Critical Elements and New Energy Technologies

Insights from a year-long study by†

American Physical Society's Panel on Public Affairs (POPA)

Materials Research Society

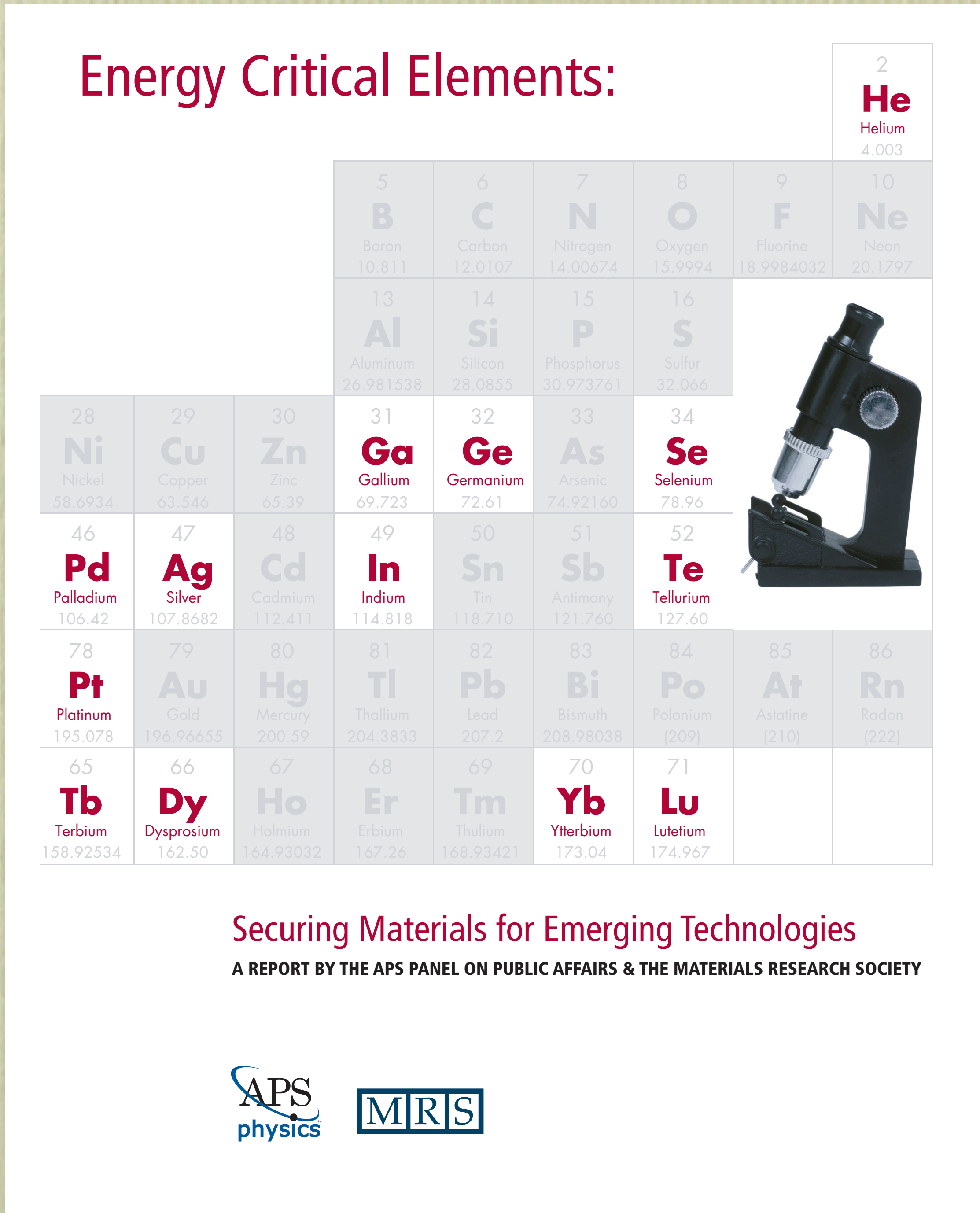
Physics, material science & engineering research

Physics & society policy studies

R L Jaffe

MIT

† Supported in part by MIT's Energy Initiative



---------------- **Material Science**

rgy

- **Economics / economic geology**

--------------- **Industrial ecology**

/ and Geophysics,

---------------- **Material science**

/Senior Metallurgist

-------------- **Economic geology**

------------- **Physical chemistry**

---------------- **Material science**

------------------------- **Physics**

----------------- **Material science**

------------- **Physical chemistry**

nair --- **Geology/mineral resources**

lines

------------------------- **Geology**

Principal take aways:

- "Energy Critical Elements" – a new category of chemical elements with common economic & scientific issues
- "Running out" – in general not the issue
- Constraints on availability; interruptions in supply – are the issues
- Domestic (US) mining   A component of a rational ECE policy, but no single country can/should want to be self-sufficient
- Features of a well-conceived federal policy:

Information – gather, digest, distribute information across the suppy chain

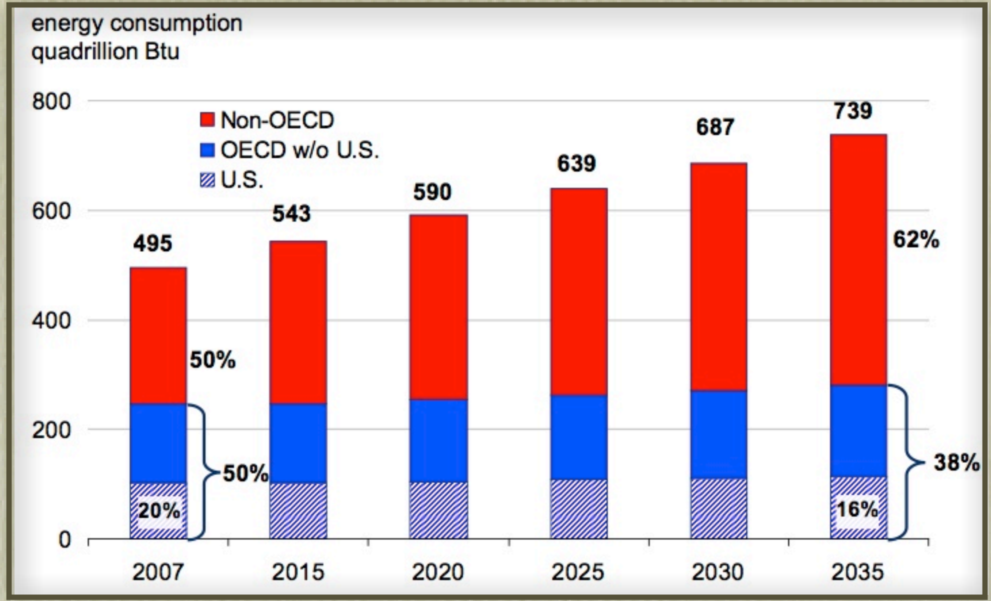
Research – across the supply chain, from geophysical to substitutional, physics, material science, engineering, policy...

Recycling – "More precious than gold", unsolved technical and economic problems

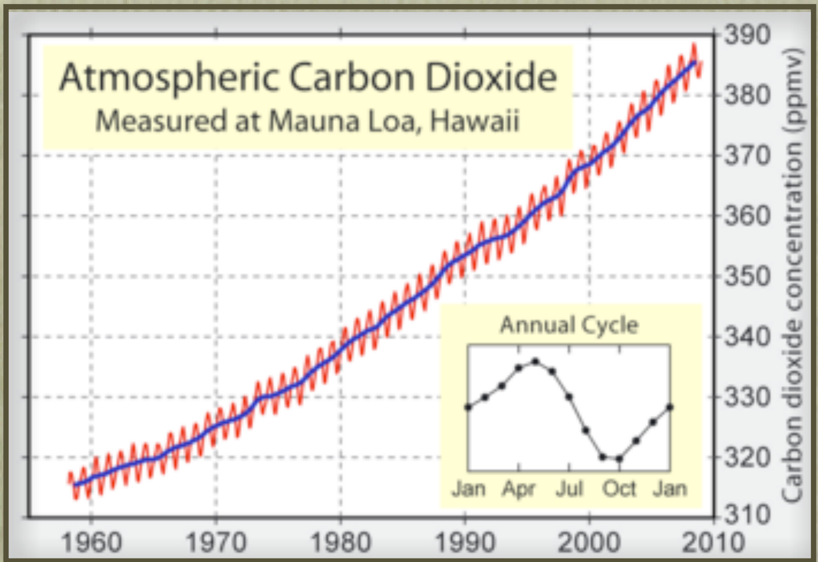
I Energy Critical Elements (ECEs)

- Increasing demand for energy

- Anthropogenic climate change

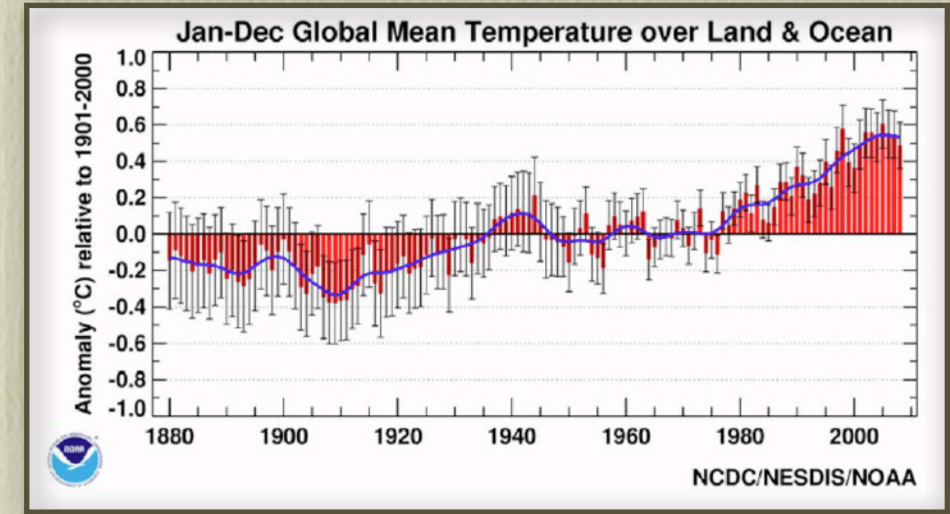


EIA International Energy Outlook 2010



The time series of atmospheric CO_2 concentration at Mauna Loa, Hawaii, started by Dave Keeling in 1958.

WHOI



National Oceanic and Atmospheric Administration

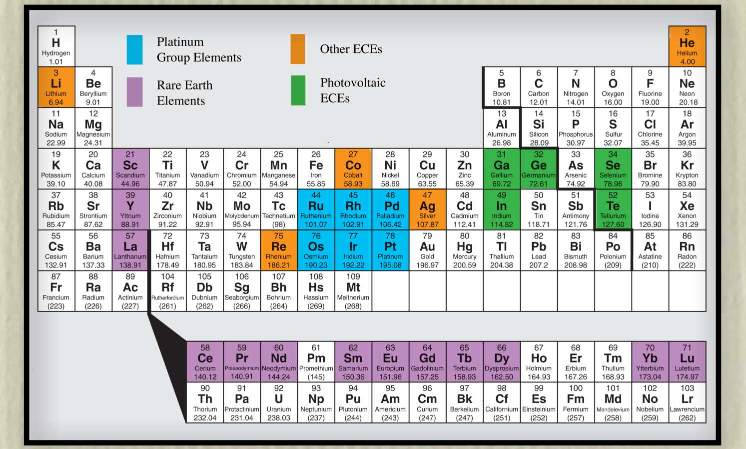
- Increasing demand for energy
- Anthropogenic climate change

→

New technologies for harvesting, transmitting, storing, or conserving energy!

Imaginative scientists & engineers

Employing the whole periodic table



Lab ⇒ Pilot ⇒ Massive Deployment

Materials intensive

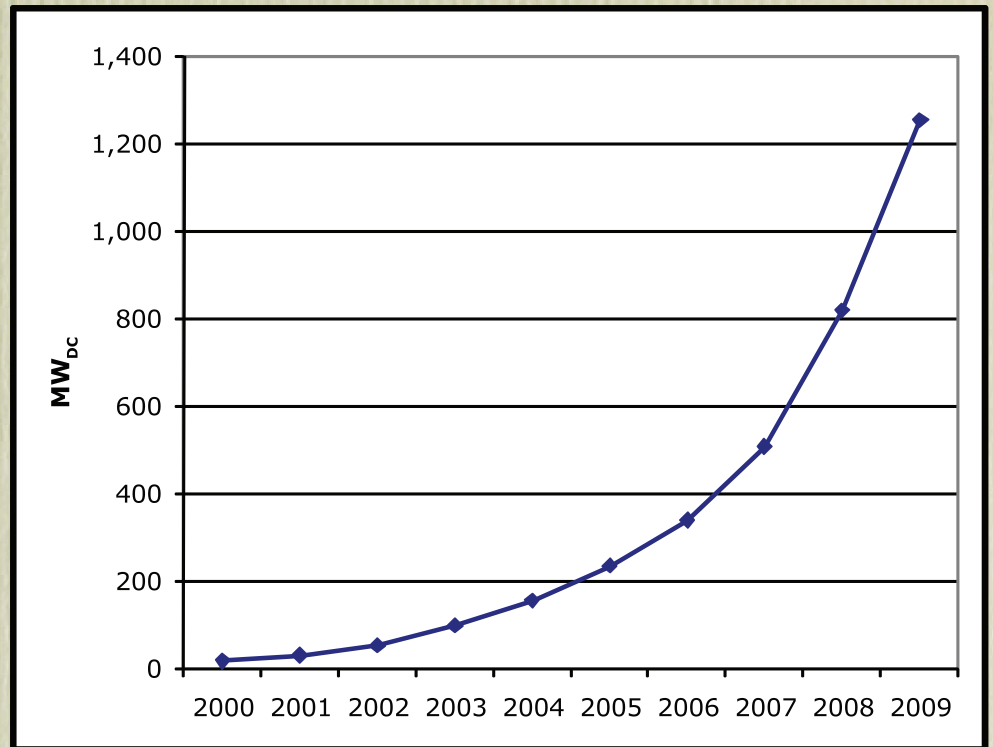
Shortage? ⇒ Inhibit, derail?

Not been widely extracted, traded, or utilized in the past

Not the focus of well-established, robust markets.

1

Deployment of grid connected photovoltaic installations in the U.S. 2000-2010



Emerging, promising technology:
Cadmium telluride thin film photovoltaics

First Solar.

Clean.
Affordable.
Sustainable.
Global.

→ **$0.76 in March 2011**

First Solar Passes $1 Per Watt Industry Milestone

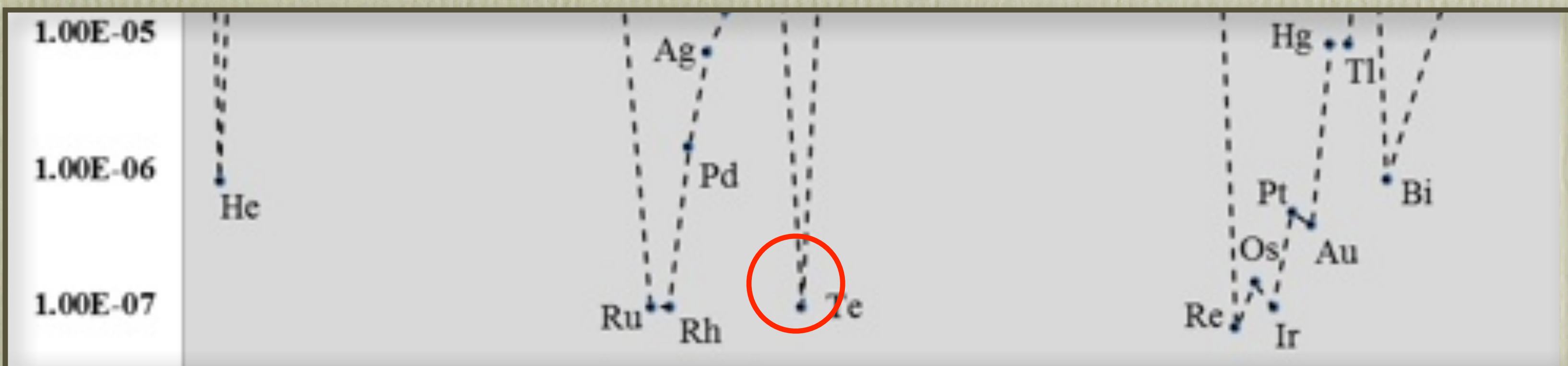
Company Cuts Manufacturing Cost to 98 Cents Per Watt in Fourth Quarter

Feb. 2009

First Solar and Ordos Take Key Step Forward in 2GW China Project

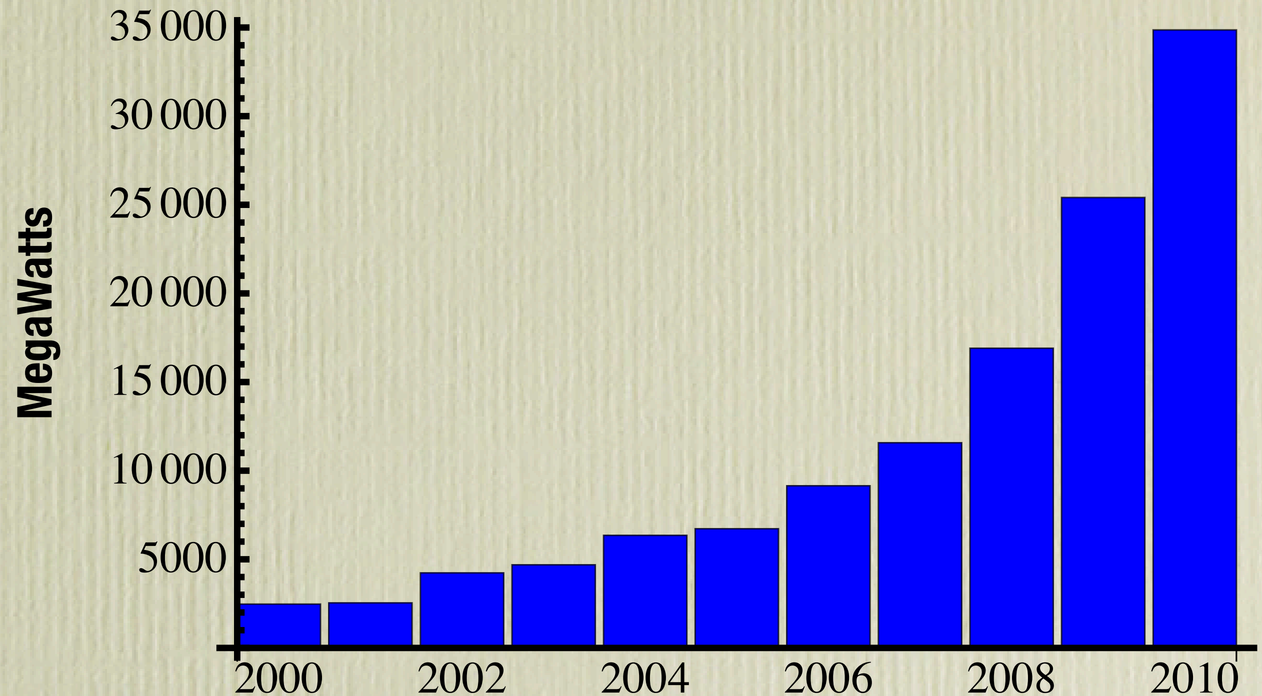
Cooperation Framework Agreement Signed During China-US Presidential Summit

Nov. 2009



Te

Total deployed wind power in the U. S. 2000-2010



†Eamon Keane, Rare Earth Study for *Alt Energy Stocks*

High capacity, esp. open ocean wind turbines require extremely high reliability & synchronous generation

Tons of neodymium-boron-iron ($Nd_2Fe_{14}B$) magnets in a 10 MW turbine

Substitutes?

USGS Mineral Commodity Summary

All Rare Earths

	Mine production[e] 2009	2010
United States	—	—
Australia	—	—
Brazil	550	550
China	129,000	130,000
Commonwealth of Independent States	NA	NA
India	2,700	2,700
Malaysia	350	350
Other countries	NA	NA
World total (rounded)	133,000	130,000

Nd/Pr

(Neodymium (and Praeseodymium) sum to about 10-20% of REE ores)†

3

Conversion of electric lighting to compact fluorescent

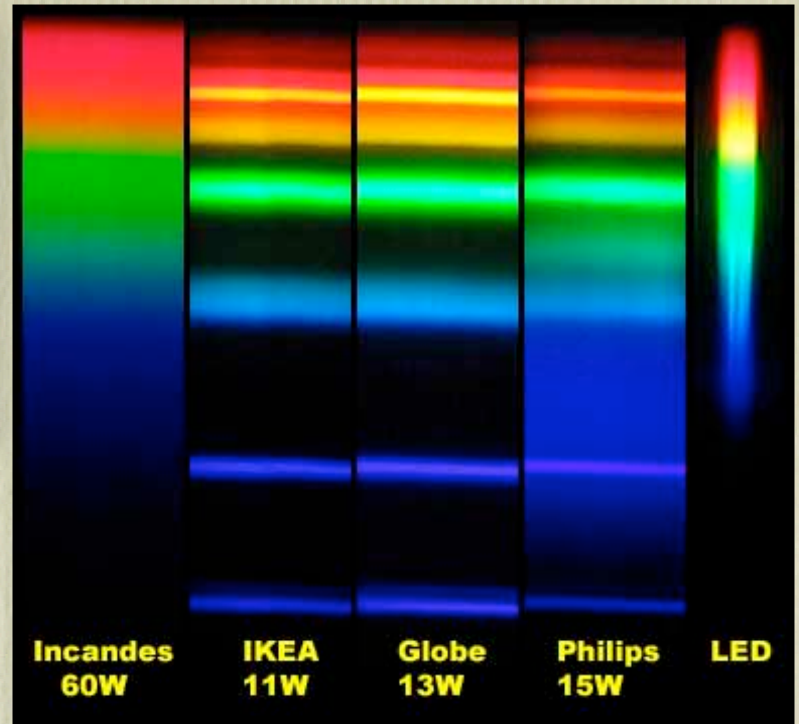
YOUR GOVERNMENT AT WORK

Congress bans incandescent bulbs

Massive energy bill phases out Edison's invention by 2014

Posted: December 19, 2007
7:18 pm Eastern

In addition to raising auto fuel efficiency standards 40 percent, an energy bill passed by Congress yesterday bans the incandescent light bulb by 2014.

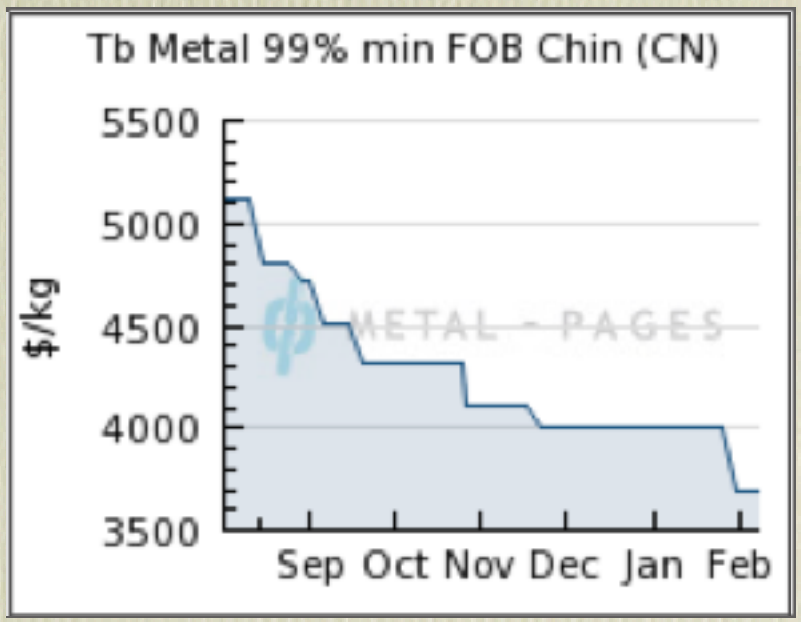


Tb

Terbium and europium provide phosphors that allow CFLs to approximate incandescent spectrum

Annual Global Production of New Metal

2008	Δ (%)	2009	Δ (%)
450 Tons	0.0	450 Tons	0.0



Doubling phosphor demand would require increase of ~375 tons of Tb†

†Eamon Keane, Rare Earth Study for *Alt Energy Stocks*

New energy technologies

- Renewable
- CO2 neutral or negative

Tellurium Gallium

Indium Germanium

Neodymium Dysprosium

Praseodymium

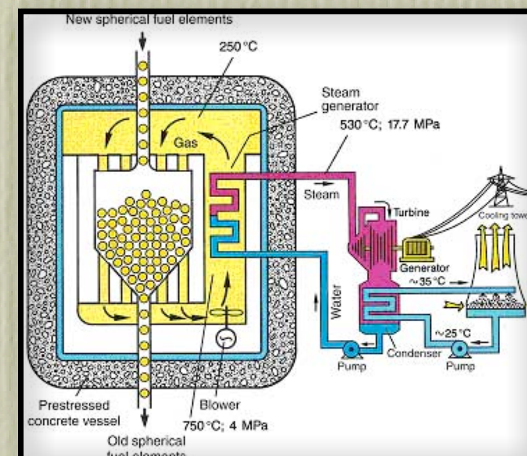
Cobalt Samarium

Lithium

Lanthanum

Terbium

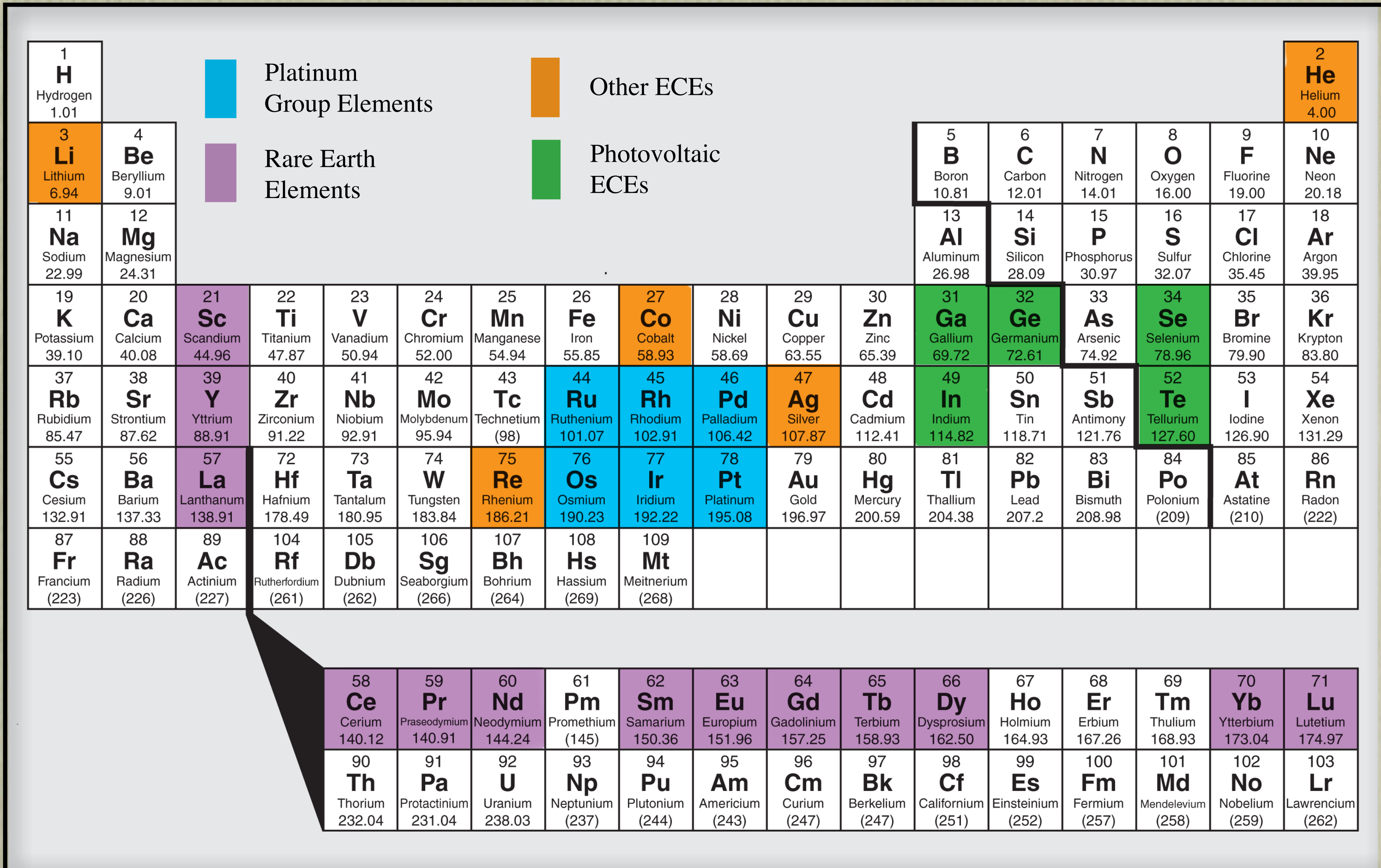
Europium

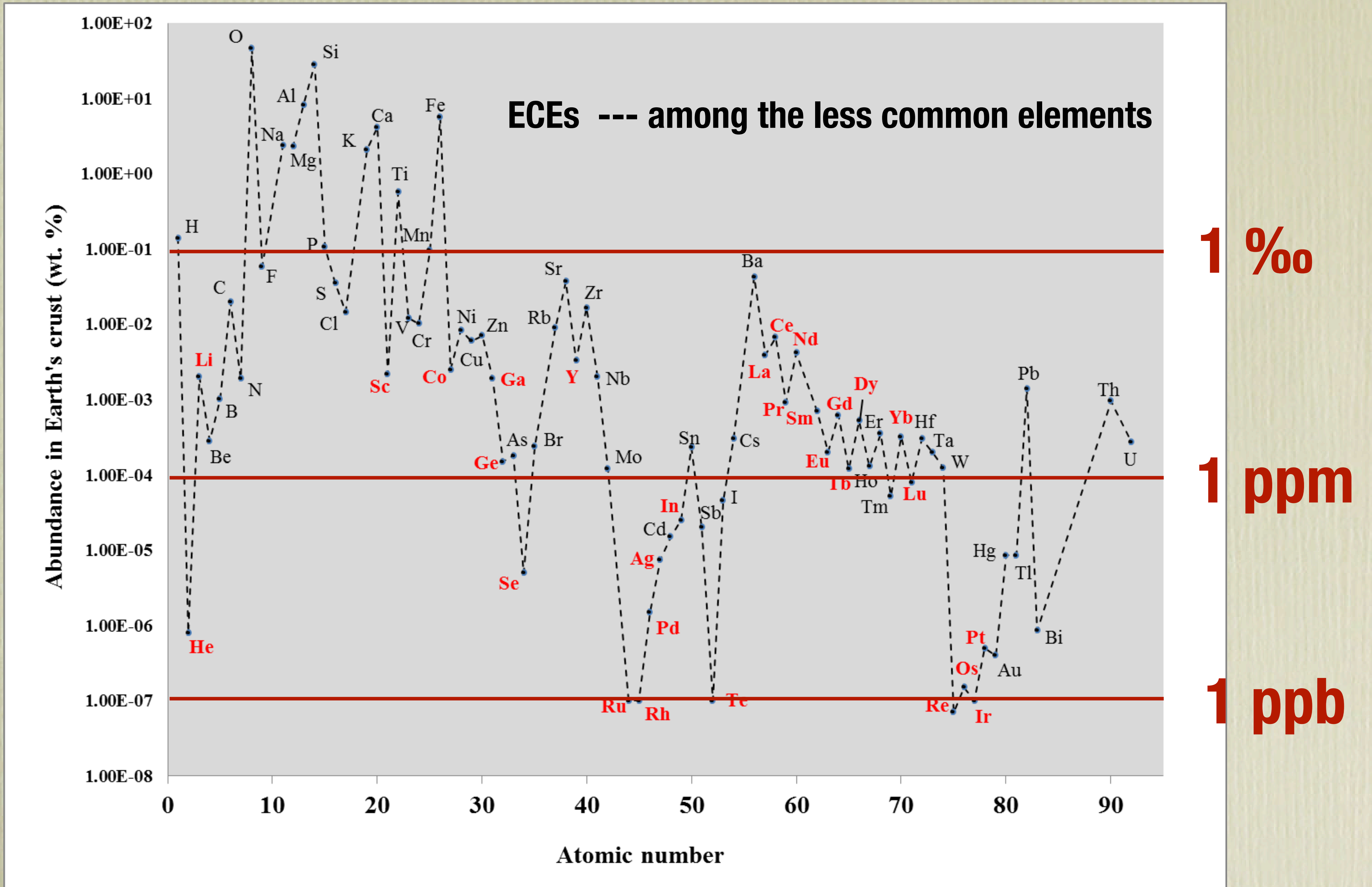


Helium

Possible ECEs today

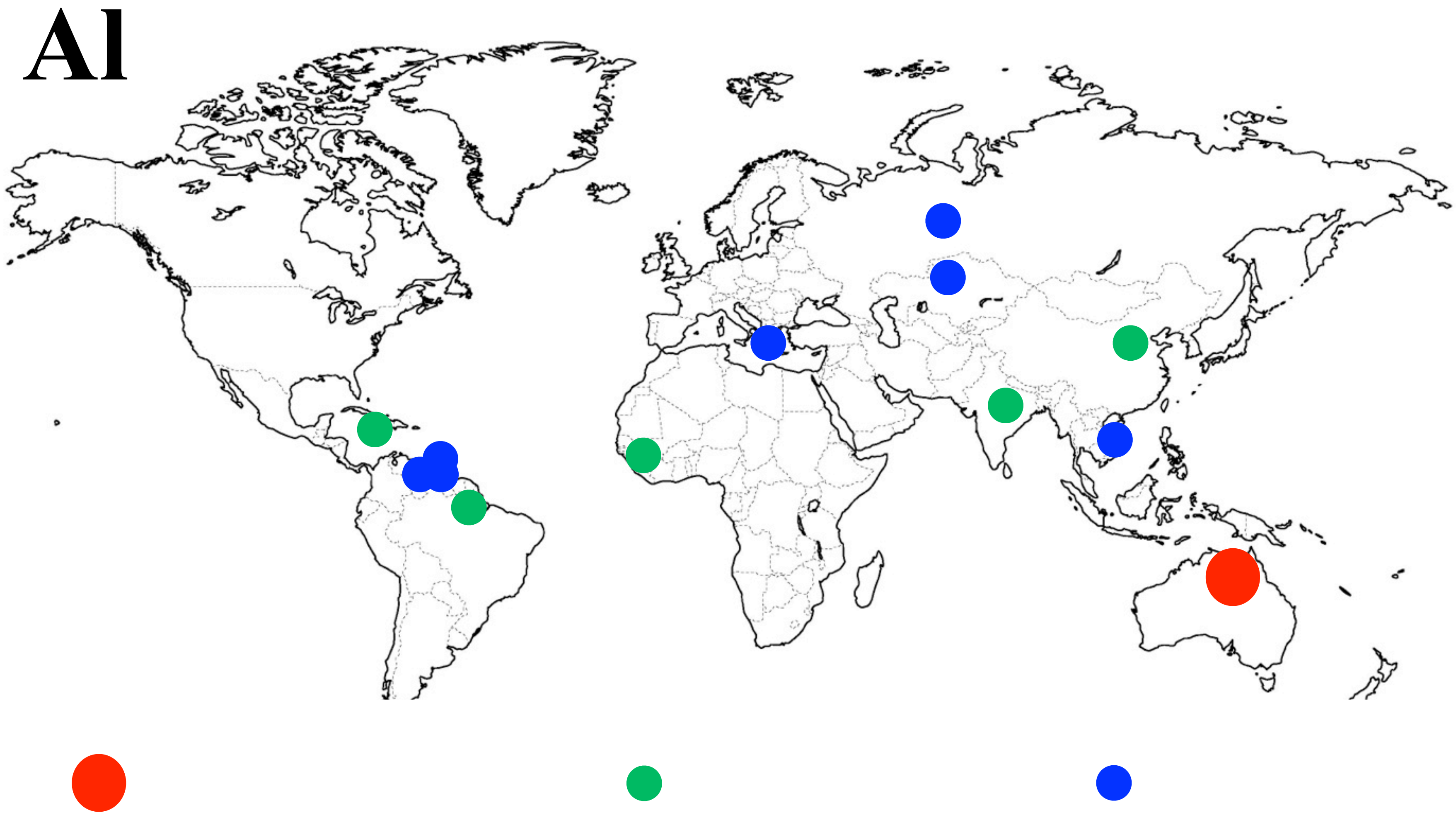
They would have been different in the past, and
They will be different in the future





Tuesday, March 6, 12

Why not aluminum? Resources are broadly distributed.

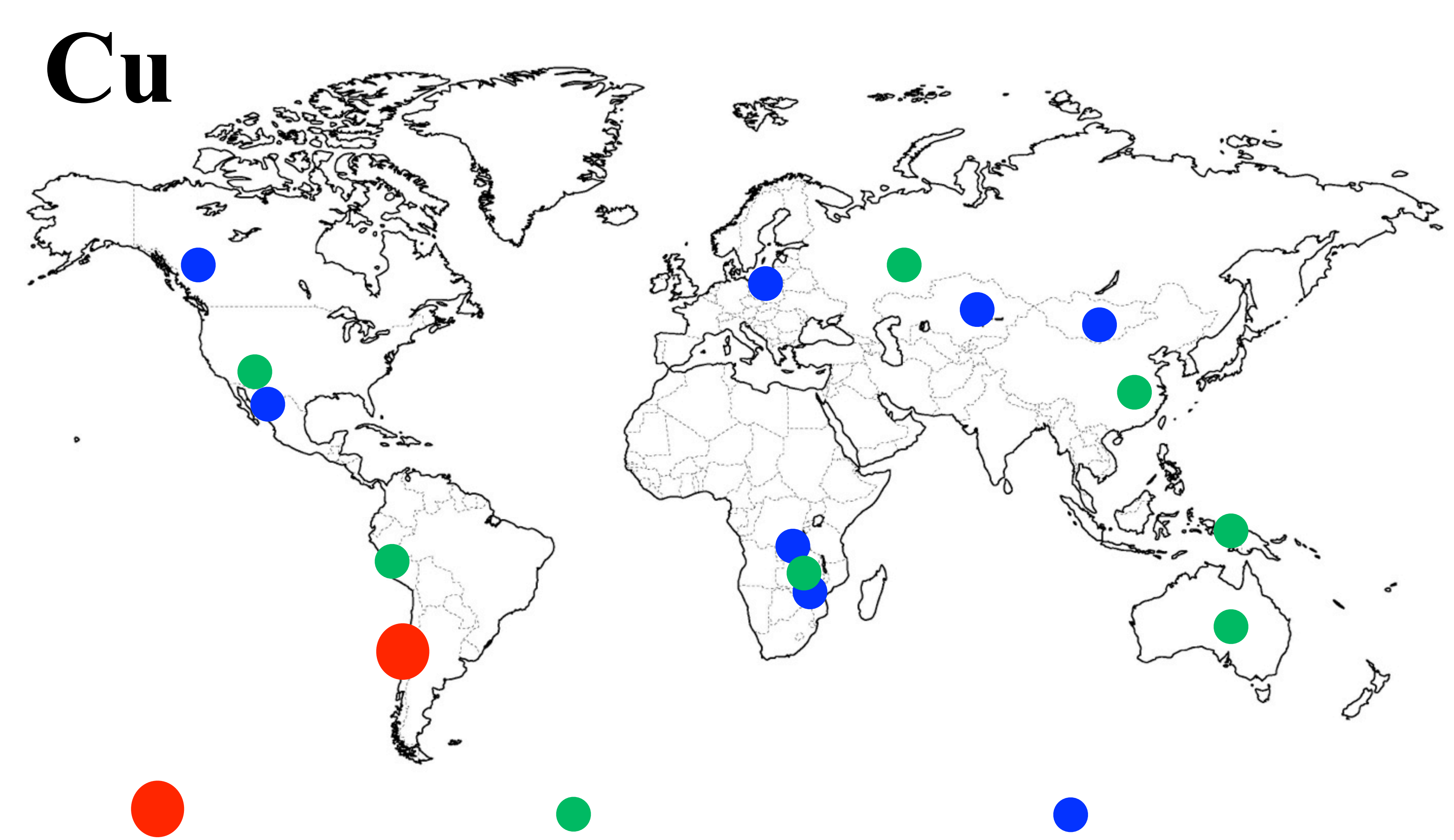


World's leading aluminum-ore producer (Australia, 33%)

Countries with 4% or more of global production

Other countries with production or major reserves

Why not copper? – resources are broadly distributed



World's leading copper producer (Chile, 34%)

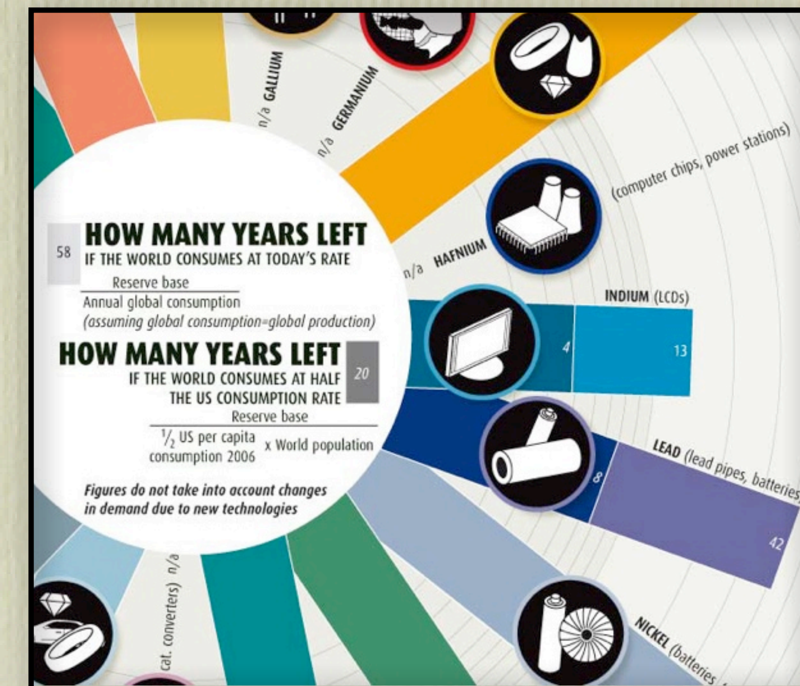
Countries with 4% or more of global production

Other countries with production or major reserves

II Some comments

- The world isn't running out of any ECEs anytime soon.

  Claims to the contrary based on misunderstandings of "reserves"



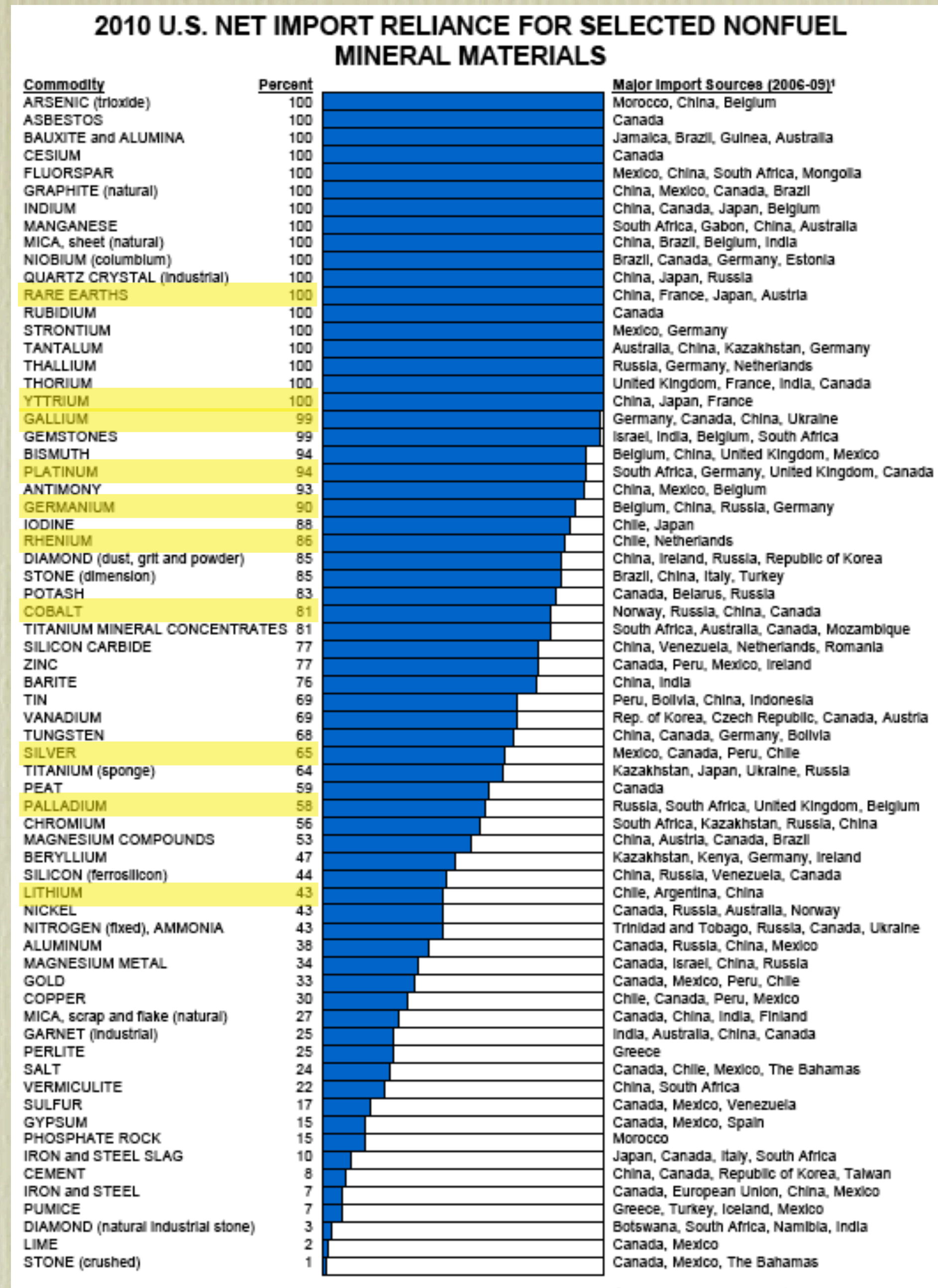
* D. Cohen, New Scientist, May 2007

- ~~“Mine, baby, mine!”~~

Clearly (environmentally acceptable, socially responsible) domestic mining is part of the solution, but...

No country can become “ECE independent”

Nor should one want to be: international trade benefits everyone



USGS 2011 Mineral Commodity Summary

- ~~Stockpiling~~ disincentive to innovation, unintended economic consequences.

- In the grand scheme of things, each element will go through the process of adjustment of application to abundance that has happened (and recurred) for better known elements in the past

Gold and Aluminum

III. ECE's: Constraints on availability

Absolute abundance & concentration — GERMANIUM...

Though not intrinsically rare, they are not mineralized efficiently by geological processes, and do not occur in viable ores.

☆ Geopolitical risks — RARE EARTHS (REEs) & PLATINUM GROUP

- Chance has concentrated them in one or two large or rich deposits.
- Complex economics and politics have led to dominance of a single or small number of countries, allowing market manipulation and raising political issues.

☆ Risks of joint production — INDIUM, GALLIUM, TELLURIUM...

They are only recovered as by-products in extraction of more common metals. Raise a host of (fascinating) economic issues (viz. tellurium)

☆ Environmental and social concerns — REEs...

Developed world will not accept environmental disruption. Countries willing to tolerate environmental degradation for short term gain can dominate markets. Rising environmental consciousness renders this unstable.

Response times in production & utilization — LITHIUM, LANTHANUM

It takes 5-15 years to bring new sources online and/or research and develop substitutes.

ABSOLUTE ABUNDANCE & CONCENTRATION

- 12 “rock forming elements” account for > 99% of Earth’s crust.
- Local enrichment of scarce elements by substitution, eg. Se & Te for S
- More frequently isolated substitution into crystal structure
- Well known rare elements --- gold, silver, platinum --- usually have exceptional chemistry
- Issues:
  - poorly understood geology, prospecting
  - low grade ores
  - unfamiliar metallurgy
  - greater waste and environmental problems

16 S Sulfur 32.07
34 Se Selenium 78.96
52 Te Tellurium 127.60

Germanium

0.00015%, 140 t/yr, ~$1000/kg

Price limits use in PV to high end CSV (concentrated solar voltaics)

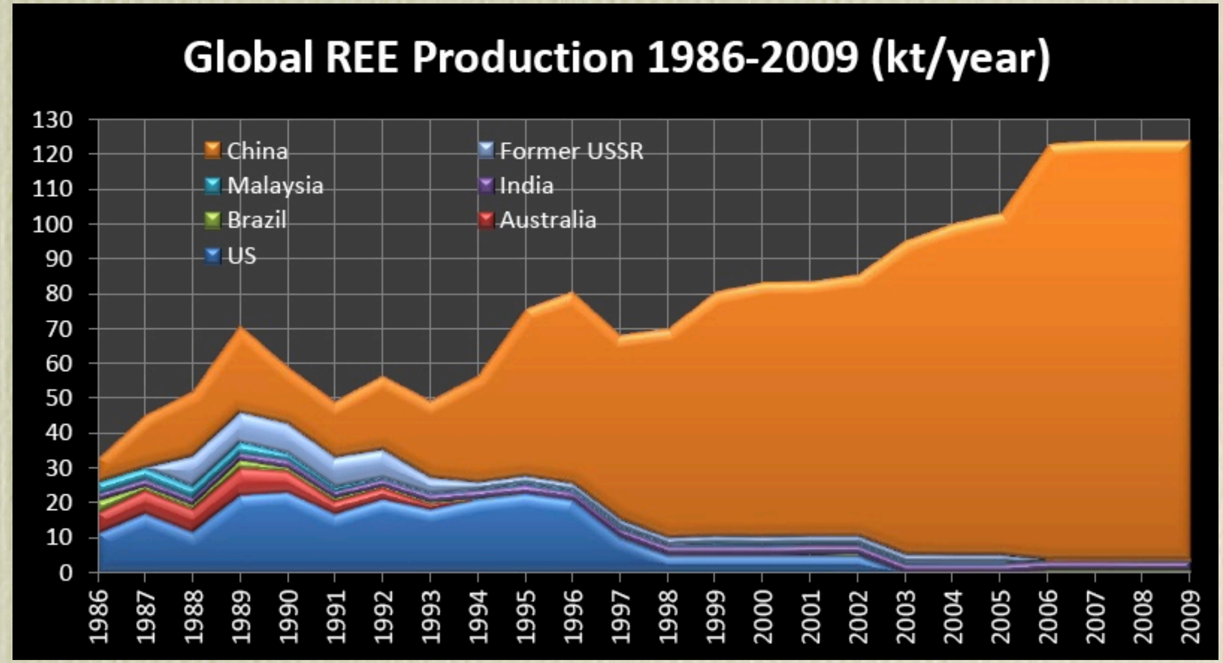
Geopolitics

- Reliance on imports is not a priori bad
- US relies on imports for over 90% of most ECEs
- Problems arise when happenstance or monopoly economic policies concentrate production in one or a very few countries
- Platinum & palladium: World's reserves are overwhelmingly concentrated in SA (Bushveld complex). Production dominated by SA and Russia.

Rare earth elements

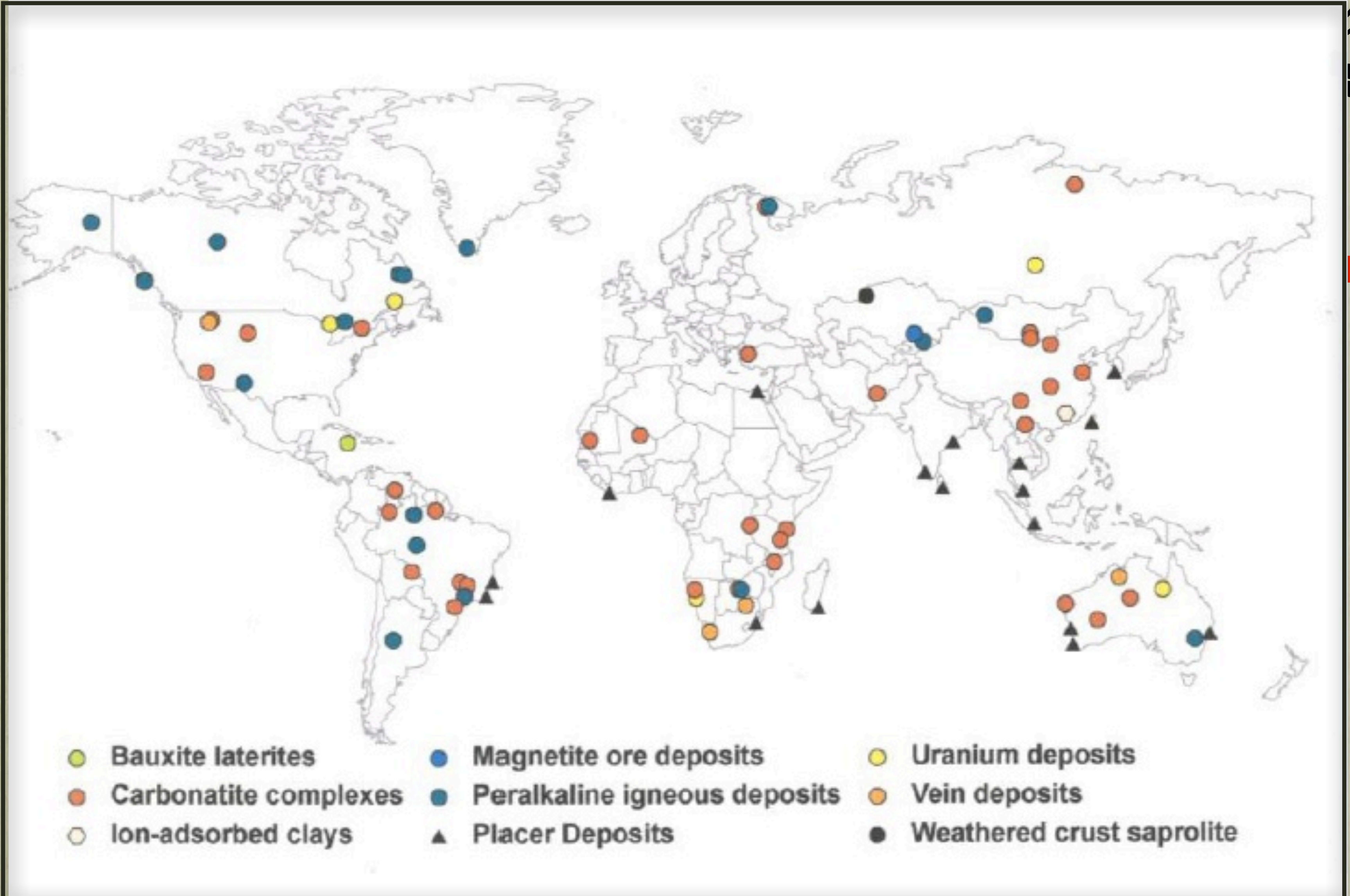
0.007 -- 0.00005%, 130 Kt/yr

95% produced in China, including all HREE



GEOPOLITICS (CONT'D)

BAYAN OBO IRON/REE MINE
MONGOLIA



分析
能"走
"中
East

A. Mariano, private communication

Coproduction economics

- Many ECE's are now produced entirely as by-products of the refining of major metals.
- Tellurium (copper), indium & germanium (zinc), gallium (aluminum)
- Prices are artificially low (economy of scope) until the coproduction saturates. By-product does not drive production of main product. Price demand inelasticity.

Tellurium

0.0000001%, ~200 -- 500 t/yr,

~$150/kg (!)

Key ingredient in CdTe PV -- quickly gaining market share.

Example — tellurium — coproduction with copper

	Main product	Byproduct
	Cu	Te
Global production (metric tons)	16,200,000	200 -- 500 ?
Price ($/kg)	$7.50	$210
Value of global production ($)	$122 x 10^9	$105 x 10^6
Ratio of global value to Cu		1200:1

Example — tellurium (continued)

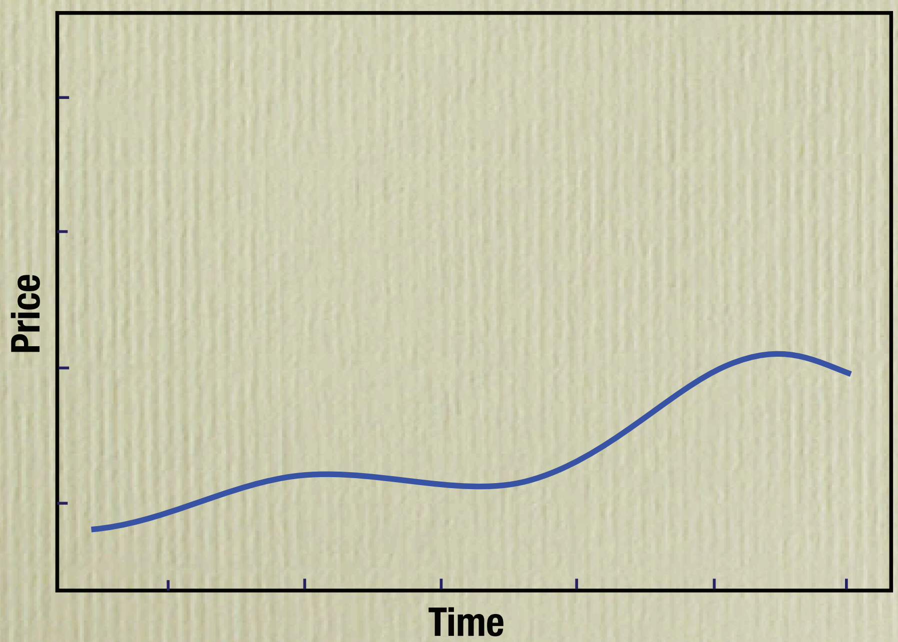
Step 1 Increase Te recovery from electrolytic copper refining

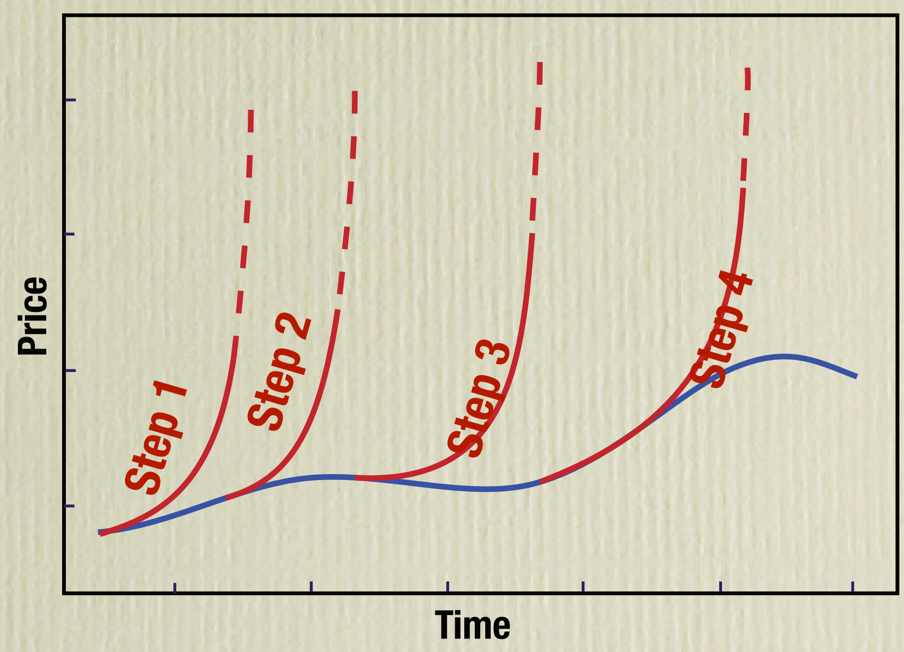
Step 2 Replace Te in traditional applications

Step 3 Recover Te from other sulfide ores (Zn, Pb, ...)

Step 4 Shift Cu refining away from solvent extraction

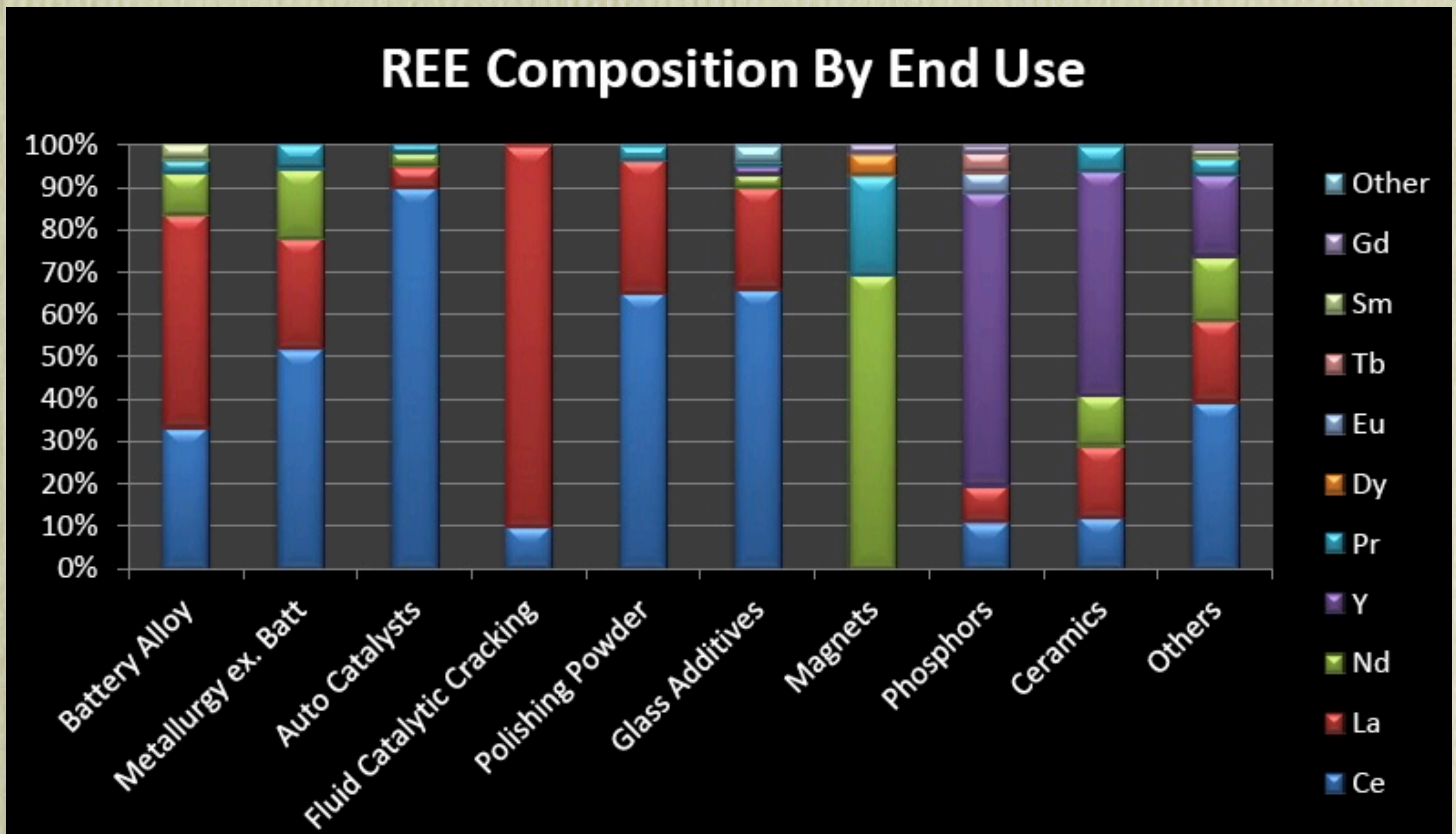
Step 5 Mine and refine (low percentage) primary Te ores





Coproduction economics (cont'd)

- The special case of the rare earths!
- The REE are all co-produced with one another.
- LREE (Sc, Ce, Pr, Nd, Pm, Sm, Eu, Gd) versus HREE (Y, Tb, Dy, Ho, Er, Tm, Yb, Lu)
- Some REE will always be in undersupply, while others will always be in oversupply

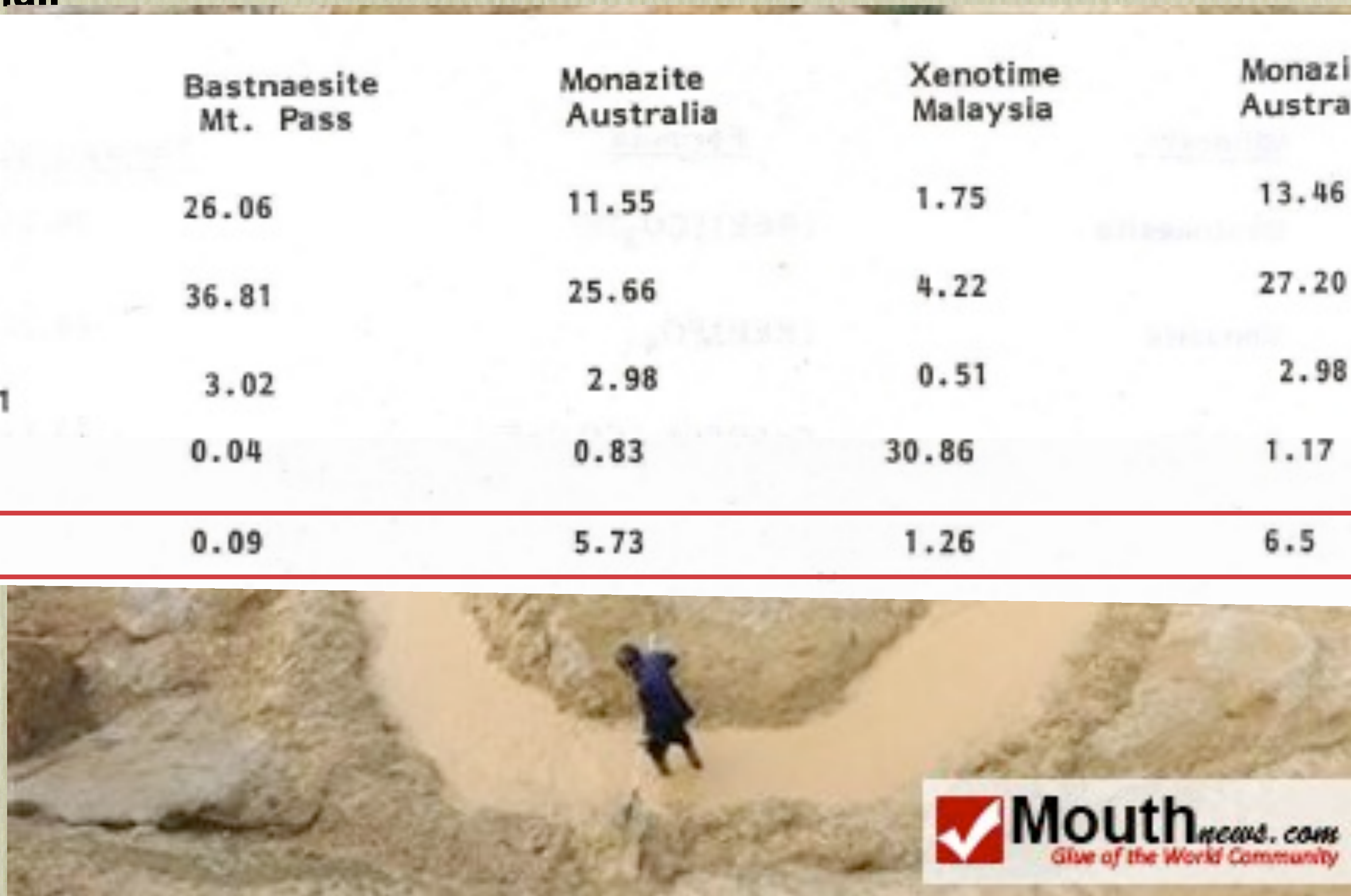


Environmental and Social Concerns

- Decades of increasing vigilance w.r.t. externalities, esp. environmental and social.
-
-

	Bastnaesite Mt. Pass	Monazite Australia	Xenotime Malaysia	Monazite Australia
La_2O_3	26.06	11.55	1.75	13.46
CeO_2	36.81	25.66	4.22	27.20
Pr_6O_{11}	3.02	2.98	0.51	2.98
Y_2O_3	0.04	0.83	30.86	1.17
ThO_2	0.09	5.73	1.26	6.5

Ex
Sc
ex
HREE



Environmental and Social Concerns (cont'd)

- History of U. S. Mountain Pass, California REE mine.
- Once was world's leading producer of REE; first operations in early 1950's; large scale in 1960's through 1990's
- Thorium & radium contamination of wastewater spills caused closing of mine in 1990's
- Molycorp has been trying to reopen the mine for better part of decade.

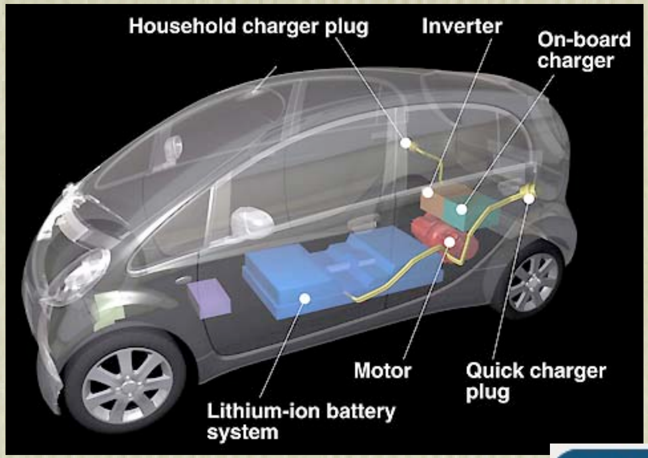
Desert Tortoise
Evaporating pools
Major new facilities
Permitting, stakeholder buy-in
$500M in financing

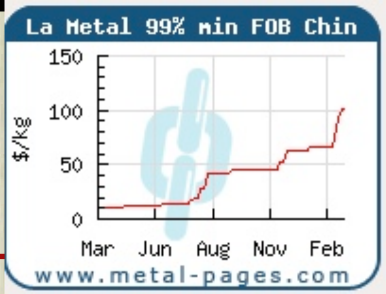
RESPONSE TIMES IN PRODUCTION AND UTILIZATION

- 5 -- 15 years from certification of resource to production of refined metals.
- 5 -- 15 years from conceptual design to production for novel technology

Batteries for all electric vehicles

- Lithium or NiMH?
- Lithium or Lanthanum?
- Typical Toyota Prius uses 10 – 25 kg of La
- Chevy Volt uses 400 lb of Li-ion batteries
- Which technology will win?





Lithium

0.002%, ~ 25 Kt/yr, ~$70/kg

Possible technology route for all-electric vehicle batteries

Lanthanum

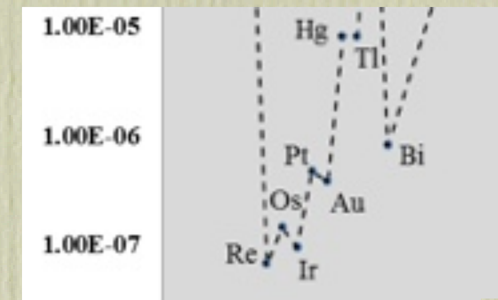
0.004%, ~ 39 Kt/yr, ~$100/kg

Possible technology route for all-electric vehicle batteries

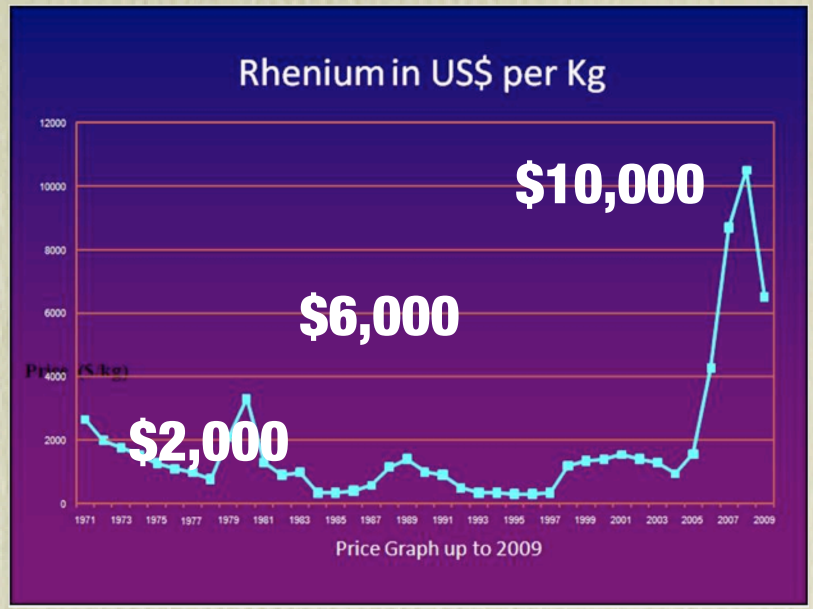
Interlude: The story of Rhenium: Information / Research & Development / Recycling

The search for a low rhenium content turbine alloy for CCGT (Brayton) cycle power

But Re is extremely rare



~ 25 kg Re per gas turbine



Rhenium 10 Years On ©Anthony Lipmann (2005) 2005

GE (major turbine manufacturer and Re consumer) anticipated supply constraint and launched a two pronged program in 2005:

- Recycle pre-consumer scrap to forestall shortage
- Develop new, low (zero?) content Re alloys
- Success over 5 years.

P. J. Fink, J. L. Miller, and D. G. Konitzer, J. Minerals Metals Mater. Soc. 62, 57 (2010).

IV. Moral of the Rhenium story and study policy recommendations

- **Information** .... GE knew the Re market in detail from years of study
- **Recycling** .... GE had the waste stream from decommissioned turbines and preconsumer scrap, and the high-tech expertise to extract Re from scrap alloys
- **Research** .... GE had the resources to mount a long range research effort on substitution
- Most companies do not have these resources, nor do university researchers.
- A legitimate role of government...

Recommendations for federal policy

I. COORDINATION

Complex, multi-dimensional issue: COMMERCE, DEFENSE, ENERGY, INTERIOR (USGS), STATE, TRANSPORTATION, EPA, OMB, COUNCIL OF ECONOMIC ADVISORS, US-TRADE REPRESENTATIVE...

Executive Office of Science and Technology Policy (OSTP) should coordinate federal response.

II. INFORMATION

High quality information is extremely valuable, promotes transparency.

Federal government should gather, analyze, and disseminate information on ECEs

From discovered and potential resources, to production, use, trade, disposal, and recycling.

Model ~ EIA

Regularly survey emerging energy technologies and the supply chain for elements throughout the periodic table, with the aim of identifying critical applications as well as potential shortfalls.

III. RESEARCH, DEVELOPMENT, AND WORKFORCE

Federal R&D: focused on energy-critical elements and possible substitutes.

GEOLOGICAL DEPOSIT MODELING, MINERAL EXTRACTION AND PROCESSING, MATERIAL CHARACTERIZATION AND SUBSTITUTION, UTILIZATION, MANUFACTURING, RECYCLING, AND LIFE-CYCLE ANALYSIS.

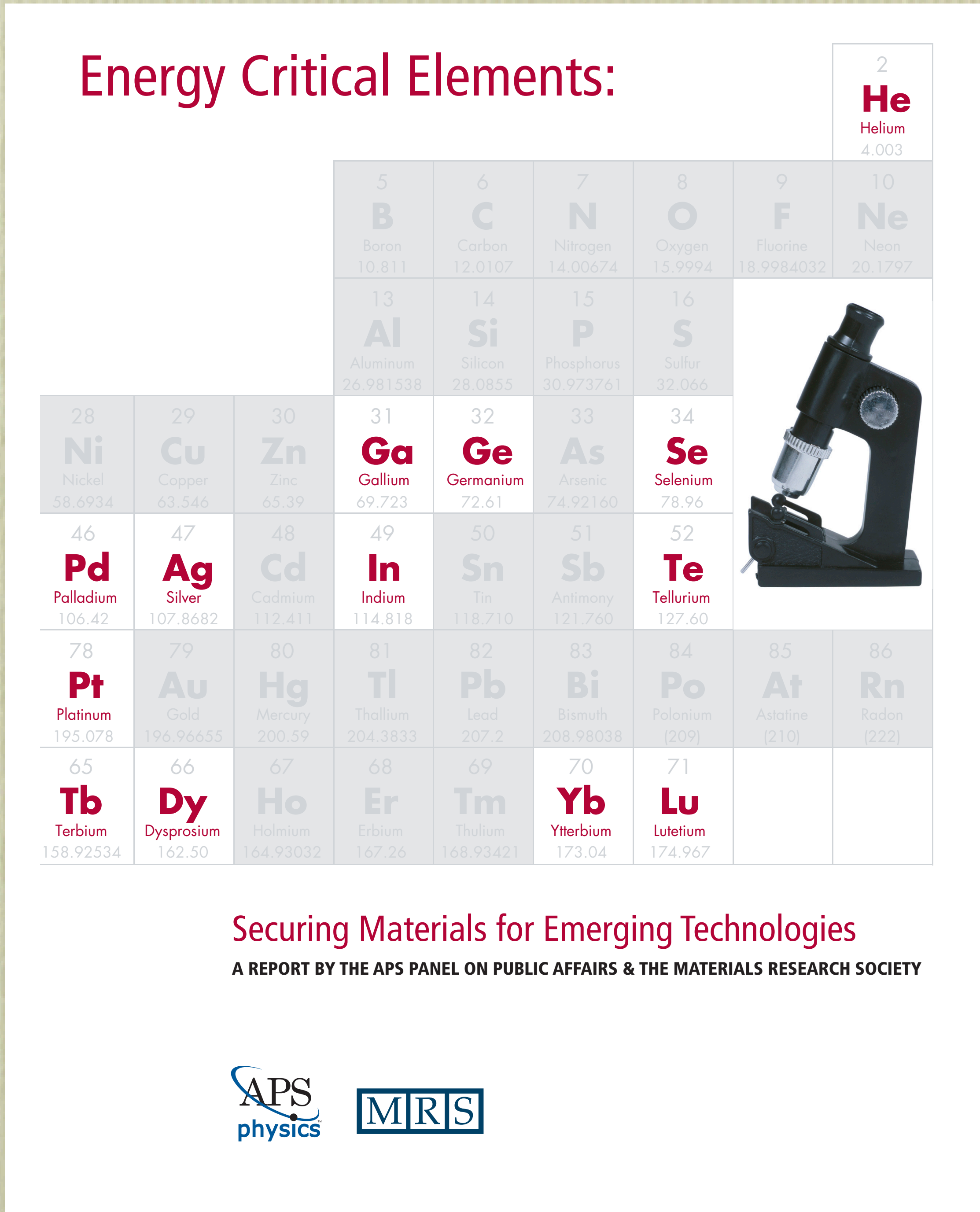
IV. THE ROLE OF MATERIAL EFFICIENCY

The federal government should establish a consumer-oriented "Critical Materials" designation for ECE-related products. The certification requirements should include the choice of materials that minimize concerns related to scarcity and toxicity, the ease of disassembly, the availability of appropriate recycling technology, and the potential for functional as opposed to non-functional recycling.

Steps should be taken to improve rates of post-consumer collection of industrial and consumer products containing ECEs, beginning with an examination of the numerous methods being explored and implemented in various states and countries.

CONGRESSIONAL BILLS
October 2011

	Interagency stewardship	Information Gathering	Research	Recycling	Principal Statistical Agency	Domestic resource survey	Workforce development	Education	Stockpiling/ inventory	Expedited permitting	Expedite domestic mining	Manufacturing stimulus	Rare Earth or ECE?
					PS A								
HOUSE													
• HR 2090 – Hultgren (IL)		✔	✔	✔	✔								ECE
• HR 2011 – Lamborn (CO)						✔	✔			✔	✔		RE
• HR 1388 – Coffman (CO)	✔					✔			✔	✔	✔	✔	RE
• HR 1314 – Johnson/Markey						✔							RE
• HR 952 – Miller (NC)	✔	✔	✔	✔								✔	ECE
SENATE													
• S 383 – Udall (CO)	✔	✔	✔				✔	✔					ECE
• S 421 – Hagan (NC)											✔	✔	Li
• S 1113 – Murkowski (AK)	✔	✔	✔	✔		✔	✔	✔		✔		✔	CE



---------------- Material Science

rgy

\- Economics / economic geology

--------------- Industrial ecology

/ and Geophysics,

---------------- Material science

/Senior Metallurgist

--------------- Economic geology

-------------- Physical chemistry

----------------- Material science

-------------------------- Physics

----------------- Material science

-------------- Physical chemistry

air --- Geology/mineral resources

lines

------------------------- Geology