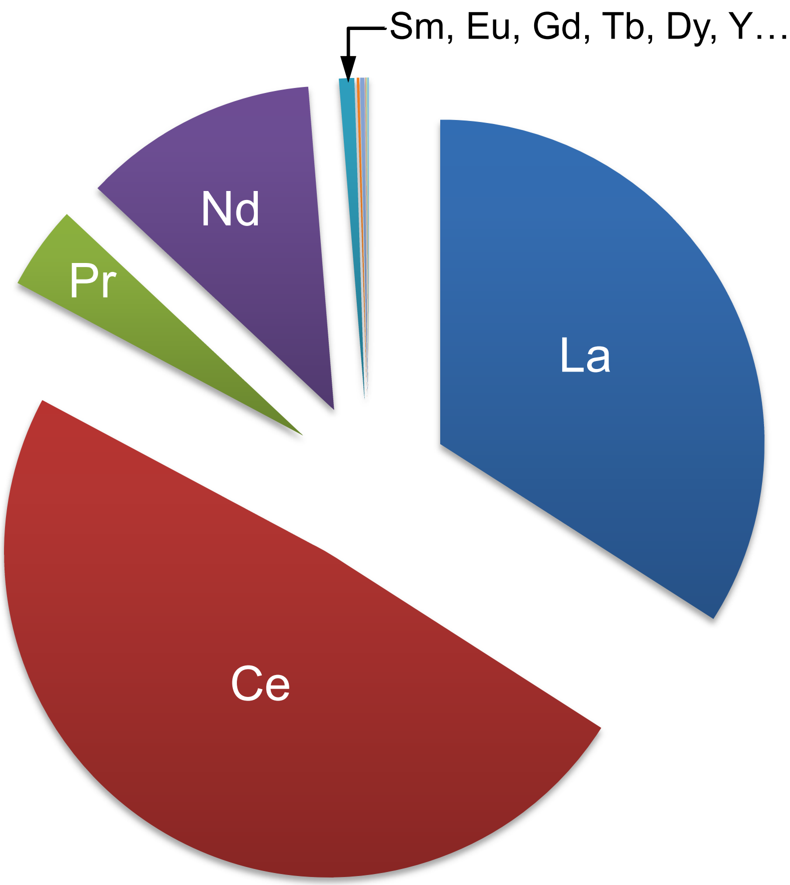
Complexity

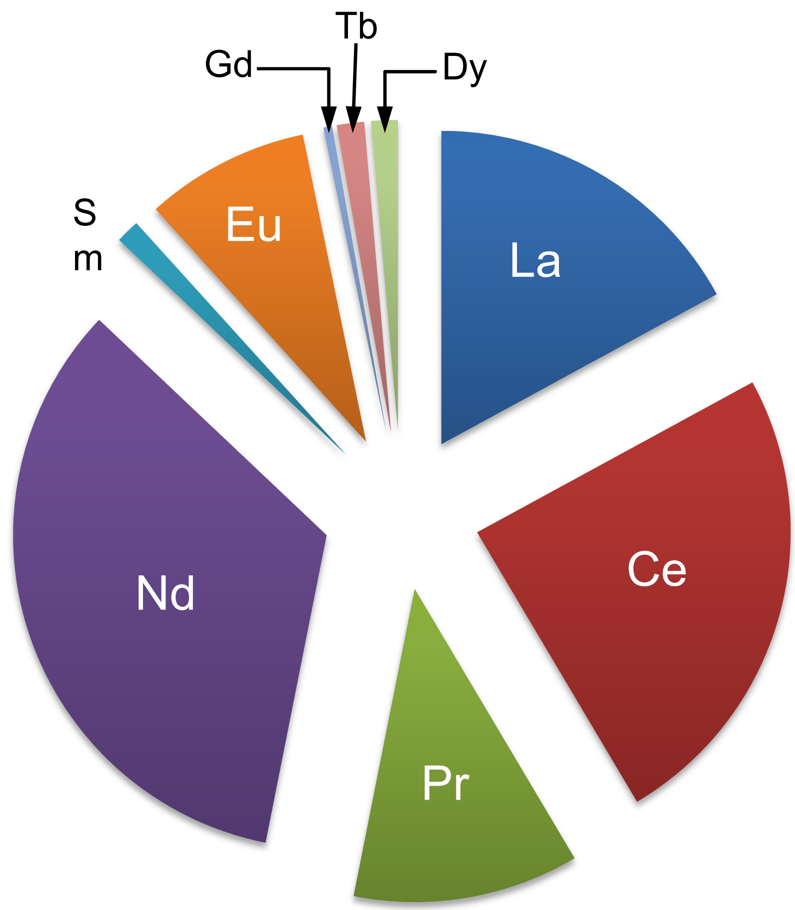


Co-production helps to provide supplies of many minor metals, but it also causes inelasticity of supply.

Mixed Source Challenges: *Bastnaesite Mines*



Typical Production by Mass



Production by Value (but not all value is realizable)

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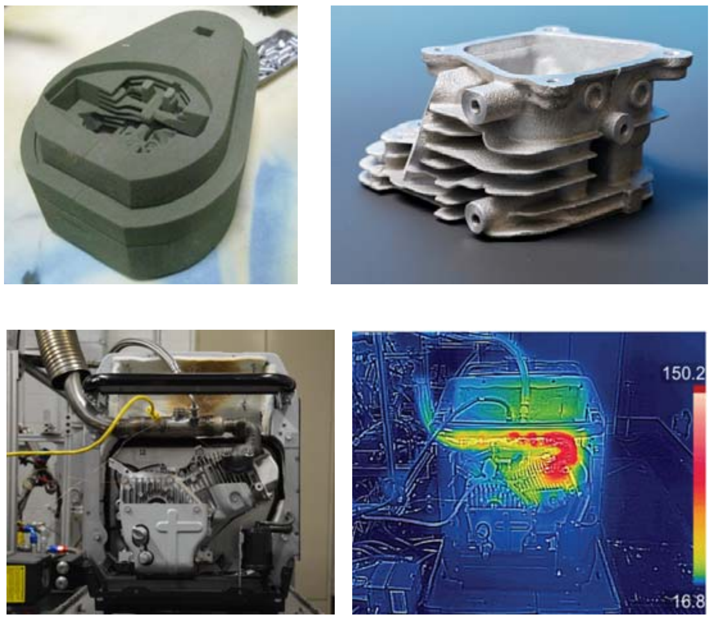
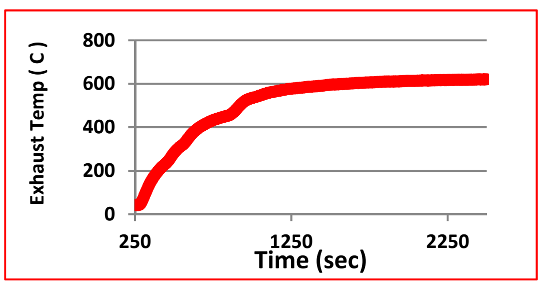
Promising new cerium-aluminum alloy for high-temperature applications demonstrated in working engine





Top row: Mold and finished part, Above: Cylinder installed on engine with thermal imaging

Achievement:

A cylinder head made with the new alloy exhibited stable operation during full load testing on a commercial engine/genset at temperatures reaching 600°C.

Significance and Impact

The Al-Ce alloy offers high performance at lower costs and could boost America's rare earth mining industry by providing a high-volume automotive application for cerium, the most abundant rare earth element mined in excess. In turn, the economics of producing critical rare earths like neodymium for magnets improves.

Research Details

- Ternary Al-Ce-X alloy was selected for testing.
- Alloy was cast into 3D printed sand molds, then machined for engine use.
- The cast cylinder head was tested on a Honda 4-stroke engine/3 kW genset at temperatures reaching 600°C.

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Supply Chain Assessment of Aluminum-Cerium Alloy Research

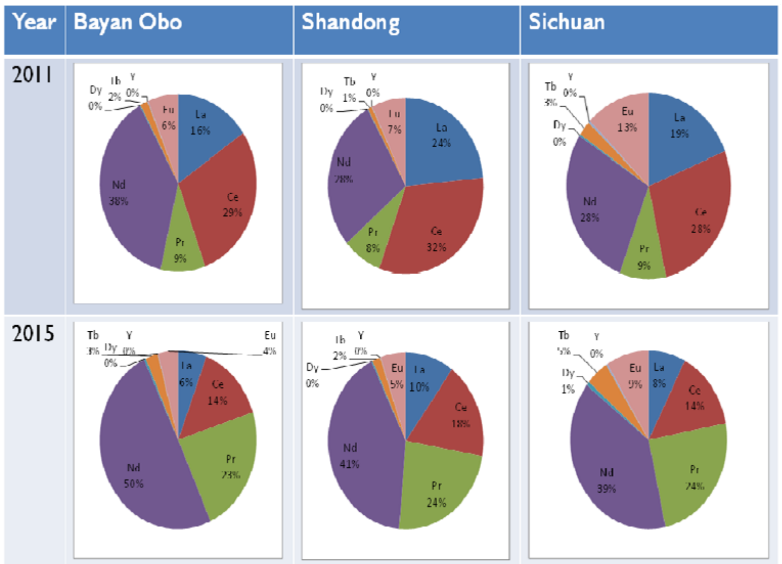

Figure 1: Percent revenue share of select Chinese LREE deposits. Notice that Ce (red) accounted for 28-32% of mine revenue in 2011 compared to 14-18% in 2015.

Achievement

A vertical supply chain assessment has been used to evaluate the benefit of introducing a new Al-Ce alloy to industry and the overall supply chain

Significance and Impact

Our preliminary analysis details 1) the potential efficiency gains that could result from Al-Ce alloy use in automobiles and 2) the resulting Ce price increase

Research Details

- The cost savings from the engine efficiency gained from using the Al-Ce alloy is greater than cost savings from thermomagnetic processing or thickness reduction in certain applications
- The estimated Al-Ce adoption rate by the Tier 3 model (~800,000 vehicles cumulative capacity) was corroborated by industry (Eck Industries)
- China would only be able to satisfy 17-80% of the global Ce demand in 2030 depending on their production policy (potential area for ROW supply)
- Ce surpassed Nd in terms of total revenue share at certain Chinese mines in 2011 during the price spike (Figure 1)
- Two manuscripts detailing Tier 2 and Tier 3 research submitted to Journal of Metals (JOM)

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Above: Journal of Metals July issue cover featuring CMI sponsored research as cover image.

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New highly castable aluminum-cerium alloy featured on journal cover.

Achievement:

Critical Materials Institute research is awarded the July cover of a JOM special issue. New Al-Ce alloys are shown to be highly castable when compared to existing aluminum alloys.

Impact:

Proof of industrial casting viability moves the Al-Ce alloy one step closer to a full industrial-scale demonstration. Successful testing of the Al-Ce systems for industrial castability opens an avenue for more lightweight, fuel-efficient vehicles, creating a high-volume application for abundant cerium that could provide economic incentive for domestic rare-earth production for clean energy.

Details:

- Al-Ce alloys were cast into complex near-net shape molds, successfully filling the mold and providing a proof of concept for industrial uses.
- Intermetallic microstructure confers strength.
- The results exemplify the power of partnerships in the CMI, from science to industrial application.

Oak Ridge National Laboratory
Eck Industries, Inc. Specialists in premium aluminum castings
Lawrence Livermore National Laboratory
The Ames Laboratory Creating Materials & Energy Solutions U.S. Department of Energy

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

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

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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Phosphate industry backs CMI options downselect

Achievement

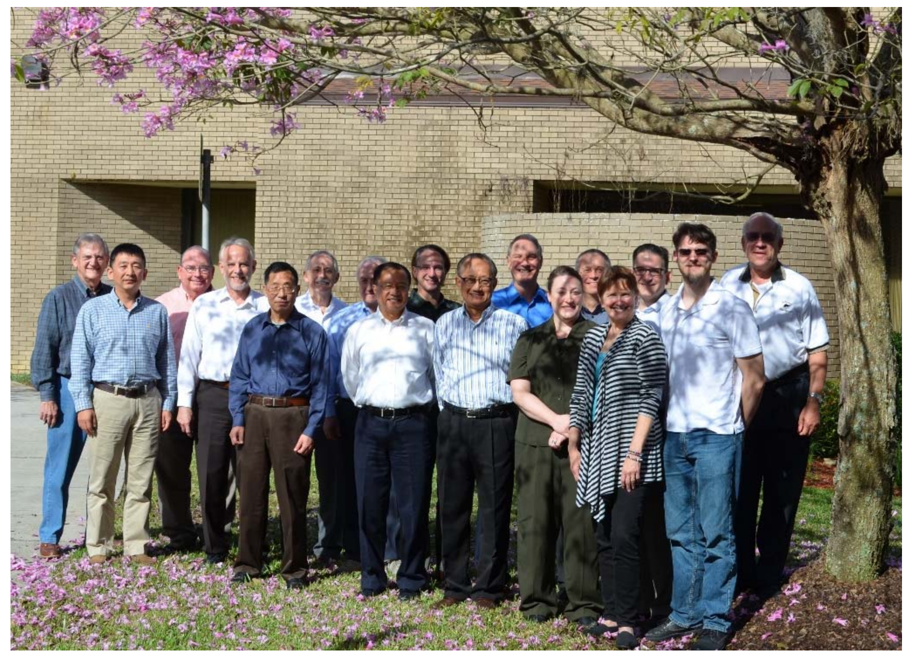
At a workshop hosted by Florida Industrial and Phosphate Research Institute (FIPR) on January 18, 2017, phosphate industry representatives supported current CMI plans toward recovery of rare earths from selected phosphate processing streams—sludge and clay.

Significance and Impact

Treating the sludge and clay streams to remove their significant rare earth content has the potential to add value to phosphate processing and therefore attracts interest from Mosaic, CMI's large industry partner in the phosphate industry. This is a good example of how a low-revenue by-product could be made accessible for diversification of supply of critical materials.

Details

- Six industry experts participated in the meeting with 11 CMI partners from 5 organizations.
- Recovery of REE from sludge was identified as the most attractive process for demonstration testing in Year 5.
- Data needed for evaluation of sludge processing was identified.
- Recovery of REE and phosphate value from clay waste was identified as an industrially attractive longer-term option.



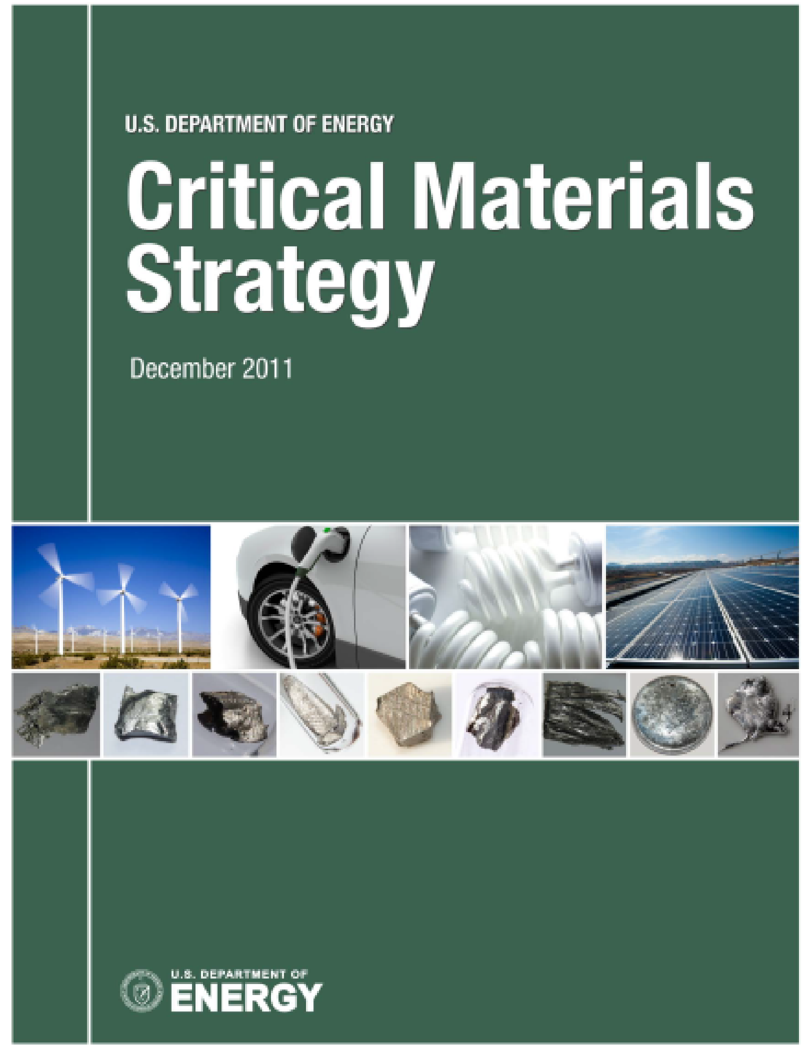
Participants at CMI 2017 Phosphate Workshop

Competition

Find ways to:

- diversify our sources;
- provide alternatives to the existing materials;
- make better use of the existing supplies through efficient manufacturing, recycling and re-use.

Some of these approaches work better than others for specific materials.



Materials and Technologies: *Lessons learned*

- It is often easier to replace a technology than provide a material.
  - Wind is the fastest-growing energy source in the U.S., but land-based wind turbines use DFIG technologies instead of direct-drive generators, to avoid the need for rare earth magnets.
  - Lighting moved rapidly to LEDs, and away from fluorescent lamps in 2013, partly as a result of the cost of rare earth phosphors.
  - Tesla PEVs use induction motors rather than rare earth permanent magnet motors, largely because of concerns about Nd and Dy supplies.
- Demand destruction follows price spikes.

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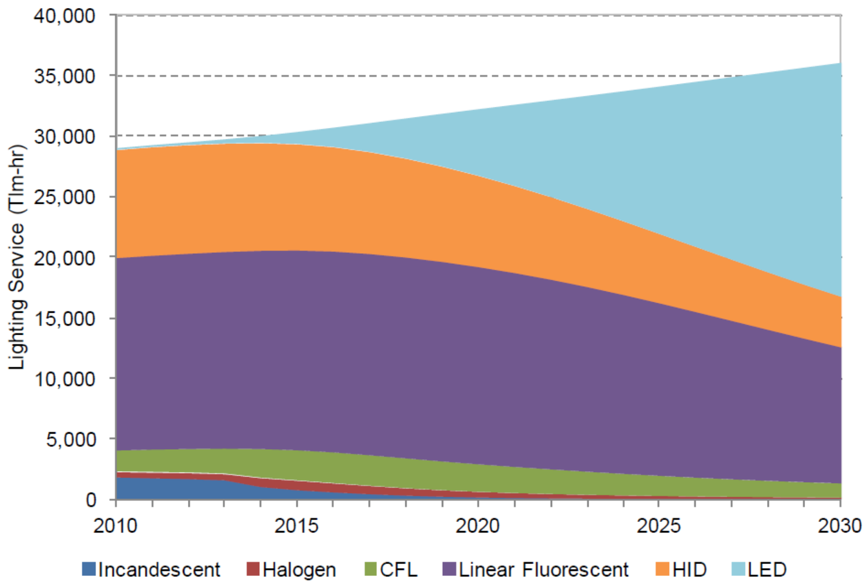
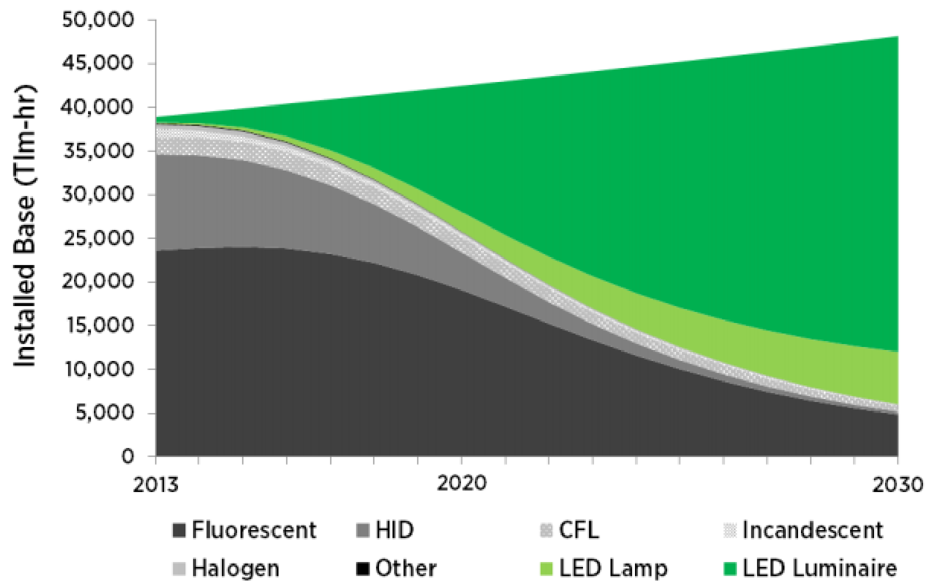
Technology shifts: *lighting*



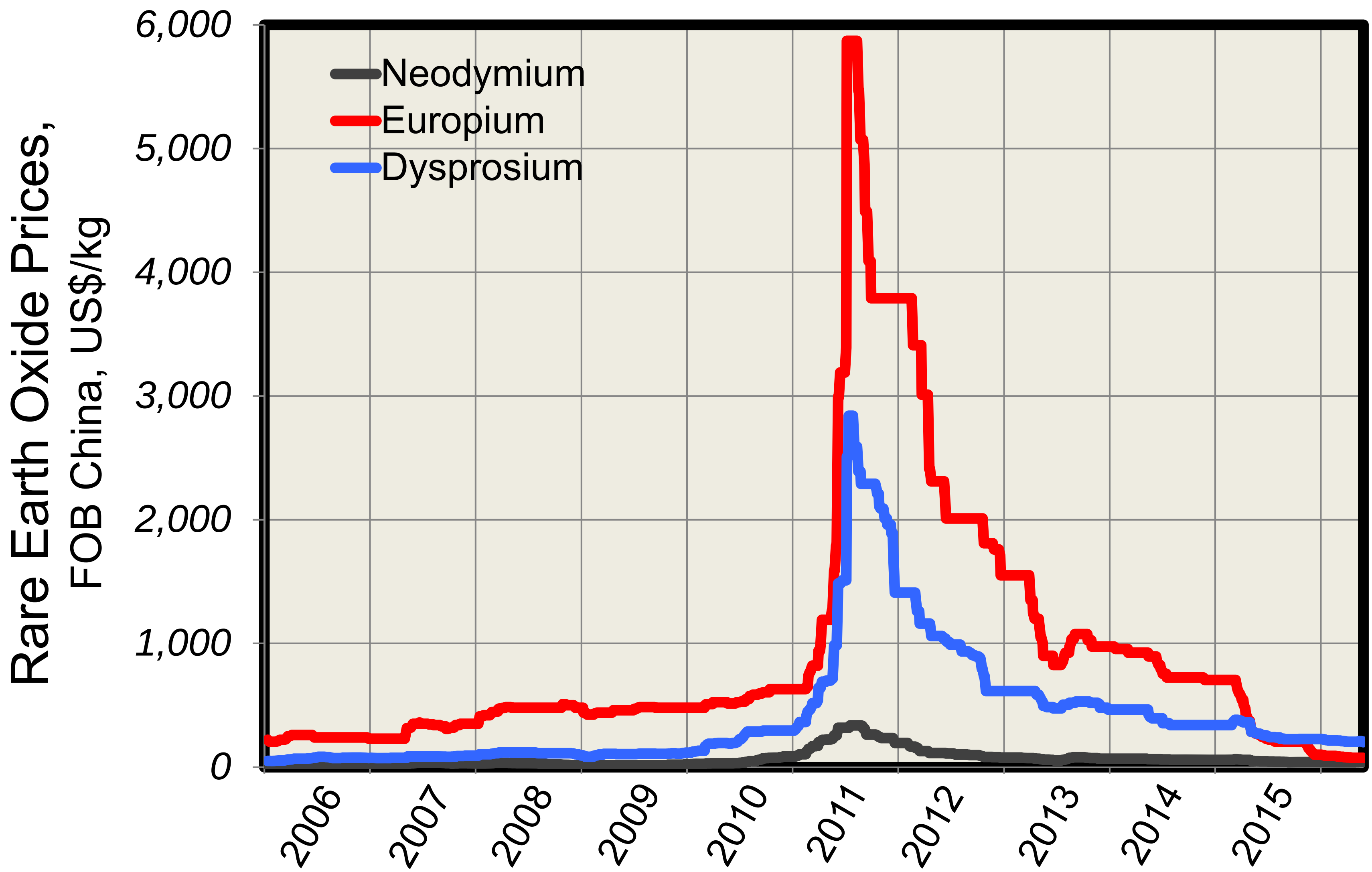
Source: US Dept. of Energy – Energy Savings Potential of Solid-State Lighting in General Illumination Applications (January 2012)



Source: US Dept. of Energy – Energy Savings Forecast of Solid-State Lighting in General Illumination Applications (August 2014)

- Why did the forecast change so much in 2 years?
- What is the impact on materials demand

Rare earth prices



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Other strategies are occasionally in play

- Trade barriers.
  - Treaties, Tarrifs, Quotas, Taxes, Standards, Government Subsidies, etc.
  - WTO actions.
- “Illegal” production.
- Monopolies.
- Market manipulation.
- Stockpiling.
- Closed markets.

Recycling & Re-Use: *Lessons learned*

- You don't recycle a material, you recycle a device.
  - This is a pathological case of materials co-production.

- Front end costs can easily exceed the value that can be recovered.
  - Focus efforts on collection and disassembly.
  - Design for disassembly is a hard, hard sell.

- Critical mass is important.
  - Economies of scale are essential to solving front end costs, and making sales.

- End use of the recycled material is paramount.
  - There have to be willing customers for the recycled materials,
  - Production levels have to be sufficient to justify qualifying the recycled materials.

Materials Substitution: *Lessons learned*

- New materials *can* be developed at an accelerated pace.
  - CMI is close to commercializing a green phosphor and a red phosphor after only three years work.

- New materials are more readily accepted if they are process-compatible with the materials they replace.
  - Close collaboration with the user is essential.

- A new material may not replace an old one in all of its applications.

- New materials that are not as good as the old ones can still have value.
  - *e.g.* "gap" magnets.

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Source Diversification: *Lessons learned*

- Financing (investment) is the rate-limiting step for starting a new mine.

- Reducing capex reduces the investment need.
  - Process improvements can have a big impact. For the rare earths, separations technologies are an important target.
  - Process technology improvement accelerates after a price spike.
  - Every new mine that comes on line operates with obsolete technology.

- Reducing opex accelerates return on investment.
  - This attracts investors and accelerates financing.

- Early revenue streams are essential.
  - Find ways to sell *all* of the mine's products.

Summarizing remarks

- Rare earths are not *commodities* in the colloquial sense.
  - There is no rare earth exchange.
  - The price you see is not the price you get.
  - Stock and flow information is hard to find.
- There is a lot of unwarranted *commotion*.
  - Mostly because of lack of information.
- Rare earth production is certainly *complex.*
  - You have to sell everything, not just the critical REEs
  - Chemistry is challenging
- There is enormous *competition* to provide solutions.
  - The fastest solution is usually the one that gets adopted.

Thank You!

Questions?

http://www.cmi.ameslab.gov