Recycling and secondary sources of the rare earth elements; why recycling is not yet a solution to REE shortages

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Rare Earth Elements… who cares?

- The REE (the 15 lanthanide elements plus Y and sometimes Sc) have distinctive physical and chemical properties that enable their use in a broad range of technologies.
- These elements provide unique magnetic, luminescence and strength characteristics to end-products they are used in.
- This has led to the REE being crucial to a wide range of modern technologies, including uses in magnets, batteries, glass, and alloys, all of which are critical to the manufacturing of modern computers, magnets, lasers, and screens.
- Makes the REE among the most critical of the critical elements.
<table>
<thead>
<tr>
<th>Element</th>
<th>Common uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>La</td>
<td>Optics, batteries, catalysis</td>
</tr>
<tr>
<td>Ce</td>
<td>Chemical applications, colouring, catalysis</td>
</tr>
<tr>
<td>Pr</td>
<td>Magnets, lighting, optics</td>
</tr>
<tr>
<td>Nd</td>
<td>Magnets, lighting, lasers, optics</td>
</tr>
<tr>
<td>Pm</td>
<td>Limited use due to radioactivity, used in paint and atomic batteries; very rare in nature</td>
</tr>
<tr>
<td>Sm</td>
<td>Magnets, lasers, masers</td>
</tr>
<tr>
<td>Eu</td>
<td>Lasers, colour TV, lighting, medical applications</td>
</tr>
<tr>
<td>Gd</td>
<td>Magnets, glassware, lasers, X-ray generation, computer applications, medical applications</td>
</tr>
<tr>
<td>Tb</td>
<td>Lasers, lighting</td>
</tr>
<tr>
<td>Dy</td>
<td>Magnets, lasers</td>
</tr>
<tr>
<td>Ho</td>
<td>Lasers</td>
</tr>
<tr>
<td>Er</td>
<td>Lasers, steelmaking</td>
</tr>
<tr>
<td>Tm</td>
<td>X-ray generation</td>
</tr>
<tr>
<td>Yb</td>
<td>Lasers, chemical industry applications</td>
</tr>
<tr>
<td>Lu</td>
<td>Medical applications, chemical industry applications</td>
</tr>
<tr>
<td>Sc</td>
<td>Alloys in aerospace engineering, lighting</td>
</tr>
<tr>
<td>Y</td>
<td>Lasers, superconductors, microwave filters, lighting</td>
</tr>
</tbody>
</table>
Rare Earth Elements... who cares?

Source: China Water Risk report. “Rare Earths: Shades Of Grey – Can China continue to fuel our clean and smart future?” (June 2016)
Rare Earth Elements... who cares?
Rare Earth Elements... who cares?

**ELEMENTS OF A SMARTPHONE**

**SCREEN**
- Indium tin oxide is a mixture of indium oxide and tin oxide, used in transparent film in the screen that conducts electricity. This allows the screen to function as a touch screen.
- The glass used on the majority of smartphones is an aluminosilicate glass, composed of a mix of aluminium (Al2O3) and silica (SiO2). This glass also contains potassium ions, which help to strengthen it.
- A variety of Rare Earth Elements compounds are used in small quantities to produce the colours in the smartphone’s screen. Some compounds are also used to reduce UV light penetration into the phone.

**ELECTRONICS**
- Copper is used for wiring in the phone, whilst copper, gold and silver are the major metals from which microelectrical components are fashioned. Tantalum is the major component of micro-capacitors.
- Nickel is used in the microphone as well as for other electrical connections. Alloys including the elements praseodymium, gadolinium and neodymium are used in the magnets in the speaker and microphone. Neodymium, terbium and dysprosium are used in the vibration unit.
- Pure silicon is used to manufacture the chip in the phone. It is oxidised to produce non-conducting regions, then other elements are added in order to allow the chip to conduct electricity.
- Tin & lead are used to solder electronics in the phone. Newer lead-free solders use a mix of tin, copper and silver.

**BATTERY**
- The majority of phones use lithium-ion batteries, which are composed of lithium cobalt oxide as a positive electrode and graphite (carbon) as the negative electrode. Some batteries use other metals, such as manganese, in place of cobalt. The battery’s casing is made of aluminium.

**CASING**
- Magnesium compounds are alloyed to make some phone cases, whilst many are made of plastics. Plastics will also include flame retardant compounds, some of which contain bromine, whilst nickel can be included to reduce electromagnetic interference.
Where are rare earths used at home?

1. Energy-efficient fridges
2. Wind turbines that supply electricity
3. Display screens, speakers, vibration units and circuitry in smartphones
4. Colour displays in television screens
5. Batteries for hybrid cars
6. Special glass, such as used in welding visors
7. Optical glasses, such as camera and telescope lenses
8. Computer display screens, speakers and hard drives
9. Fluorescent lighting
Rare Earth Elements... who cares?

- LCD screen
  - Europium
  - Yttrium
  - Cerium

- Glass and mirrors polishing powder
  - Cerium

- Component sensors
  - Yttrium

- Hybrid electric motor and generator
  - Neodymium
  - Praseodymium
  - Dysprosium
  - Terbium

- UV cut glass
  - Cerium

- Diesel fuel additive
  - Cerium
  - Lanthanum

- Hybrid NiMH battery
  - Lanthanum
  - Cerium

- Headlight glass
  - Neodymium

- 25+ electric motors throughout vehicle
  - Neodymium magnets

- Catalytic converter
  - Cerium
  - Lanthanum
Rare Earth Elements… who cares?

- Military applications, e.g. aircraft components, missile guidance systems, antimissile defense, range finding, communications...
  - AIM-9X Sidewinder
  - Nd:YAG designator-range finder laser
  - Avionics with REE phosphors
  - La-optics
  - Laser targeting system
Nd:YAG laser technology
(neodymium-doped yttrium aluminium garnet; Nd:Y₃Al₅O₁₂)
Not just military lasers but also energy research

National Ignition Facility (NIF)
Lenz’s Law in action; dropping a Nd magnet through a Cu pipe
Lenz’s Law in action; dropping a Nd magnet through a Cu pipe
Nd magnet and magnetic putty
Rare Earth Elements… who cares?

- The REE are also crucial for green technologies and low CO$_2$ energy generation
- World Bank estimates suggest that wind technologies alone will require large amounts of the REE (e.g. Nd) if CO$_2$ targets are to be met
- Effectively means to move to lower CO$_2$ futures we need lots more metal, especially the critical metals (including the REE)
Rare Earth Elements… who cares?

**FIGURE 2.2** Ranges for Cumulative Neodymium Demand for Global Wind Turbine Production through 2050

- Onshore wind goes from 10% to 25% of capacity being direct drive by 2050, and direct drive retains a 75% market share in offshore wind.
- Onshore wind goes from 10% to 50% of capacity being direct drive by 2050, and direct drive retains 75% market share in offshore wind.

Current total annual neodymium production: 7,000 tons
# USDoe Critical Materials Strategy

**Key Material Addressed in Strategy:**

<table>
<thead>
<tr>
<th>H</th>
<th>Li</th>
<th>Be</th>
<th>B</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>F</th>
<th>Ne</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Li</td>
<td>4 Be</td>
<td>11 Na</td>
<td>12 Mg</td>
<td>19 K</td>
<td>20 Ca</td>
<td>21 Sc</td>
<td>22 Ti</td>
<td>23 V</td>
</tr>
<tr>
<td>27 Co</td>
<td>28 Ni</td>
<td>29 Cu</td>
<td>30 Zn</td>
<td>31 Ga</td>
<td>32 Ge</td>
<td>33 As</td>
<td>34 Se</td>
<td>35 Br</td>
</tr>
<tr>
<td>36 Kr</td>
<td>37 Rb</td>
<td>38 Sr</td>
<td>39 Y</td>
<td>40 Zr</td>
<td>41 Nb</td>
<td>42 Mo</td>
<td>43 Tc</td>
<td>44 Ru</td>
</tr>
<tr>
<td>45 Rh</td>
<td>46 Pd</td>
<td>47 Ag</td>
<td>48 Cd</td>
<td>49 In</td>
<td>50 Sn</td>
<td>51 Sb</td>
<td>52 Te</td>
<td>53 I</td>
</tr>
<tr>
<td>54 Xe</td>
<td>55 Cs</td>
<td>56 Ba</td>
<td>72 Hf</td>
<td>73 Ta</td>
<td>74 W</td>
<td>75 Re</td>
<td>76 Os</td>
<td>77 Ir</td>
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<tr>
<td>78 Pt</td>
<td>79 Au</td>
<td>80 Hg</td>
<td>81 Tl</td>
<td>82 Pb</td>
<td>83 Bi</td>
<td>84 Po</td>
<td>85 At</td>
<td>86 Rn</td>
</tr>
<tr>
<td>87 Fr</td>
<td>88 Ra</td>
<td>104 Rf</td>
<td>105 Db</td>
<td>106 Sg</td>
<td>107 Bh</td>
<td>108 Hs</td>
<td>109 Mt</td>
<td>110Ds</td>
</tr>
<tr>
<td>111 Rg</td>
<td>112 Cn</td>
<td>113 Uut</td>
<td>114 Uuo</td>
<td>115 Uup</td>
<td>116 Uuh</td>
<td>117 Uus</td>
<td>118 Uuo</td>
<td></td>
</tr>
</tbody>
</table>

**Lanthanides:**

| 57 La | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb |
| 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | 71 Lu |

**Actinides:**

| 89 Ac | 90 Th | 91 Pa | 92 U | 93 Np | 94 Pu | 95 Am | 96 Cm | 97 Bk |
| 98 Cf | 99 Es | 100 Fm | 101 Md | 102 No | 103 Lr |
Criticality for clean/green energy uses

Recycling of the REE

- Current global primary REE production is about 130,000 metric tons of rare-earth oxide (REO) equivalent content per year.
- Majority of REE consumption is by mature markets (e.g., catalysts, glassmaking, lighting and metallurgy; ~59%).
- Newer high growth markets such as magnets, ceramics and batteries take up the remaining 41%.
- Global demand for these elements has steadily increased although vast majority of demand for the REE is met by primary production, primarily from China (although some being mined down the I-15).
- One major issue; only 1% of the REE is recycled…
- But hold on, why do we need to recycle?
Primary REE production

- China
- USA
- India
- Australia
- Other
## Elemental recycling rates (UNEP, 2011)

<table>
<thead>
<tr>
<th>Element</th>
<th>Recycling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actinides</td>
<td>&gt;50%</td>
</tr>
<tr>
<td>Lanthanides</td>
<td>&gt;25-50%</td>
</tr>
<tr>
<td>Others</td>
<td>&gt;10-25%</td>
</tr>
</tbody>
</table>

### Periodic Table

<table>
<thead>
<tr>
<th>Period</th>
<th>Group</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Metals</td>
<td>H, He</td>
</tr>
<tr>
<td>2</td>
<td>Alkali Metals</td>
<td>Li, Be, B, C, N, O, F, Ne</td>
</tr>
<tr>
<td>3</td>
<td>Alkaline Earth Metals</td>
<td>Na, Mg</td>
</tr>
<tr>
<td>4</td>
<td>Transition Metals</td>
<td>K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr</td>
</tr>
<tr>
<td>5</td>
<td>Pnic</td>
<td>Al, Si, P, S, Cl, Ar</td>
</tr>
<tr>
<td>6</td>
<td>Sore</td>
<td>As, Se, Br, Kr</td>
</tr>
<tr>
<td>7</td>
<td>Halogen</td>
<td>Br, Kr</td>
</tr>
<tr>
<td>8</td>
<td>Noble Gases</td>
<td>Kr, Xe, Rn</td>
</tr>
</tbody>
</table>

### Elements with Specific Recycling Rates

- **Actinides**: >50%
- **Lanthanides**: >25-50%
- **Others**: >10-25%
DEPARTMENT OF THE INTERIOR

Office of the Secretary

[178D0102DM, DS6CS00000, DLSN00000.000000, DX.6CS25]

Final List of Critical Minerals 2018

AGENCY: Office of the Secretary, Interior.

ACTION: Notice.

SUMMARY: The United States is heavily reliant on imports of certain mineral commodities that are vital to the Nation’s security and economic prosperity. This dependency of the United States on foreign sources creates a strategic vulnerability for both its economy and military to adverse foreign government action, natural disaster, and other events that can disrupt supply of these key minerals. Pursuant to Executive Order 13817 of December 20, 2017, “A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals,” the Secretary of the Interior
But hold on, why do we need to recycle?

- The REE are not rare compared to certain elements like gold, platinum and palladium, so why are they critical?
- The key issue is extraction; they are predominantly extracted from two mineral deposit types, carbonatites (enriched in the light REE like La, Ce, Pr) and ionic clays (enriched in the heavy REE, like Dy, Ho, Yb).
- Once mined, the REE need to be separated into individual elements or elemental compounds; energy intensive, and environmentally problematic.
- The REE are also associated with U and Th enrichments, creating both NORM and radioactive waste disposal issues.
Just down the I-15
This is what needs to be produced for the REE to be useful.
This is what needs to be produced for the REE to be useful
But this could be the cost; Bayan Obo, China
Atmospheric thorium pollution and inhalation exposure in the largest rare earth mining and smelting area in China

Lingqing Wang, Buqing Zhong, Tao Liang, Baoshan Xing, Yifang Zhu

HIGHLIGHTS

- Atmospheric thorium pollution was investigated around the Bayan Obo Rare Earth Mine.
- $^{232}$Th concentrations were significantly higher than the world reference of 0.2 ng m$^{-3}$.
- A self-organising map was used to identify spatio-temporal patterns of airborne thorium.
- The inhalation exposure results show a high radioactive risk for local dwellers.

ABSTRACT

Exposure to radionuclide thorium (Th) has generated widespread public concern, mainly because of its radiological effects on human health. Activity levels of airborne $^{232}$Th in total suspended particulate (TSP) were measured in the vicinity of the largest rare earth mine in China in August 2012 and March 2013. The mean activity concentrations of $^{232}$Th in TSP ranged from 820 Bq m$^{-3}$ in a mining area in August 2012 to 39,720 Bq m$^{-3}$ in a smelting area in March 2013, much higher than the world reference of 0.5 Bq m$^{-3}$. Multistatistical analysis and Kohonen’s self-organising maps suggested that $^{232}$Th in TSP was mainly derived from rare earth mining and smelting practices. In addition, personal inhalation exposures to $^{233}$Th associated with respirable particulate ($\text{PM}_{10}$) were also measured among local dwellers via personal monitoring. The mean dose values for different age groups in the smoking and non-smoking areas ranged from 57.86 to 417 μSv year$^{-1}$ and from 101.03 to 430.83 μSv year$^{-1}$, respectively. These results indicate that people living in the study area are exposed to high levels of widespread $^{232}$Th.
Other reasons to recycle the REE

- Security of supply also a key issue given trade discussions with China (and the fact that China could restrict REE supply on short notice)
- Mountain Pass remains the one REE producer in the US… but currently all production is exported to China for further processing
- Heavy mineral sands could produce LREE from monazite, but this again is discarded as low level radioactive waste rather than processed
- Multiple potential other sources, but none online, and there are social, environmental and potentially economic barriers to more primary production (e.g. Lynas)
- No other sources of the REE as yet…barring recycling
Malaysia environment groups, Lynas workers rally over rare earths plant

Liz Lee

KUALA LUMPUR (Reuters) - Malaysian environmental groups and Lynas Corp workers held rival demonstrations in Kuala Lumpur on Wednesday over concerns about radioactive waste from the company's rare earths processing plant in the country.

People take part in a protest calling on the government to suspend a rare earths processing plant in the country operated by Australia's Lynas Corp in Kuala Lumpur, Malaysia April 30, 2019. REUTERS/Liz Lee

Following the rallies outside the country's parliament, both groups handed statements to government representatives over the plant's license to operate, which is up for renewal in September.
Recycling to address security of supply

- We use a load of REE-bearing products; there are probably a large number in this room
- Why not extract the REE at their end-of-life; secure, domestic source of the REE?
- One other key issue with REE supply and demand is the balance problem; vast majority of REE production is dominated by La and Ce, whereas the vast majority of REE demand is for Nd or Dy
- Could lead to a situation where La and Ce are overproduced by primary production, but this primary production cannot meet Nd or Dy demand
- Recycling potentially can address this
Recycling of the REE

- This balance problem issue can at least partly be overcome by recycling
- Products that would be recycled predominantly contain potentially undersupplied Nd or Dy rather than the potentially overproduced lighter REE, e.g. La, Ce
- Not as easy as that… for one, not everything can be recycled
- Even the things that potentially can be recycled are currently not; 1% or less of the REE are currently recycled for a number of reasons
- Exemplified by barriers to e-waste recycling
What can and cannot be recycled?

End-uses \(\rightarrow\) Market shares

- **In-use dissipated**
  - Se, Mn in fertilizers
  - Al, Cu, Mg in pyrotechnics

- **Currently unrecyclable**
  - REEs in polishing powders
  - Al in steelmaking

- **Potentially recyclable**
  - Alloying elements recoverable/recyclable

- **Unspecified**
  - Miscellaneous applications

<table>
<thead>
<tr>
<th>Barriers to e-waste recycling</th>
<th>Applicable to the REE?</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-products contain small amounts of metals targeted for recycling (g to &lt;mg)</td>
<td>Yes</td>
</tr>
<tr>
<td>Lack of economic incentive to recycle as a result of low metal value per unit; primary sources used instead</td>
<td>Yes, after reduction in REE prices associated with removal of Chinese export restrictions in 2014</td>
</tr>
<tr>
<td>Current commercial recycling technologies cannot recover the small amounts of metals present in modern products</td>
<td>Yes, but laboratory experiments that may scale to industry may remove this barrier</td>
</tr>
<tr>
<td>End-products to be recycled contain a complex mixture of metals that change over time as a result of technological advances</td>
<td>Yes, although the recycling of mischmetals and REE alloys may remove some obstacles</td>
</tr>
<tr>
<td>End-product collection procedures are scarce or do not exist</td>
<td>Yes, although less the case for e.g. REE magnets</td>
</tr>
<tr>
<td>Prohibitive cost of the collection and transportation of end-products to recycling facilities</td>
<td>Unclear</td>
</tr>
<tr>
<td>The recycling process is not part of a collection chain that incorporates smelters</td>
<td>Unclear</td>
</tr>
<tr>
<td>End-product design and incorporation of target metals makes separation of recyclable material difficult</td>
<td>Yes</td>
</tr>
<tr>
<td>Public awareness of impending loss of crucial resources is low</td>
<td>Somewhat; the public are aware of the criticality of the REE but there are abundant REE resources already known</td>
</tr>
</tbody>
</table>
RECYCLING RATES OF SMARTPHONE METALS

COLOUR KEY: ● < 1% RECYCLE RATE ● 1–10% RECYCLE RATE ● 10–25% RECYCLE RATE ● 25–50% RECYCLE RATE ● > 50% RECYCLE RATE ● NON-METAL (OR RECYCLE RATE UNKNOWN)

SCREEN

TOUCH: INDIUM TIN OXIDE
Used in a transparent film over the phone's screen that conducts electricity. This allows the screen to function as a touch screen. This is the major use of indium.

GLASS: ALUMINA & SILICA
On most phones the glass is aluminosilicate glass, a mix of aluminium oxide & silicon dioxide. It also contains potassium ions which help strengthen it.

COLOURS: RARE EARTH METALS
A variety of rare earth metal-containing compounds are used to help to produce the colours in a smartphone's screen. Some of these compounds are also used to help reduce light penetration into the phone. Many of the 'rare earths' occur commonly in the Earth's crust, but often at levels too low to be economically extracted.

ELECTRONICS

WIRING & MICROELECTRONICS
Copper is used for wiring, and for micro-electrical components along with gold and silver. Tantalum is the major component in micro-capacitors.

MICROPHONES & VIBRATIONS
Nickel is used in the microphone and for electrical connections. Rare earth element alloys are used in magnets in the speaker and microphone, and the vibration unit.

THE SILICON CHIP
Pure silicon is used to manufacture the chip, which is then oxidised to produce non-conducting regions. Other elements are added to allow the chip to conduct electricity.

CONNECTING ELECTRONICS
Tin & lead were used in older solders: newer, lead-free solders use a mix of tin, copper & silver.

BATTERY

Most phones use lithium ion batteries, composed of lithium cobalt oxide as a positive electrode and graphite (carbon) as the negative electrode. Sometimes other metals, such as manganese, are used in place of cobalt. The battery casing is often made of aluminum.

CASING

Magnesium alloy is used to make some phone cases, whilst many others are made of plastics, which are carbon-based. Plastics will also include flame retardant compounds, some of which contain bromine, whilst nickel can be included to reduce electromagnetic interference.
Recycling of the REE

- Four main REE-bearing end-products (of many!) that are currently recycled in any major way:
  - Permanent magnets (Nd, Pr, Tb, Dy)
  - NiMH hydride batteries (La, Ce)
  - Lamp phosphors (Eu, Tb, Y, Ga, La, Ce)
  - Catalysts (Ce, Pr, Nd) – although at a very low level
### Current REE recycling sources and approaches

<table>
<thead>
<tr>
<th>Source for Recycling</th>
<th>Targeted REE</th>
<th>Primary Recycling Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Industrial Process &amp; Residues</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid Catalytic Cracking (FCC) Catalysts</td>
<td>LREE (La, Ce)</td>
<td>Hydrometallurgy, Microbial leaching</td>
</tr>
<tr>
<td>Other Industrial Process Residues</td>
<td>Depending on the source material, the REE recycling process can target differing REE</td>
<td>Pyrometallurgy, Hydrometallurgy, Physical separation and microbial leaching</td>
</tr>
<tr>
<td><strong>Waste Electric and Electronic Equipment (WEEE) &amp; 'End of Life' Consumer Goods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluorescent Material (phosphor powder, fluorescent lamps etc.)</td>
<td>La, Ce, Tb, Y</td>
<td>Pyrometallurgy, Hydrometallurgy, and Gas phase extraction</td>
</tr>
<tr>
<td>Magnets</td>
<td>Nd, Dy and other REE</td>
<td>Hydrometallurgy</td>
</tr>
<tr>
<td>Batteries</td>
<td>La, Ce, Pr, and Nd</td>
<td>Hydrometallurgy, Pyrometallurgy</td>
</tr>
</tbody>
</table>
Pyrometallurgical recovery; NiMH batteries

Elwert et al., 2016
Hydrometallurgical recovery; Nd magnets

Elwert et al., 2016
Bioleaching approach to catalyst recycling

Thompson et al., 2018
Recycling of the REE

- Future potential for the recycling of the REE is prevalent on the type of material being recycled.
- Laboratory-based research to date focused on developing potentially scalable approaches that would enable the broader recycling of the REE.
- One major issue is that the recycling of the REE currently requires extensive dismantling and the development of efficient collection infrastructure – not just a separation problem.
Recycling of the REE

- Currently a significant lack of cost effective methods to purify the mixtures generated during the recycling of consumer devices such as WEEE.
- Some possible approaches include binding organic compounds to REE cations; enables segregation of the LREE and HREE
- Much more to do in this area; modelling suggests significant outcomes if we can do better than 1%
- Even if not in terms of total tonnes of REE, then potential positive impact on balance problems
Recycling of the REE

### Possible REE recycling scenarios (Binnemans et al., 2013)

<table>
<thead>
<tr>
<th>REE application</th>
<th>Estimated REE stocks in 2020 (tons)</th>
<th>Estimated average lifetime (years)</th>
<th>Estimated REE old scrap in 2020 (tons)</th>
<th>Pessimistic scenario: recycled REE in 2020 (tons)</th>
<th>Optimistic scenario: recycled REE in 2020 (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets</td>
<td>300,000</td>
<td>15</td>
<td>20,000</td>
<td>3300</td>
<td>6600</td>
</tr>
<tr>
<td>Lamp Phosphors</td>
<td>25,000</td>
<td>6</td>
<td>4167</td>
<td>1333</td>
<td>2333</td>
</tr>
<tr>
<td>Nickel-metal-hydride batteries</td>
<td>50,000</td>
<td>10</td>
<td>5000</td>
<td>1000</td>
<td>1750</td>
</tr>
<tr>
<td>Total</td>
<td>375,000</td>
<td>29,167</td>
<td></td>
<td>5633</td>
<td>10,683</td>
</tr>
</tbody>
</table>

Pessimistic = 30% collection of REE in end-of-life materials, 55% recovery; Optimistic = 60% collection, 55% recovery.
Possible secondary sources?

- Optimistic scenario yields 10,683 t REE vs current production of 130,000 t REO primary production; but could help with balance and also reflects amount of scrap/recyclable material available (will increase over time)
- Recycling is just one possible response to perceived REE supply risks
- Secondary sources should also be investigated given significant potential REE resources in low-grade REE industrial residues (e.g. phosphogypsum, slags, bauxite residue (red mud), mine tailings, metallurgical slags, coal ash, incinerator ash and waste water streams)

Narayanan et al., 2018
Possible secondary sources?

- Recovering the REE from acid mine drainage and other mine wastes could also have economic, environmental, and strategic benefits.
- Supply side research should also focus on potential to adapt existing mines to process the REE (e.g. Olympic Dam in Australia; lots of REE, but no attempt to produce any).
- Other methods of recycling should also be researched, e.g. bioleaching has a much lower environmental footprint compared to other REE recycling methods.
Understanding flows; need to know where we use/lose metals
Conclusions

- The REE are among the most critical of the critical elements yet current efforts to recycle these valuable commodities remain seemingly relatively ineffective.
- Significant potential to increase the amount of the REE recycled from major end-uses, such as permanent magnets, fluorescent lamps, batteries, and catalysts.
- More research is needed in all of these areas to increase the amount of these elements that is recycled.
- Increased amounts of REE recycling can play a key role in addressing a number of criticality issues with these elements, including meeting increased demand, increasing their security of supply, and overcoming the balance problem.
And now, on a slightly lighter note, REE magnets in a blender

**did you know?**

This is what happens when you put Buckyballs (toy magnets made of the rare earth metal neodymium) in a blender: