Rare Earth Elements

New Value Streams for Coal, New Products for Appalachia

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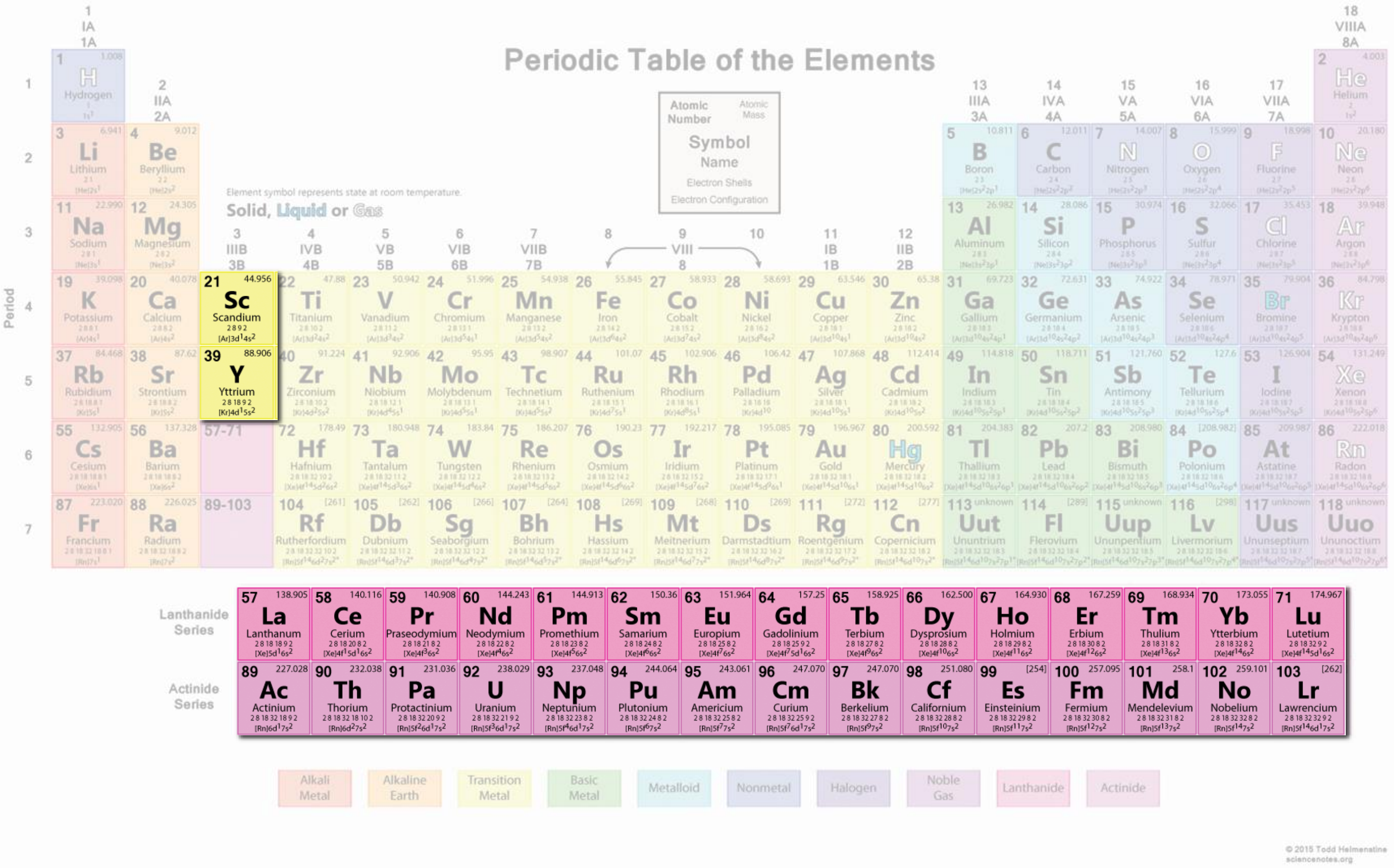
U.S. DEPARTMENT OF ENERGY

What are Rare Earth Elements (REEs)?



Average total crustal concentration = 184 ppm

**Wedephol, 1995*

What are Rare Earth Elements Used For?

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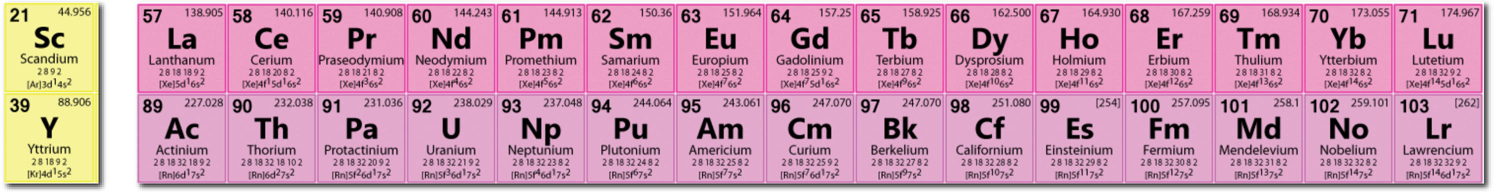

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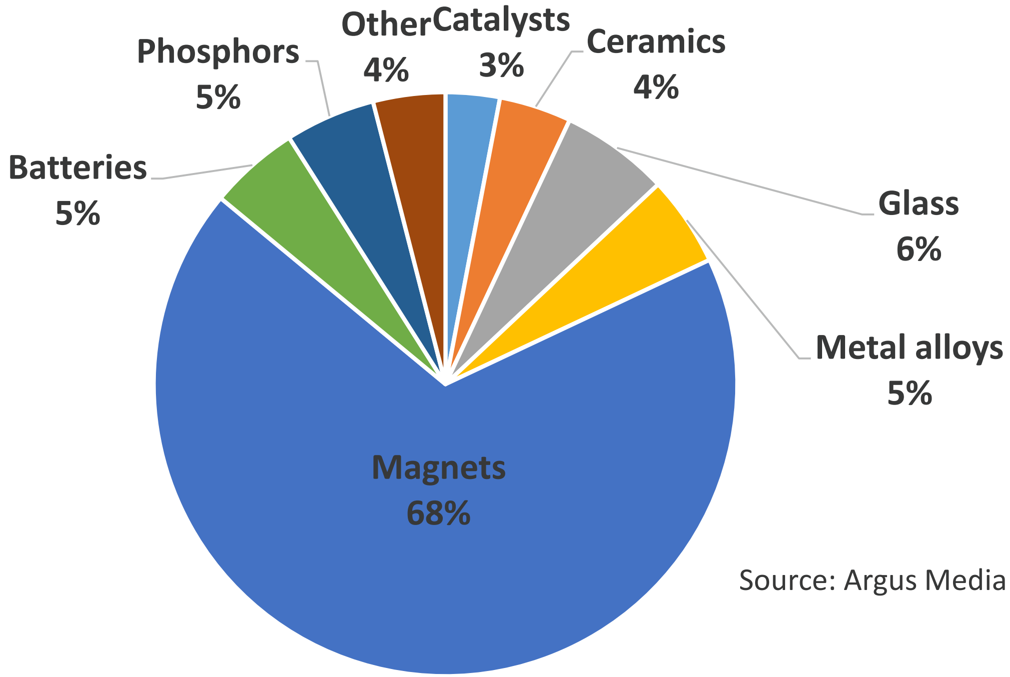
Rare Earth Elements Market

- **Annual global market ~$5 billion in 2015**
  - U.S. consumes ~11%, by volume
  - Almost all REEs are imported
- **Majority of REEs imported as part of finished goods, not raw materials**
  - US imported $1.2 trillion worth of REE-containing finished goods in 2017
  - Electronic equipment imports : ~$357 billion in 2017 (14.8% of total)
  - Phone devices (e.g. iPhone) almost a third of that at $113 billion
  - Cellular phone can contain as many as 16 different REEs
- **Market remains complicated**
  - Risks of substitution
  - Current oversupply
  - All global enrichment and processing is done in China



Source: Argus Media

2017 Estimated REO Consumption by Industrial (Value)

Source: http://www.worldstopexports.com/united-states-top-10-imports/

REE from Coal: The Challenge

Where do we get it? and What do we produce?

- **Low Concentration in Coal Feedstocks**
  - Ranges from parts per billion (ppb) in AMD to ~1,500 parts per million (ppm) in certain ashes
  - Global REE ores in current use range from 0.5 wt% (5,000 ppm) to 50wt% (500,000 ppm) with major deposits generally near 8wt%

- **Currently No Domestic Supply Chain**
  - No clear domestic off-take except for "saleable" (>90+%) REO or "REO baskets"
  - Creates uncertainty as to what concentration domestic processes should target

- **Very Broad Problem**
  - Almost too many coal and related feedstocks to target: which is best?
  - Are REE the product or co-product?
  - Each coal-related feedstock is different, even within same category

REE from Coal: A Unique Opportunity

Importance to the Fossil Energy and DOE Mission

- **National Security**
  - 5% of total domestic demand is deemed "critical" by the Department of Defense (DoD)
  - Required for numerous critical industries (energy, manufacturing, etc.)
  - Necessary for numerous clean energy technologies which have been deemed a national priority

- **Power the U.S. Economy and keep electricity affordable:**
  - Additional value streams make coal more cost competitive & keep electricity prices low
  - Drives U.S. coal competitiveness in international markets, driving exports
  - Creates or maintains jobs in economically hard hit regions, such as Appalachia
  - Provides an important new domestic resource, allowing more manufacturing to locate in the U.S.

- **Environmental Stewardship**
  - Opportunity for remediation, and reducing waste streams from coal production & use
  - Beneficiated coal will burn more efficiently, creating less emissions
  - Produce REEs with a dramatically lower environmental footprint than overseas

NETL's REE Strategy

How We are Approaching the Problem

- **Understanding the "Where" and "How" (Characterization)**
  - Driving the understanding of how REEs occur in coal and by-products
  - Developing the technologies needed for prospecting and new production means
- **"Cheap" and Environmentally Benign Production (Separations)**
  - Producing ore-quality and greater REE from coal and related materials
  - Combining processes for further efficiency and enrichment
  - Maturing promising transformational separations technologies and continuing to push the envelope
- **Smarter, Not Harder (CFD & Systems Analysis)**
  - Developing the cutting edge CFD models to help drive commercialization and scale up
  - Identifying process bottlenecks, research targets, and market opportunities through systems analysis
- **Driving Innovation, Unlocking the REE Potential of Coal**
  - Developing the tools for REE prospecting in coal basins
  - Identifying the best resources for exploitation – be it fly ash with high Ca content, underclays, or raw lignite

Recent Successes for Appalachia

Maturing Technologies to Commercialization

Acid Mine Drainage (AMD) Cleanup

- Direct water conditioning to remove over 85% of REE down to parts per trillion (ppt)
- Creating high purity (96wt%) REE products from AMD sludge & treatment solids
- Potential to extract other high value minerals: Cobalt, Alumina, and more

Immobilized amine/ amine sorbent

Processing Coal Waste and Underclays

- Low impact process removes easily accessible REE (up to 33% of total)
- Demonstrated successes with Appalachian clays

Enabling REE Recovery at the Power Plant

- New invention leverages existing pollution control technologies to enhance REE extractability from ash

Image from https://www.flickr.com/photos/piedmont_fossil/5710636433

Thanks for your Attention!

Rare Earth Element Usage

Global Rare Earth Oxide (REO) Usage from 2005-2015

Most used REOs were:

- Cerium Oxide (32%)
  - Catalyst related products and glass polishing powders and additives
- Lanthanum Oxide (31%)
  - Catalyst related products and glass polishing powders and additives
- Neodymium Oxide (18%)
  - Permanent magnets
- Yttrium Oxide (10%)
  - Ceramics, pigments and glazes, and glass polishing and powder additives
- Praseodymium Oxide (5%)
  - Permanent magnets

- **Global consumption of LREOs increased at a CAGR OF 2.8%, while global consumption of HREOs increased at a CAGR of 1.5%**