Systems Perspective on REE from Coal

NETL

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Clockwise from top center: praseodymium, cerium, lanthanum, neodymium, samarium, and gadolinium. (Photo by Peggy Greb).

U.S. DEPARTMENT OF ENERGY

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What are Rare Earth Elements (REEs)?

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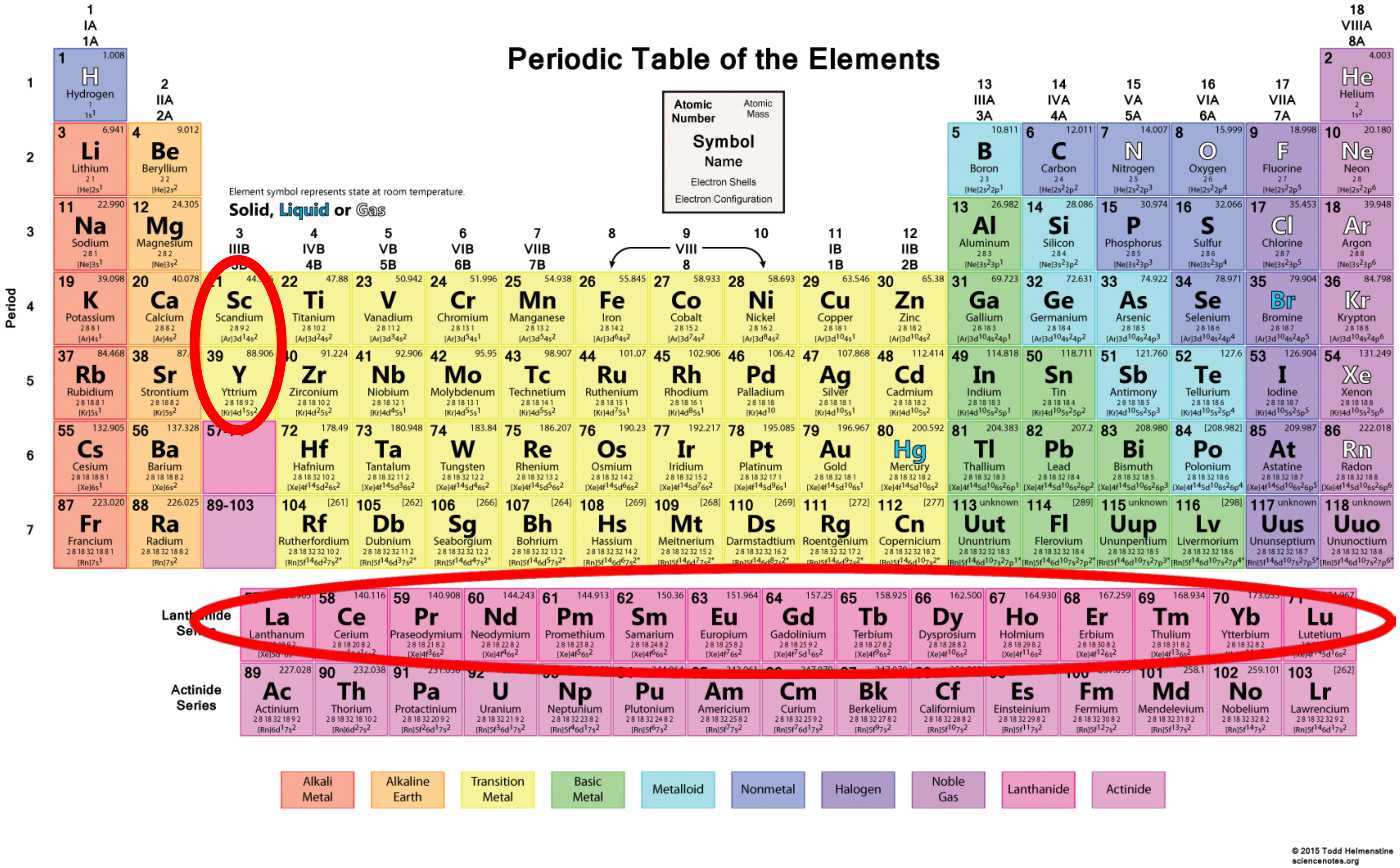
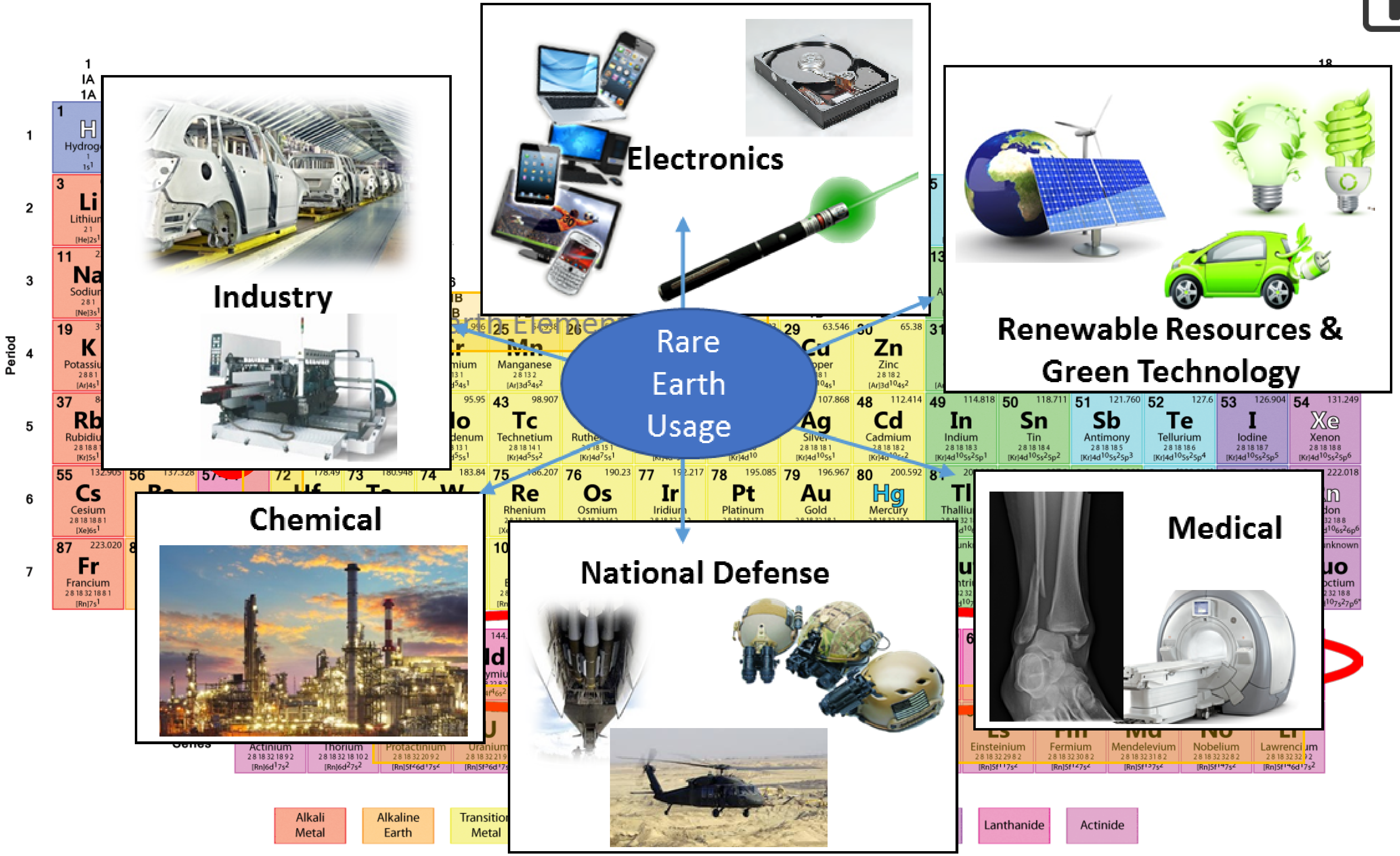


Average total crustal concentration = 184 ppm

**Wedephol, 1995*

Uses for Rare Earth Elements



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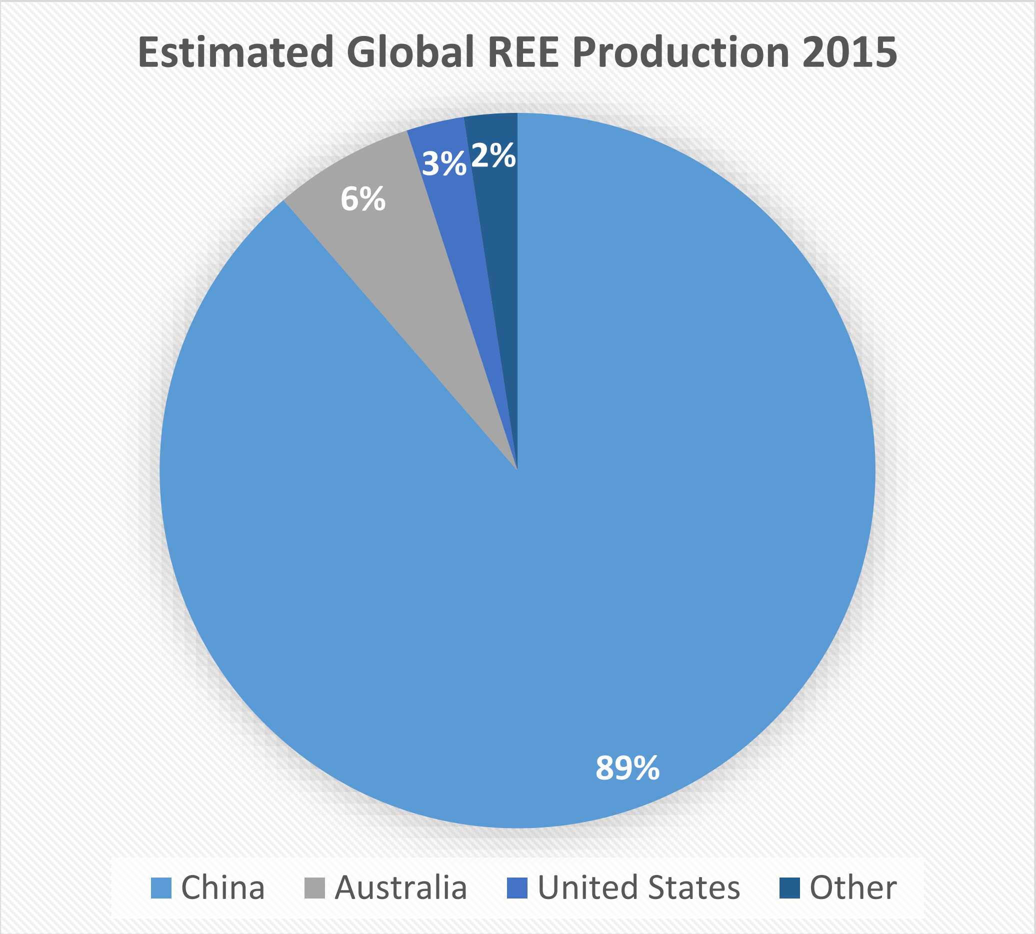
1. genius.com 2. Mos-Tech.co.uk 3. greenliving4live.com 4. cleantechica.com 5.ishareimage.com 6. USGS Rare Earth Fact Sheet (2014) 7. lowereasternshorenews.com 8. osa.opn.org 9. army-technology.com 10. oilinvestigatingnews.com 11. alibaba.com 12. cardvice.com.au 13. demopolistimes.com 14. defenseimagery.mil

REEE Market Assessment

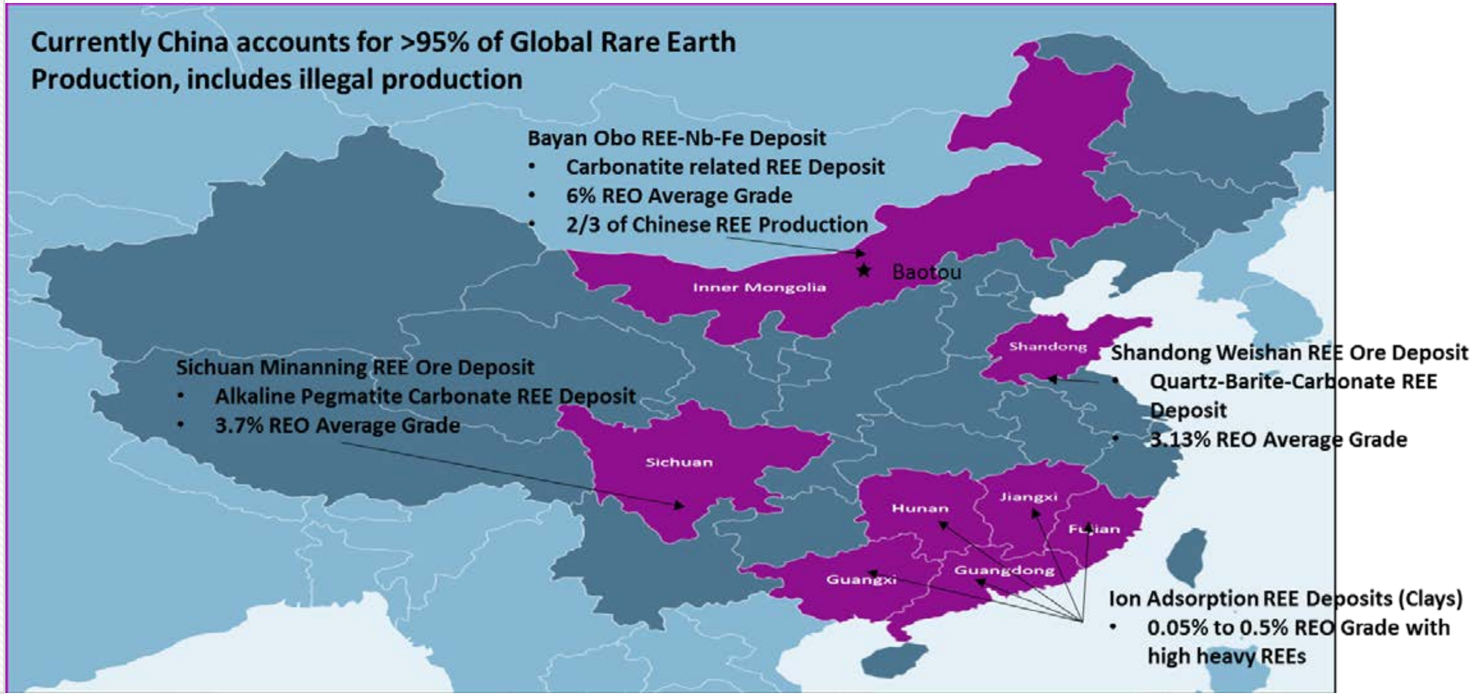
- **The Annual Global Rare Earth Market was ~$5 billion in 2015**
  - The US only consumes around 11% ($550 million)
  - Almost all rare earths are currently being imported
- **The US imported $2.3 trillion worth of finished products in 2015**
  - The top 4 product groups account for ~50% of the imported value
    - Electronic equipment: US$332.9 billion (14.4% of total US imports)
    - Machines, engines, pumps: $329.3 billion (14.3%)
    - Vehicles: $283.8 billion (12.3%)
    - Oil: $201.2 billion (8.7%)
- **The majority of REE's imported into the US come in the finished goods, and not as a raw material**

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

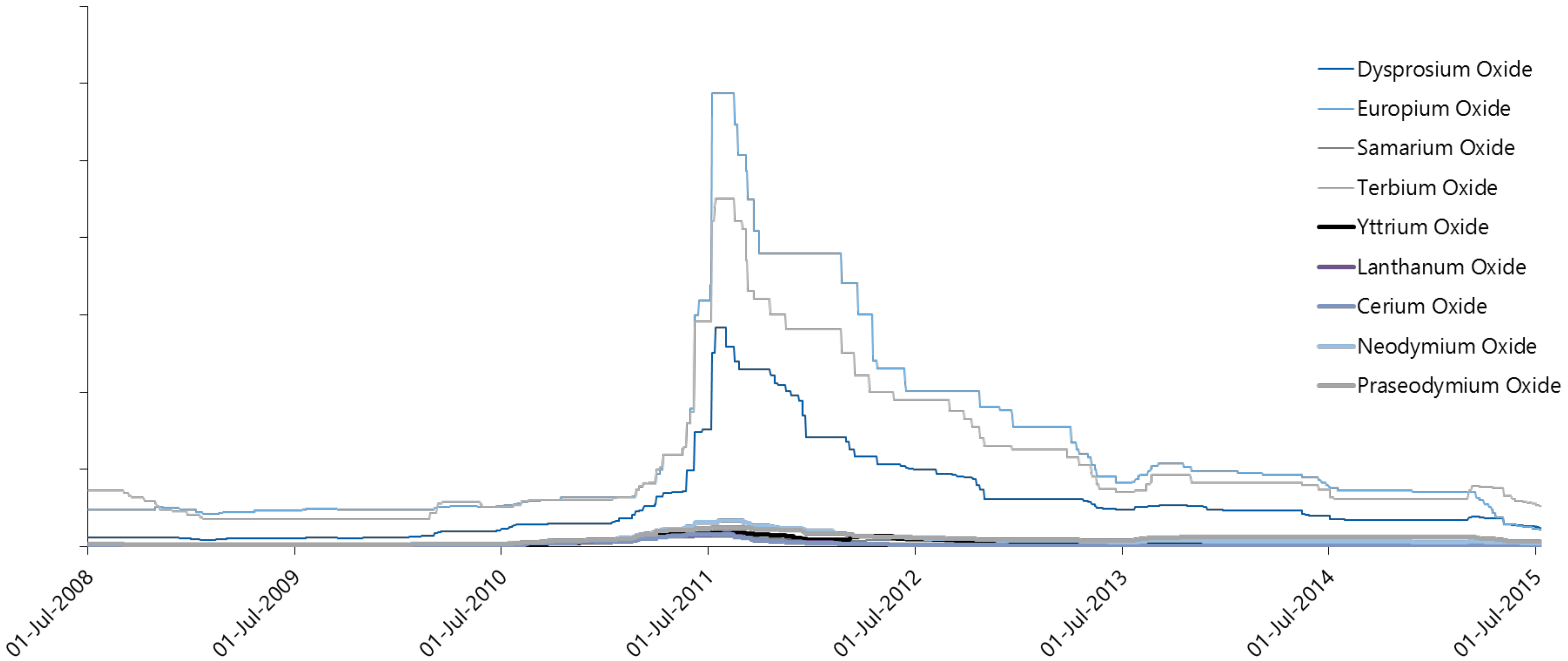
REEs Production



- Total REO Production Estimated at 170,000 tonne/year
- Total REO Demand Estimated at ~150,000 tonne/year
- US accounts for ~11% of Global Demand
- Actual Chinese production >95% including illegal mining



REE Price History

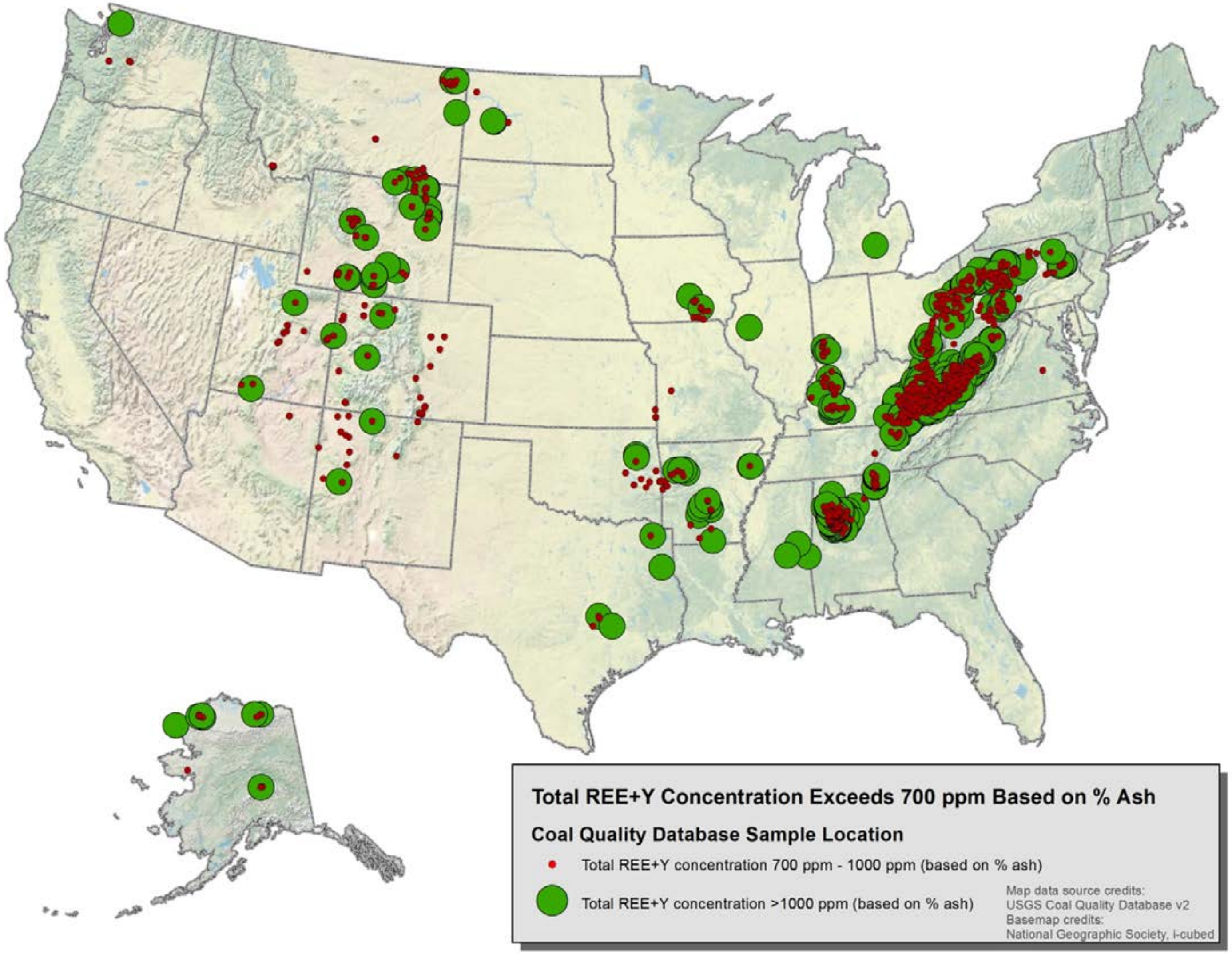


Source: Argus Media

Rare earth elements associated with coal deposits

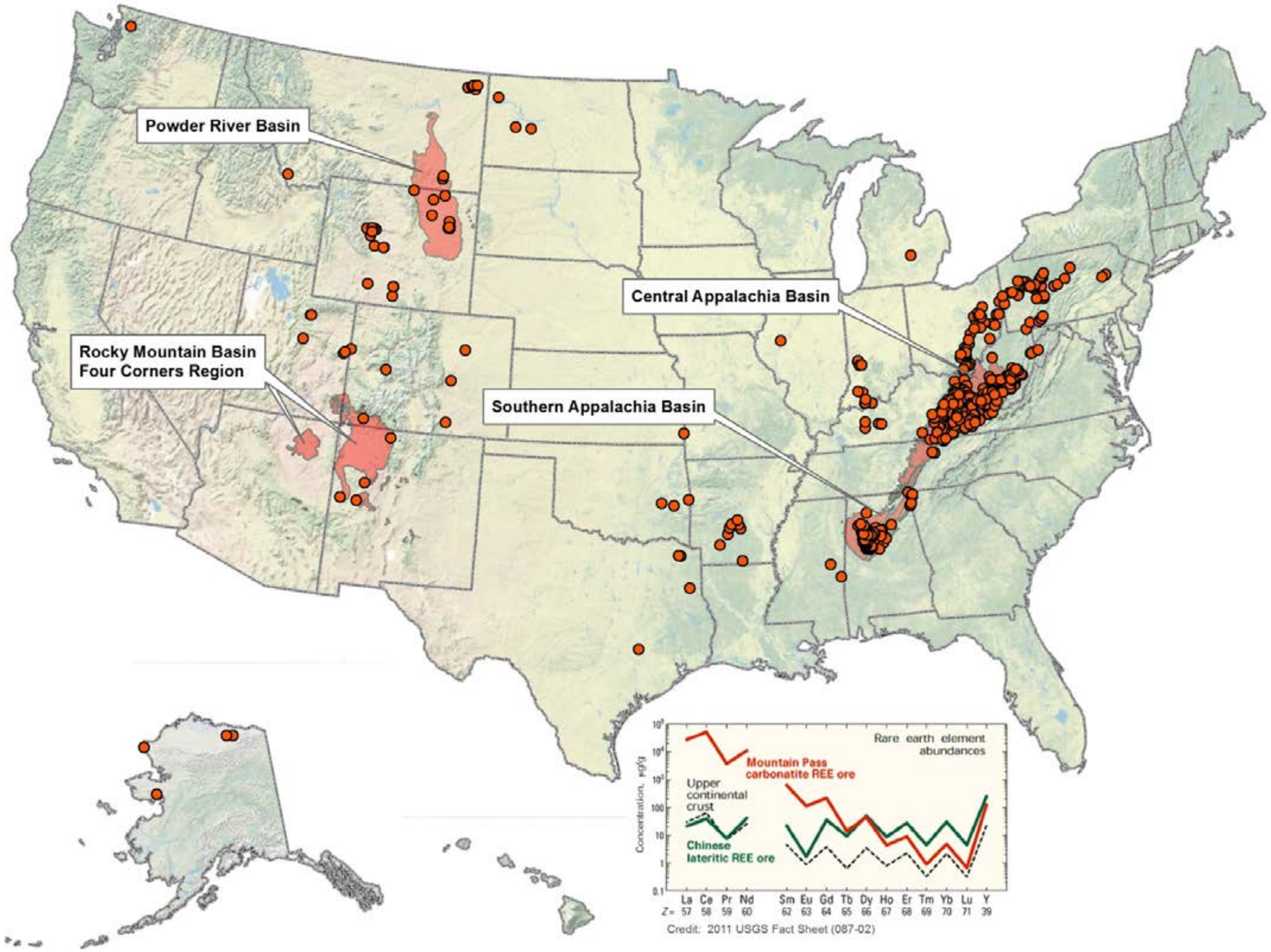
A subset of all U.S. coal formations have been found to contain levels of REE above crustal averages.

For each of the four regions identified, the average value for all samples with a total REE concentration on an ash-only basis greater than 700 ppm were calculated to be greater than 900 ppm and less than 1000 ppm.



Coals with significant amounts of Heavy REE

Assessment of candidate regions suggests that HREE+ Y, in coals with >700 ppm total REE, represented 25 to 40% of amount of total REE for the samples in the COALQUAL database



Systems Engineering and Analysis

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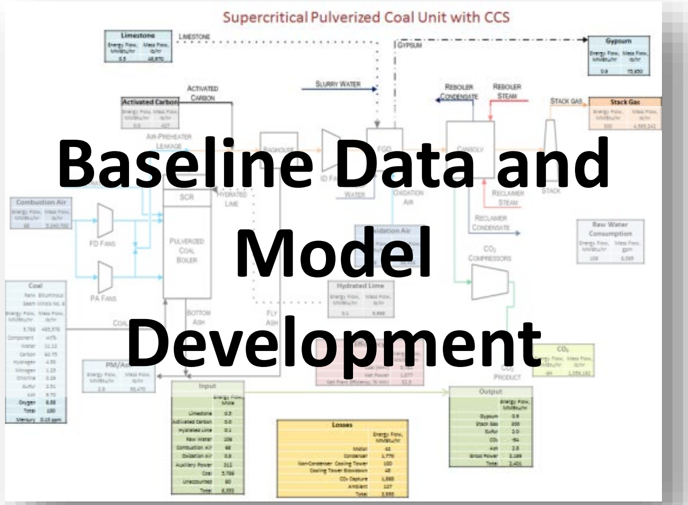
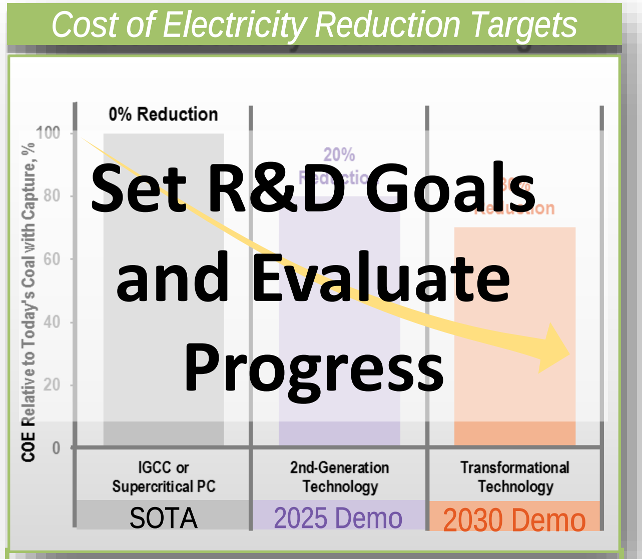
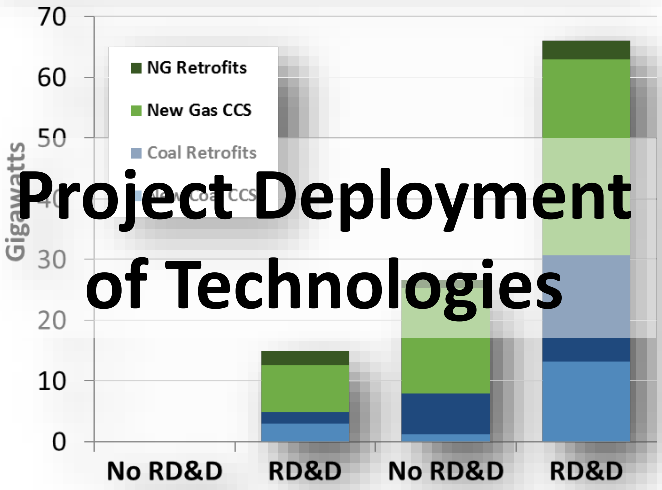


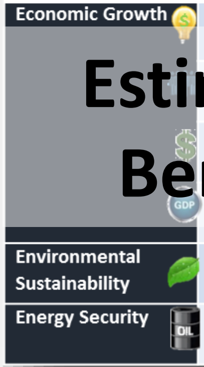
Baseline Data and Model Development



Set R&D Goals and Evaluate Progress



Project Deployment of Technologies



U.S. Benefits of the Program, Cumulative through 2040

Benefit Area	Metric
Economic Growth	Total Electricity Expenditure Savings
	Income
	Gross Domestic Product (GDP)
Environmental Sustainability	CO_2 Captured at Coal and Gas CCS Facilities
Energy Security	Additional Domestic Oil Production via EOR

Estimate Potential Benefits of R&D

Objectives of Systems Analysis

- **Understand the cost and performance of rare earth element (REE) concentration and separation from a fossil based feedstocks**
- **Identify cost and performance R&D needs in the extraction of REEs from fossil based feedstocks**
- **Evaluate the economic benefits of in-house transformational processes within the REE supply chain**

Initial Vision

- **Build a high level generic process and economic model for concentrating and separating REEs from all coal based feedstocks**
- **Use this baseline process to calculate the cost and performance for processing REEs from various samples that were collected**

It was gonna be great… One Process to Rule Them All…

Reality…

- **Concentrating and separating REEs into a pure salable product, from any raw feedstock, is a painstaking process that involves chaining highly customized physical and chemical processing steps in sequence to achieve the desired products.**

What do we need to know to build a process?

- **Find a specific feedstock**
- **Analyze everything about the feedstock**
- **Begin developing a metallurgical flow diagram of the required processes.**
  - Physical Beneficiation: crushing, grinding, magnetic separation, gravity separation, flotation, floatation with reagents (depressant, collector, frother).
    - Unusual or complex arrangements of multiple processes may be required.
  - Hydrometallurgical Processing: decomposition of REE containing minerals and leaching of REEs into solution
  - REE Separation: solvent extraction, ion-exchange, chemical precipitation, or novel approach (MRT, rare earth salts, electrophoresis, affinity chromatography)

Understanding the Process and its Cost

- **Problems: Most of the global REE processing occurs in China but information about the processes used and especially the costs associated with these processes are limited**
- **Other options?**
  - REE price spike in 2010 and 2011 spurred the development of many REE projects globally, mostly by junior mining companies

Rare Earth Projects: North America

- **Sources of information for proposed projects**
  - National Instrument (NI) 43-101 is a national instrument for the *Standards of Disclosure for Mineral Projects* within Canada. The Instrument is a codified set of rules and guidelines for reporting and displaying information related to mineral properties owned by, or explored by, companies which report these results on stock exchanges within Canada. All entities that trade on Canadian stock exchanges must submit an NI 43-101 for any mineral project in development.
- **Any projects utilizing a feedstock similar to coal-based feedstocks**
  - Orbite, Canada
  - Mineracao Serra Verde, Brasil
  - Tantalus Rare Earths, Madagascar

REE Economic Challenges

- **Traditional processing methods for concentrating and separating REEs from a feedstock have high capital and operating costs**
- **Each feedstock has a unique process with a unique set of capital and operating expenses**
- **Impurities within the feedstock can have a high disposal cost if concentrated**
- **REE market has demonstrated volatility due to external forces**
- **Market prices for intermediate REE concentrates are not readily available and are usually negotiated privately**

Challenges to Recovering REEs from Coal

- **Low concentrations of REE (300- 1000ppm)**
  - Mountain pass 8%, Bayan Obo 6%, Ion Adsorption Clays from China 0.05% to 0.5%
- **Combustion increases concentrations but REEs become encapsulated in fly ash**
- **Disposal fees for impurities (Th & U) can be high if concentrated**
- **No commercial precedence for recovering REEs from coal by-products**

Economic Model

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- **Developed a flexible discounted cashflow model to help evaluate proposed REE projects**
- **Model Inputs: CAPEX, O&M, financing scenario (D/E ratio, tax rate, cost of debt, cost of equity, payback period), construction period, plant life, deprecation rate, feedstock price, product prices**
- **Flexible Model Outputs: required return on investment (IRROE), product prices (basket price), NPV**

Model Uses

- Independently evaluate project capital and operating expenses
- Evaluate a wide range of financing scenarios to determine favorable economics (i.e. tax incentives, guaranteed product pricing, government loans, funding, etc.)
- Conduct sensitivities around product recovery rates and consumable usage
- Highlight processing bottlenecks to be solved by R&D
- Help develop an economic path to producing REEs from coal

Initial Conclusions: Path to an Economic Process

- **Design process around a specific feedstock**
- **Produce salable products from a high percentage of the feed**
- **Minimize operating expenses when possible**
- **Minimize waste disposal**

Path Forward

- Identify specific feedstocks
- Demonstrate that coal is a viable source for REEs
- Identify RD&D opportunities to improve the extraction of REEs from coal to improve economics and efficiencies
- Further development of a vertically integrated REE supply chain
- Evaluate other markets for coal that maybe enabled through the production of REEs

What if….

Series of Processes

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“Pilot, Pilot, Pilot.” –
John Goode (REE Expert, IMPC 2016)

Response when asked, “what’s the secret to building a successful REE recovery project in the US?”