I. Background

II. Analysis
   A. Supply
   B. Demand
   C. Criticality

III. Program and Policy Directions

IV. Next Steps
Project Timeline

- **March 2010 - Project launched**
  
  “I am today announcing that the Department of Energy will develop its first-ever strategic plan for addressing the role of rare earth and other strategic materials in clean energy technologies. “

  “As a society, we have dealt with these types of issues before...We can and will do so again.”

  David Sandalow
  Assistant Secretary for Policy and International Affairs
  U.S. Department of Energy
  March 17, 2010

- **June 2010 – Responses to public Request for Information**

- **Summer 2010 – Performed analysis, internal and inter-agency consultations, and drafted strategy**

- **December 2010 – Public release of the Critical Materials Strategy**

- **Spring 2011 – 2nd public Request for Information issued**

- **Fall 2011 – Release update of Critical Materials Strategy**
Strategic Pillars

- **Diversify global supply chains**
- **Develop substitutes**
- **Reduce, reuse and recycle**

Material supply chain with environmentally-sound processes
<table>
<thead>
<tr>
<th>Nation</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Australia</strong></td>
<td>Maintain mining <em>investment</em> while fairly taxing depletion of national resources</td>
</tr>
<tr>
<td><strong>Canada</strong></td>
<td>Promote <em>sustainable development</em> of mineral resources, protect environment, public health, and ensure attractive <em>investment</em> climate</td>
</tr>
<tr>
<td><strong>China</strong></td>
<td><em>Balance domestic and international market</em> through industry consolidation, mitigating overproduction and reducing illegal trade</td>
</tr>
<tr>
<td><strong>European Union</strong></td>
<td><em>Limit impact</em> of supply <em>shortages</em> on the European economy</td>
</tr>
<tr>
<td><strong>Japan</strong></td>
<td>Secure a <em>stable supply</em> of raw materials for industries</td>
</tr>
<tr>
<td><strong>Korea</strong></td>
<td>Ensure a <em>reliable supply</em> of materials for industries</td>
</tr>
<tr>
<td><strong>Netherlands</strong></td>
<td><em>Reduce material consumption</em> through “managed austerity”</td>
</tr>
</tbody>
</table>
II. Analysis
Rare earth metals are not rare – found in many countries including the United States

>95% of rare earth supply currently from China

Source: Industrial Minerals
Coproduction Complications

Materials analyzed for clean energy are often lower revenue co-products or byproducts and may not drive production decisions

<table>
<thead>
<tr>
<th>Material</th>
<th>Other Typical Extraction Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rare Earth Elements <em>(commonly found with thorium)</em></td>
<td>Iron  (Bautou mine)</td>
</tr>
<tr>
<td>Cobalt</td>
<td>Nickel and copper</td>
</tr>
<tr>
<td>Gallium</td>
<td>Aluminum and zinc</td>
</tr>
<tr>
<td>Indium</td>
<td>Zinc</td>
</tr>
<tr>
<td>Tellurium</td>
<td>Copper</td>
</tr>
</tbody>
</table>
# Current and Projected Rare Earth Supply by Element

## Rare Earth Supply by Element: Production Sources and Volume (tonnes/yr)

<table>
<thead>
<tr>
<th>Element</th>
<th>Estimated 2010 Production</th>
<th>Assumed Additional Production by 2015</th>
<th>Total Additional Production by 2015</th>
<th>Estimated 2015 Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lanthanum</td>
<td>33,887</td>
<td>3,900</td>
<td>6,640</td>
<td>585</td>
</tr>
<tr>
<td>Cerium</td>
<td>49,935</td>
<td>7,650</td>
<td>9,820</td>
<td>1,101</td>
</tr>
<tr>
<td>Praseodymium</td>
<td>6,292</td>
<td>600</td>
<td>868</td>
<td>120</td>
</tr>
<tr>
<td>Neodymium</td>
<td>21,307</td>
<td>2,250</td>
<td>2,400</td>
<td>423</td>
</tr>
<tr>
<td>Samarium</td>
<td>2,666</td>
<td>270</td>
<td>160</td>
<td>75</td>
</tr>
<tr>
<td>Europium</td>
<td>592</td>
<td>60</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Gadolinium</td>
<td>2,257</td>
<td>150</td>
<td>40</td>
<td>63</td>
</tr>
<tr>
<td>Terbium</td>
<td>252</td>
<td>15</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Dysprosium</td>
<td>1,377</td>
<td>30</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>Yttrium</td>
<td>8,750</td>
<td>0</td>
<td>20</td>
<td>474</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>127,315</strong></td>
<td><strong>14,925</strong></td>
<td><strong>19,968</strong></td>
<td><strong>2,913</strong></td>
</tr>
</tbody>
</table>

Sources: Kingsnorth, Roskill, and USGS
### Current and Projected Supply of Non-Rare Earth Elements

#### Supply of Other Elements Assessed: Production Sources and Volume (tonnes)

<table>
<thead>
<tr>
<th>Element</th>
<th>Estimated 2010 Production</th>
<th>Additional amount</th>
<th>Potential Sources of Additional Production between 2010 and 2015</th>
<th>Estimated 2015 Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indium</td>
<td>1,345</td>
<td>267</td>
<td>Recovery (co-produced) from additional zinc production mainly and recycling</td>
<td>1,612</td>
</tr>
<tr>
<td>Gallium</td>
<td>207</td>
<td>118$^{76}$</td>
<td>Recovery (co-produced) from additional alumina and bauxite production and recycling$^{77}$</td>
<td>325</td>
</tr>
<tr>
<td>Tellurium</td>
<td>500</td>
<td>720</td>
<td>Recovery (co-produced) from copper anode Slimes</td>
<td>1,220</td>
</tr>
<tr>
<td>Cobalt</td>
<td>75,900</td>
<td>197,830</td>
<td>Mines</td>
<td>273,730</td>
</tr>
<tr>
<td>Lithium (carbonate equivalent)</td>
<td>134,600</td>
<td>115,400</td>
<td>Mines$^{78}$</td>
<td>250,000</td>
</tr>
</tbody>
</table>

Sources: USGS 2008a-e and Evans 2010.

$^{76}$ For indium, the additional amount is only the difference between the 2010 production and the maximum current production capacity for mining and refining the material. No new capacity is projected by 2015.

$^{77}$ Based on multiple correspondences with USGS, October 4-7, 2010.

**Demand Projections: Four Trajectories**

**Material Demand Factors**

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Market Penetration</th>
<th>Material Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trajectory D</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Trajectory C</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Trajectory B</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Trajectory A</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

- **Market Penetration** = *Deployment* (total annual units of a clean energy technology) * Market Share (% of units using materials analyzed)
- **Material Intensity** = Material demand per unit of the clean energy technology
Low Technology Deployment Scenarios

**Electric Drive Vehicle Additions**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Million Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV</td>
<td></td>
</tr>
<tr>
<td>PHEV</td>
<td></td>
</tr>
<tr>
<td>HEV</td>
<td></td>
</tr>
</tbody>
</table>

**Wind Additions**

<table>
<thead>
<tr>
<th>Baseline</th>
<th>GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offshore</td>
<td></td>
</tr>
<tr>
<td>Onshore</td>
<td></td>
</tr>
</tbody>
</table>

**Global CFL Demand**

2.2% Growth

**Global PV Additions**

<table>
<thead>
<tr>
<th>Baseline</th>
<th>GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV additions</td>
<td></td>
</tr>
</tbody>
</table>
High Technology Deployment Scenarios

Electric Drive Vehicle Additions

Wind Additions

Global CFL Demand

Global PV Additions

IEA Energy Technology Perspectives

IEA World Energy Outlook

IEA: Phase Out of Incandescent Lights

Source: IEA estimated.
Material Intensity

<table>
<thead>
<tr>
<th>Technology</th>
<th>Component</th>
<th>Material</th>
<th>High Intensity</th>
<th>Low Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>Generators</td>
<td>Neodymium</td>
<td>186 kg/MW</td>
<td>124 kg/MW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dysprosium</td>
<td>33 kg/MW</td>
<td>22 kg/MW</td>
</tr>
<tr>
<td>Vehicles</td>
<td>Motors</td>
<td>Neodymium</td>
<td>0.62 kg/vehicle</td>
<td>0.31 kg/vehicle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dysprosium</td>
<td>0.11 kg/vehicle</td>
<td>0.055 kg/vehicle</td>
</tr>
<tr>
<td></td>
<td>Li-ion Batteries (PHEVs and EVs)</td>
<td>Lithium</td>
<td>5.1-12.7 kg/vehicle</td>
<td>1.4-3.4 kg/vehicle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cobalt</td>
<td>9.4 kg/vehicle</td>
<td>0 kg/vehicle</td>
</tr>
<tr>
<td></td>
<td>NiMH Batteries (HEVs)</td>
<td>Rare Earths (Ce, La, Nd, Pr)</td>
<td>2.2 kg/vehicle</td>
<td>1.5 kg/vehicle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cobalt</td>
<td>0.66 kg/vehicle</td>
<td>0.44 kg/vehicle</td>
</tr>
<tr>
<td>PV Cells</td>
<td>CIGS Thin Films</td>
<td>Indium</td>
<td>110 kg/MW</td>
<td>16.5 kg/MW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gallium</td>
<td>20 kg/MW</td>
<td>4 kg/MW</td>
</tr>
<tr>
<td></td>
<td>CdTe Thin Films</td>
<td>Tellurium</td>
<td>145 kg/MW</td>
<td>43 kg/MW</td>
</tr>
<tr>
<td>Lighting</td>
<td>Phosphors</td>
<td>Rare Earths (Y, Ce, La, Eu, Tb)</td>
<td>6715 metric tons* total demand in 2010, 2.2% (low) or 3.5% (high) annually</td>
<td></td>
</tr>
</tbody>
</table>

- *Calculation methods differed by component based on available data*
- *High Intensity = material intensity with current generation technology*
- *Low Intensity = intensity with feasible improvements in material efficiency*
Supply Chain for Rare Earth Element Permanent Magnet Technologies

• Illustrates the supply chain for vehicle and wind turbine applications using Neodymium-Iron-Boron (NdFeB) permanent magnets
This Year’s Rare Earth Price Volatility

Neodymium Oxides (Purity 99% min)

- Prices have been generally increasing over the past 10 years
- Prices have leveled off after rising dramatically over the past 18 months. (A year ago, Nd Oxide was about $30,000/ton

Source: Metal Pages
Clean energy’s share of total material use currently small... but could grow significantly with increased deployment.

**2010 Dysprosium Use**
- 84% Global Non-Clean Energy Demand
- 12% Rest of World Clean Energy Demand
- 4% US Clean Energy Demand

**2025 Dysprosium Use (High Deployment)**
- 53% Global Non-Clean Energy Demand
- 38% Rest of World Clean Energy Demand
- 9% US Clean Energy Demand

**Comparison:**
- 16% is for Clean Energy in 2010
- 62% is for Clean Energy in 2025 (High Deployment)
Clean energy’s share of total material use currently small

...but could grow significantly with increased deployment.

- **2010 Lithium Use**
  - 0% is for Clean Energy
  - 0% is for Rest of World Clean Energy Demand
  - 100% is for Global Non-Clean Energy Demand

- **2025 Lithium Use (High Deployment)**
  - 50% is for Clean Energy
  - 7% is for Rest of World Clean Energy Demand
  - 42% is for Global Non-Clean Energy Demand

< 1% is for Clean Energy

50% is for Clean Energy
Neodymium - Supply and Demand Projections

Neodymium Oxide Future Supply and Demand

**Demand**
- High Deployment, High Materials Intensity
- High Deployment, Low Material Intensity
- Low Deployment, High Material Intensity
- Low Deployment, Low Material Intensity
- Non-Clean Energy Use

**Supply**
- 2015 Estimated Supply
- Plus Mountain Pass
- Plus Mount Weld
- 2010 Supply
Dysprosium - Supply and Demand Projections

Dysprosium Oxide Future Supply and Demand

**Demand**
- High Deployment, High Materials Intensity
- High Deployment, Low Material Intensity
- Low Deployment, High Material Intensity
- Low Deployment, Low Material Intensity
- Non-Clean Energy Use

**Supply**
- 2015 Estimated Supply
- Plus Mountain Pass
- Plus Mount Weld
- 2010 Supply
Lithium – Supply and Demand Projections

Lithium Carbonate Future Supply and Demand

**Demand**
- High Deployment, High Materials Intensity
- High Deployment, Low Material Intensity
- Low Deployment, High Material Intensity
- Low Deployment, Low Material Intensity
- Non-Clean Energy Use

**Supply**
- 2015 Estimated Supply
- 2010 Supply
• Adapted from National Academy of Sciences methodology

• *Criticality* is a measure that combines
  • Importance to the clean energy economy
  • Clean Energy Demand; Substitutability Limitations
  • Risk of supply disruption
    • Basic Availability; Competing Technology Demand; Political, Regulatory and Social Factors; Co-Dependence on Other Markets; Producer Diversity

• Time frames:
  • Short-term (0-5 years)
  • Medium-term (5-15 years)
Medium-Term Criticality

<table>
<thead>
<tr>
<th>Importance to clean energy</th>
<th>Supply risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (high)</td>
<td>1 (low)</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>1 (low)</td>
<td>4 (high)</td>
</tr>
</tbody>
</table>

- Critical
- Near-critical
- Not Critical

- Gallium
- Indium
- Lithium
- Tellurium
- Europium
- Yttrium
- Terbium
- Cerium
- Cobalt
- Lanthanum
- Praseodymium
- Samarium
- Neodymium
- Dysprosium
Criticality Movement: Short to Medium Term

Importance to clean energy

<table>
<thead>
<tr>
<th>Importance to clean energy</th>
<th>Supply risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (low)</td>
<td>1 (low)</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4 (high)</td>
<td>4 (high)</td>
</tr>
</tbody>
</table>

Critical
Near-critical
Not Critical

Elements:
- Gallium, Tellurium, Lithium, Indium, Cerium, Lanthanum, Cobalt, Praseodymium, Samarium, Neodymium, Yttrium, Terbium, Dysprosium

Criticality levels:
- Critical
- Near-critical
- Not Critical
III. Program and Policy Directions
Program and Policy Directions

- Research and development
- Information-gathering
- Permitting for domestic production
- Financial assistance for domestic production and processing
- Stockpiles
- Recycling
- Education
- Diplomacy

*Some are within DOE’s core competence, others aren’t*
DOE’s Current Programs – Office of Science

Basic research at Ames Laboratory

- Extraordinarily Responsive Rare Earth Magnetic Materials
- Novel Materials Preparation and Processing Methodologies
- Correlations and Competition Between the Lattice, Electrons and Magnetism
- Nanoscale and Ultrafast Correlations and Excitations in Magnetic Materials
DOE’s Current Programs – EERE
Alternatives to permanent magnets and motors

Permanent Magnet Development for Automotive Traction Motors

**Ames Lab**

A New Class of Switched Reluctance Motors

**Oak Ridge**

Novel Flux Coupling Machine without Permanent Magnets

**Oak Ridge**

Development of Improved Powder for Bonded Permanent Magnets

**Ames Lab**

---

Source: Universal (Ningbo) Magnetech Co., Ltd.

Source: Honda Civic Hybrid 2003
DOE’s Current Programs:
ARPA-E Nanocomposite Permanent Magnets

Core@Shell Hard/Soft Exchange Spring Coupled Nanocomposite Magnets with:
- 80 MGOe (vs 59 MGOe NdFeB)
- 59 MGOe with 80% less rare earth

With low rare earth

Nanocomposite exchange spring coupled permanent magnets with high energy product and less rare earths
Recent DOE Critical Materials Workshops & International Meetings

• Japan-US Workshop (Lawrence Livermore National Lab - Nov 18-19, 2010)

• Transatlantic Workshop (MIT - Dec 3, 2010)

• ARPA-E Workshop (Ballston, VA – Dec 6, 2010)

• US- Australia Joint Commission Meeting (DC – Feb 14)
Conclusions

• Some materials analyzed at risk of supply disruptions.
  
  *Five rare earth metals (dysprosium, neodymium, terbium, europium and yttrium) and indium assessed as most critical.*

• Clean energy’s share of material use currently small
  
  *...but could grow significantly with increased deployment.*

• Critical materials are often a small fraction of the total cost of clean energy technologies.
  
  *Demand does not respond quickly when prices increase.*
Conclusions (continued)

• Data are sparse.  
  *More information is required.*

• Sound policies and strategic investments can reduce risk.  
  *...especially in the medium and long term.*
IV. Next Steps
Next Steps for U.S. Department of Energy

• Develop an *integrated research plan*, building on three recent workshops.
• Strengthen *information-gathering capacity*.
• Analyze additional technologies.
• Continue to work closely with:
  • *International partners*
  • *Interagency colleagues*
  • *Congress*
  • *Public stakeholders*
• *Update the strategy* by the end of 2011.
2011 RFI Topics

• Technology Critical Material Content
• Supply Chain and Market Projections
• Financing and Purchase Transactions
• Research, Education and Training
• Energy Technology Transitions and Emerging Technologies
• Recycling Opportunities
• Mine and Processing Plant Permitting
• Additional Information
Beginnings of an R&D Plan:
Technology R&D Topics from ARPA-E Workshop

Geologic or Recycled Feedstocks

Material Extraction & Separation Processes

Permanent Magnets

Catalysts & Separators

Lighting Phosphors

Electric Motors
Wind Generators

Solid Oxide Fuel Cells
Gasoline Refining
Auto Exhaust Conversion

Supply Technologies

Application Technologies

2011 EERE VTP Solicitation ($6 million)

2011 EERE Wind Power Drive Train Solicitation ($7.5 million)

2011 ARPA-E Solicitation ($30 million)

2012 Critical Materials Innovation Hub - $20 million/year
Next Week: EU-Japan-US Trilateral Seminar and R&D Workshop

• Seminar: Strategic Implications of Global Shortages of Critical Materials

• R&D Workshop Topics
  • Reducing Neodymium and Dysprosium Requirements for Permanent Magnets
  • Component and System-Level Substitutions for Rare Earth Materials
  • Materials and Processes for Environmentally Sound, Economical Separation of Rare Earths in Diverse Ore Bodies and Recycling Streams
  • Rare Earth Recycling Technologies and Optimization
New Interagency Working Group
Addressing Critical and Strategic Mineral Supply Chains

• Led by the White House Office of Science and Technology Policy (OSTP), the group includes multiple departments and agencies
  • DOE, DOD, USGS, DOC, EPA, DOJ, DOS and USTR
• Initial focus
  • Critical mineral prioritization and early warning mechanism
  • R&D prioritization
  • Responsible development of global supply chains
  • Transparency of information (both geologic and market)
DOE welcomes comments

Comments and additional information can be sent to materialstrategy@hq.doe.gov