

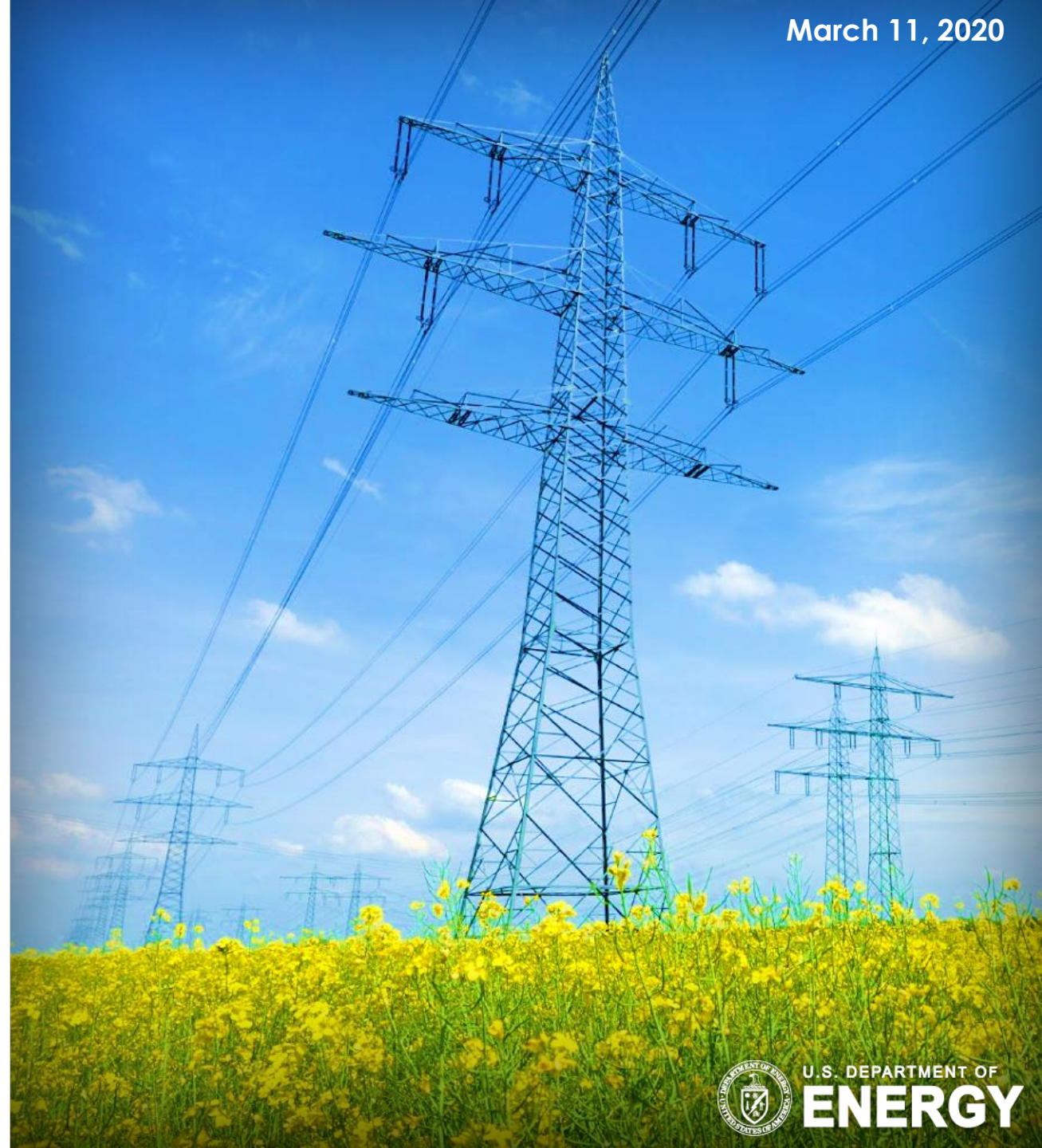
# Rare Earth Elements

*New Value Streams for Coal,  
New Products for Appalachia*

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# What are Rare Earth Elements (REEs)?

Periodic Table of the Elements

Element symbol represents state at room temperature.  
Solid, Liquid or Gas

Atomic Number, Atomic Mass, Symbol, Name, Electron Shells, Electron Configuration

1	2																	18
1	2																	2
3	4																	10
11	12																	18
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	
55	56	57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	
87	88	89-103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	

57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

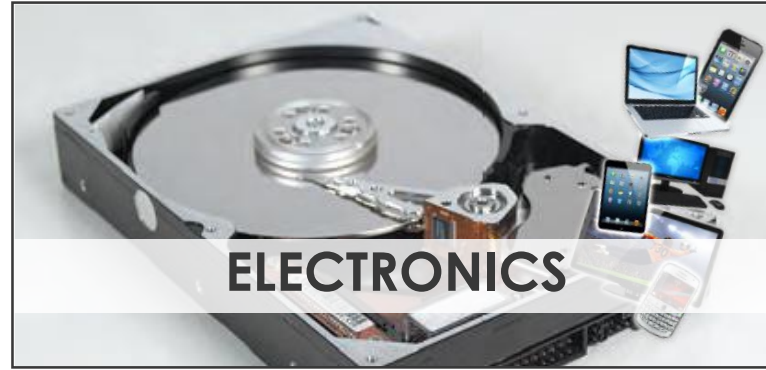
- Alkali Metal
- Alkaline Earth
- Transition Metal
- Basic Metal
- Metalloid
- Nonmetal
- Halogen
- Noble Gas
- Lanthanide
- Actinide

Average total crustal concentration = 184 ppm  
\*Wedephol, 1995

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# What are Rare Earth Elements Used For?



21 44.956 <b>Sc</b> Scandium 2 8 18 19 2 (Ar)3d <sup>1</sup> 4s <sup>2</sup>	57 138.905 <b>La</b> Lanthanum 2 8 18 19 2 (Xe)5d <sup>1</sup> 6s <sup>2</sup>	58 140.116 <b>Ce</b> Cerium 2 8 18 20 8 2 (Xe)4f <sup>1</sup> 5d <sup>1</sup> 6s <sup>2</sup>	59 140.908 <b>Pr</b> Praseodymium 2 8 18 21 8 2 (Xe)4f <sup>3</sup> 6s <sup>2</sup>	60 144.243 <b>Nd</b> Neodymium 2 8 18 22 8 2 (Xe)4f <sup>4</sup> 6s <sup>2</sup>	61 144.913 <b>Pm</b> Promethium 2 8 18 23 8 2 (Xe)4f <sup>5</sup> 6s <sup>2</sup>	62 150.36 <b>Sm</b> Samarium 2 8 18 24 8 2 (Xe)4f <sup>6</sup> 6s <sup>2</sup>	63 151.964 <b>Eu</b> Europium 2 8 18 25 9 2 (Xe)4f <sup>7</sup> 6s <sup>2</sup>	64 157.25 <b>Gd</b> Gadolinium 2 8 18 25 9 2 (Xe)4f <sup>7</sup> 5d <sup>1</sup> 6s <sup>2</sup>	65 158.925 <b>Tb</b> Terbium 2 8 18 27 8 2 (Xe)4f <sup>9</sup> 6s <sup>2</sup>	66 162.500 <b>Dy</b> Dysprosium 2 8 18 28 8 2 (Xe)4f <sup>10</sup> 6s <sup>2</sup>	67 164.930 <b>Ho</b> Holmium 2 8 18 29 8 2 (Xe)4f <sup>11</sup> 6s <sup>2</sup>	68 167.259 <b>Er</b> Erbium 2 8 18 30 8 2 (Xe)4f <sup>12</sup> 6s <sup>2</sup>	69 168.934 <b>Tm</b> Thulium 2 8 18 31 8 2 (Xe)4f <sup>13</sup> 6s <sup>2</sup>	70 173.055 <b>Yb</b> Ytterbium 2 8 18 32 8 2 (Xe)4f <sup>14</sup> 6s <sup>2</sup>	71 174.967 <b>Lu</b> Lutetium 2 8 18 32 9 2 (Xe)4f <sup>14</sup> 5d <sup>1</sup> 6s <sup>2</sup>
39 88.906 <b>Y</b> Yttrium 2 8 18 9 2 (Kr)4d <sup>1</sup> 5s <sup>2</sup>	89 227.028 <b>Ac</b> Actinium 2 8 18 32 18 9 2 (Rn)6d <sup>1</sup> 7s <sup>2</sup>	90 232.038 <b>Th</b> Thorium 2 8 18 32 18 10 2 (Rn)6d <sup>2</sup> 7s <sup>2</sup>	91 231.036 <b>Pa</b> Protactinium 2 8 18 32 20 9 2 (Rn)5f <sup>2</sup> 6d <sup>1</sup> 7s <sup>2</sup>	92 238.029 <b>U</b> Uranium 2 8 18 32 21 9 2 (Rn)5f <sup>3</sup> 6d <sup>1</sup> 7s <sup>2</sup>	93 237.048 <b>Np</b> Neptunium 2 8 18 32 23 8 2 (Rn)5f <sup>4</sup> 6d <sup>1</sup> 7s <sup>2</sup>	94 244.064 <b>Pu</b> Plutonium 2 8 18 32 24 8 2 (Rn)5f <sup>6</sup> 7s <sup>2</sup>	95 243.061 <b>Am</b> Americium 2 8 18 32 25 8 2 (Rn)5f <sup>7</sup> 7s <sup>2</sup>	96 247.070 <b>Cm</b> Curium 2 8 18 32 25 9 2 (Rn)5f <sup>7</sup> 6d <sup>1</sup> 7s <sup>2</sup>	97 247.070 <b>Bk</b> Berkelium 2 8 18 32 27 8 2 (Rn)5f <sup>9</sup> 7s <sup>2</sup>	98 251.080 <b>Cf</b> Californium 2 8 18 32 28 8 2 (Rn)5f <sup>10</sup> 7s <sup>2</sup>	99 [254] <b>Es</b> Einsteinium 2 8 18 32 29 8 2 (Rn)5f <sup>11</sup> 7s <sup>2</sup>	100 257.095 <b>Fm</b> Fermium 2 8 18 32 30 8 2 (Rn)5f <sup>12</sup> 7s <sup>2</sup>	101 258.1 <b>Md</b> Mendelevium 2 8 18 32 31 8 2 (Rn)5f <sup>13</sup> 7s <sup>2</sup>	102 259.101 <b>No</b> Nobelium 2 8 18 32 32 8 2 (Rn)5f <sup>14</sup> 7s <sup>2</sup>	103 [262] <b>Lr</b> Lawrencium 2 8 18 32 32 9 2 (Rn)5f <sup>14</sup> 6d <sup>1</sup> 7s <sup>2</sup>

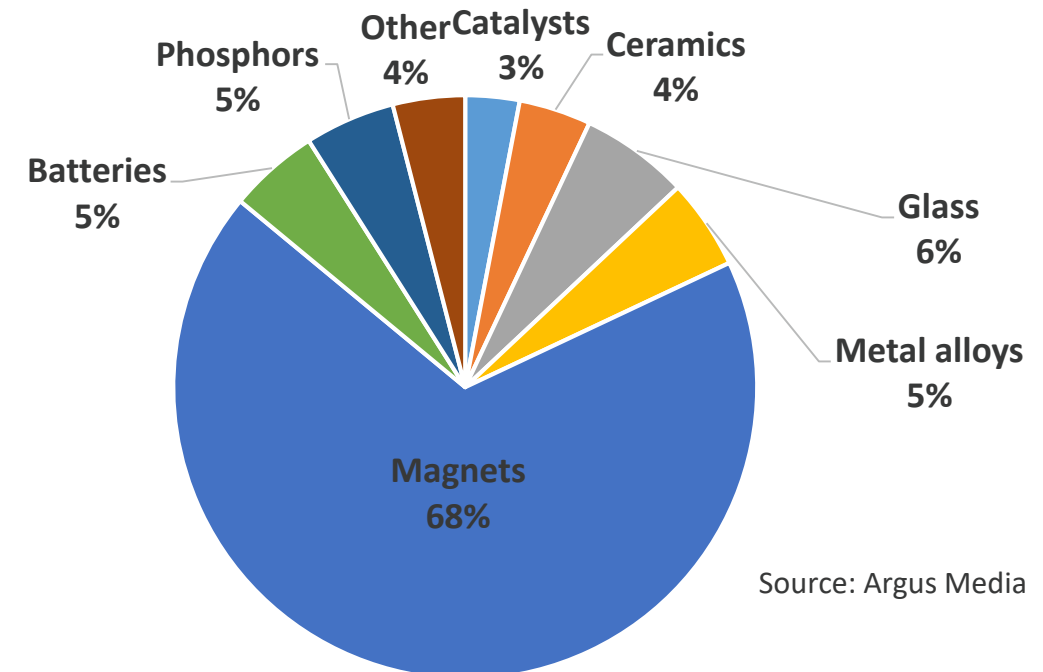


Average total crustal concentration = 184 ppm

\*Wedephol, 1995

# 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)

# 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

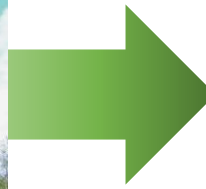
- Direct water conditioning to remove over 85% of REE down to parts per trillion (ppt)
- Creating high purity (96wt%) REE products from AMD sludge & treatment solids
- Potential to extract other high value minerals: Cobalt, Alumina, and more



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



**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%**

### Average Percentage Consumption from 2005-2015

