Critical Elements for New Energy Technologies

R. L. Jaffe, MIT

Progress report from an APS-POPA/MRS study*

- American Physical Society

  Panel on Public Affairs

- Materials Research Society

* a personal perspective

Study group

Gerbrand Ceder (MIT) -- Material Science

R. P. Simmons Professor of Materials Science and Engineering Metallurgy

Rod Eggert (Colorado School of Mines) ------------- Economics / economic geology

Professor and Director of the Division of Economics and Business

Thomas Graedel (Yale) --------------------------------------- Industrial ecology

Musser Professor of Industrial Ecology, Chemical Engineering, Geology and Geophysics,
Director of the Center for Industrial Ecology

Karl Gschneidner (Iowa State/Ames Lab) ------------------------ Material science

Marston Distinguished Professor of Material Science and Engineering/Senior Metallurgist

Murray Hitzman (Colorado School of Mines) ------------------- Economic geology

Fogarty Professor of Economic Geology

Frances Houle (InVisage Technologies, Inc.) ------------------- Physical chemistry

Manager, Materials Development

Alan Hurd (LANL) --- Material science

Director of the Manuel Lujan, Jr. Neutron Scattering Center

*Robert Jaffe (MIT) --- Physics

Morningstar Professor of Physics

Alex King (Ames Lab) -- Material science

Director of the Ames Laboratory

Delia Milliron (Lawrence Berkeley Lab) ------------------------ Physical chemistry

Director of the Molecular Foundary

*Jonathan Price (University of Nevada, Reno) ----------- Geology/mineral resources

Professor, State Geologist of Nevada and Director, Nevada Bureau of Mines

Brian Skinner (Yale) --- Geology

Professor of Geology

* Co-chair

APS/POPA Study

- Relatively rapid, in-depth, but co the intersection of physics and p
- Interest in 2009 leading to collab
- October 2009: POPA approva
- April 2010: MITEI/APS-POPA/MR September 2010: Publication of r workshop
- September 2010: 2nd workshop in Washington
- January 2011: Target date for public release of report

Critical Elements
for New Energy
Technologies

MITei

APS physics
PANEL ON PUBLIC AFFAIRS

MRS Materials Research Society

An MIT Energy Initiative Workshop Report

April 29, 2010

Massachusetts Institute of Technology

http://web.mit.edu/miteicomm/web/reports/critical_elements/CritElem_Report_Final.pdf

Energy Critical Elements (ECEs)

First step: Recognize commonality of issues that define a category

Chemical elements that currently appear critical to one or more new energy-related technologies.   A shortage of these elements would significantly inhibit large-scale deployment, which could otherwise be capable of transforming the way we produce, transmit, store, or conserve energy.

ENERGY & SCALE

ECEs: chemical elements that have the potential for transformative impact but have not been widely extracted, traded, or utilized in the past, and are therefore not the focus of well-established and relatively stable markets

Issues, rather than element, focused

Increased demand: a novelty and perhaps a shock to the system

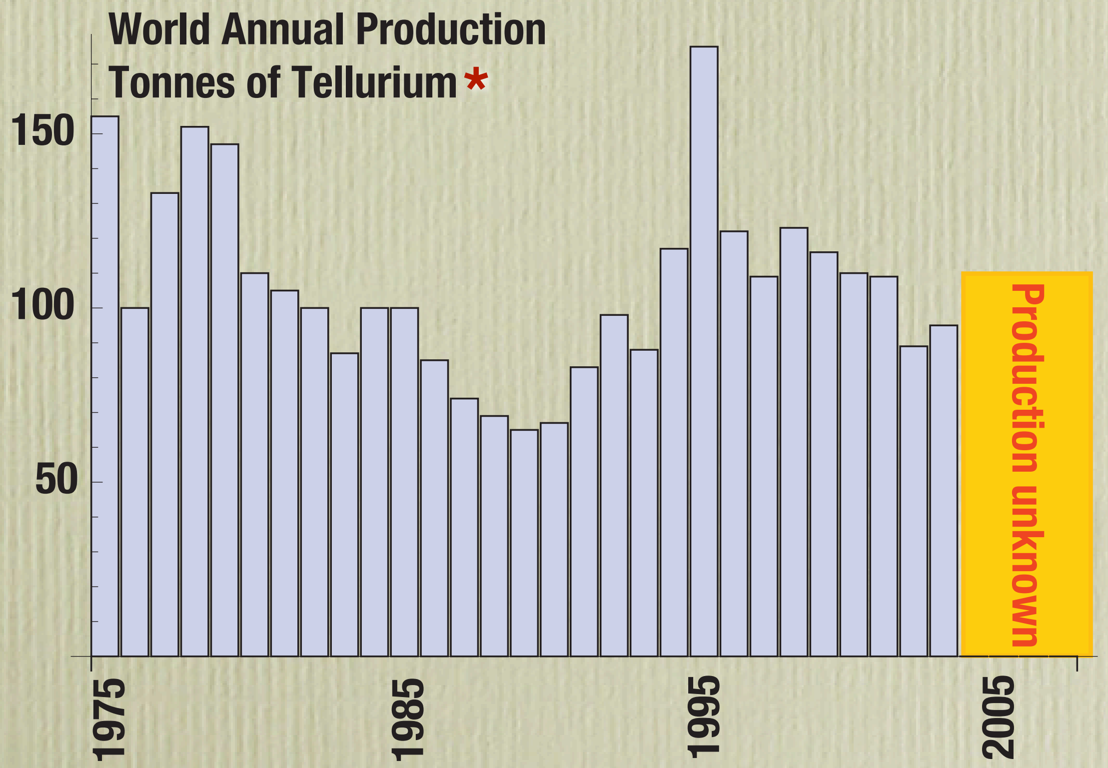
Minerals availability is a huge subject -- related studies ...

Minerals, Critical Minerals, and the U. S. Economy (NAS/NRC) 2008

Managing Materials for a Twenty-first Century Miliary (NAS/NRC) 2008

Tellurium (I)

- 0.0000001% of earth’s crust (compare gold -- 0.0000004%)
- Key in CdTe thin-film photovoltaics
- 9 gm/m^2 & 10% efficiency → 1/10 gm(Te)/W or 100 tonnes/GW^1
- ÷ 20 - 25% capacity factor → 400 tonnes(Te)/GW ^{2}


World Annual Production
Tonnes of Tellurium *

- World electric consumption (2006) ~ 2000 GW †
- Te “Reserve base” ~ 48,000 tonnes* → 120 GW

[1] Capacity – assumes 1000 W/m^2 constant insolation

[2] Delivered – assumes 250 W/m^2 average insolation

* USGS Mineral Commodity Summary

† USEIA

Tellurium (II)

- Will constraints on availability of tellurium obstruct the large scale deployment of CdTe thin film photovoltaics?

- Studies ask "Is there enough Te to build ... over ... years ..."

- Zweibel → "yes"
  Ojebouboh → "probably"
  Fthenakis → "maybe"
  Green → "maybe not"
  Feltrin & Freundlich → "no"

* D. Cohen, New Scientist, May 2007

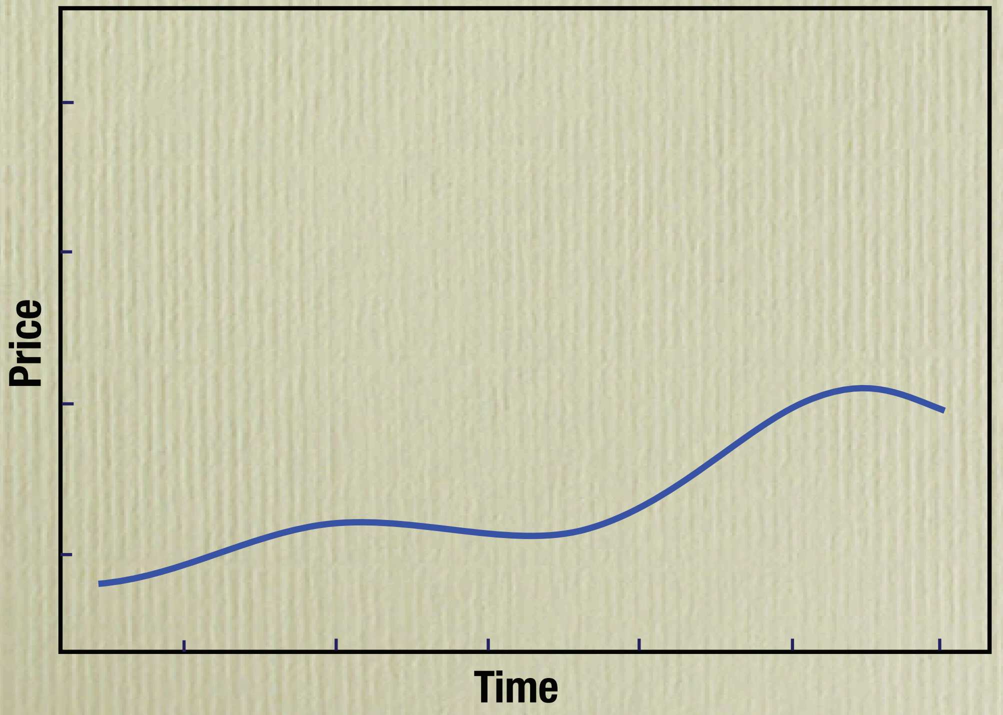
- But

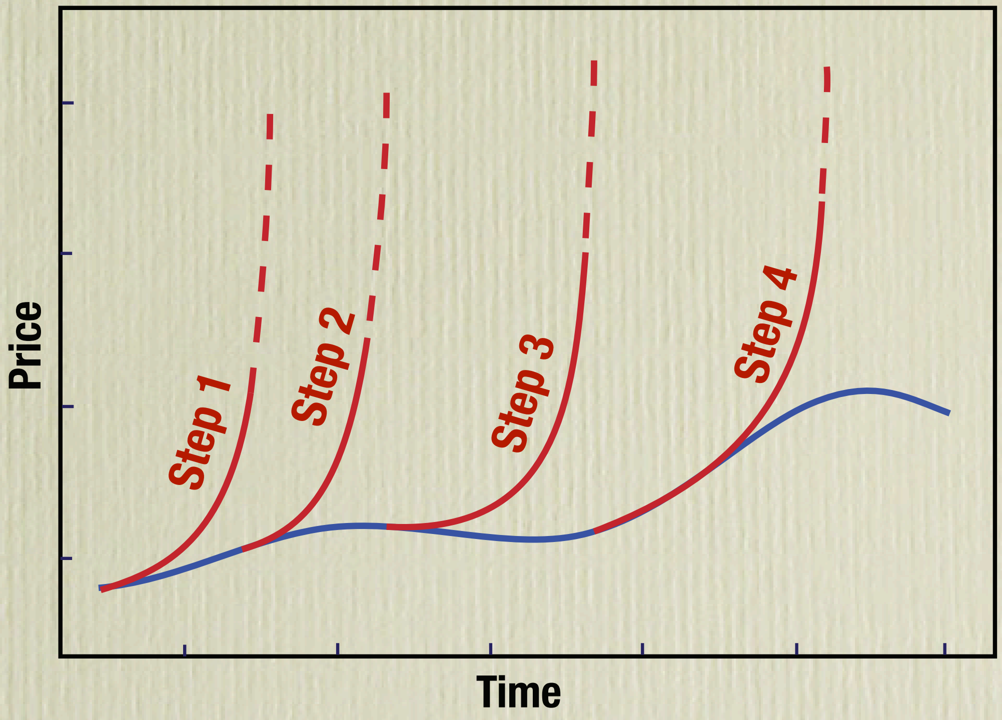
Running out is not the problem!

- Disruptions and discontinuities in supply and price are much more likely and immediate issues

Tellurium (III)

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





Other issues/constraints with EXAMPLES

Absolute abundance & concentration **GERMANIUM...**

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

Geopolitics **RARE EARTHS (REEs)...**

Complex economics and politics have led to dominance of a single or small number of countries, allowing market manipulation and raising political issues.

Localization **PLATINUM GROUP ELEMENTS (PGEs)...**

Chance has concentrated them in one or two large or rich deposits.

Coproduction economics **INDIUM, GALLIUM, TELLURIUM...**

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

Environmental and social concerns **REEs...**

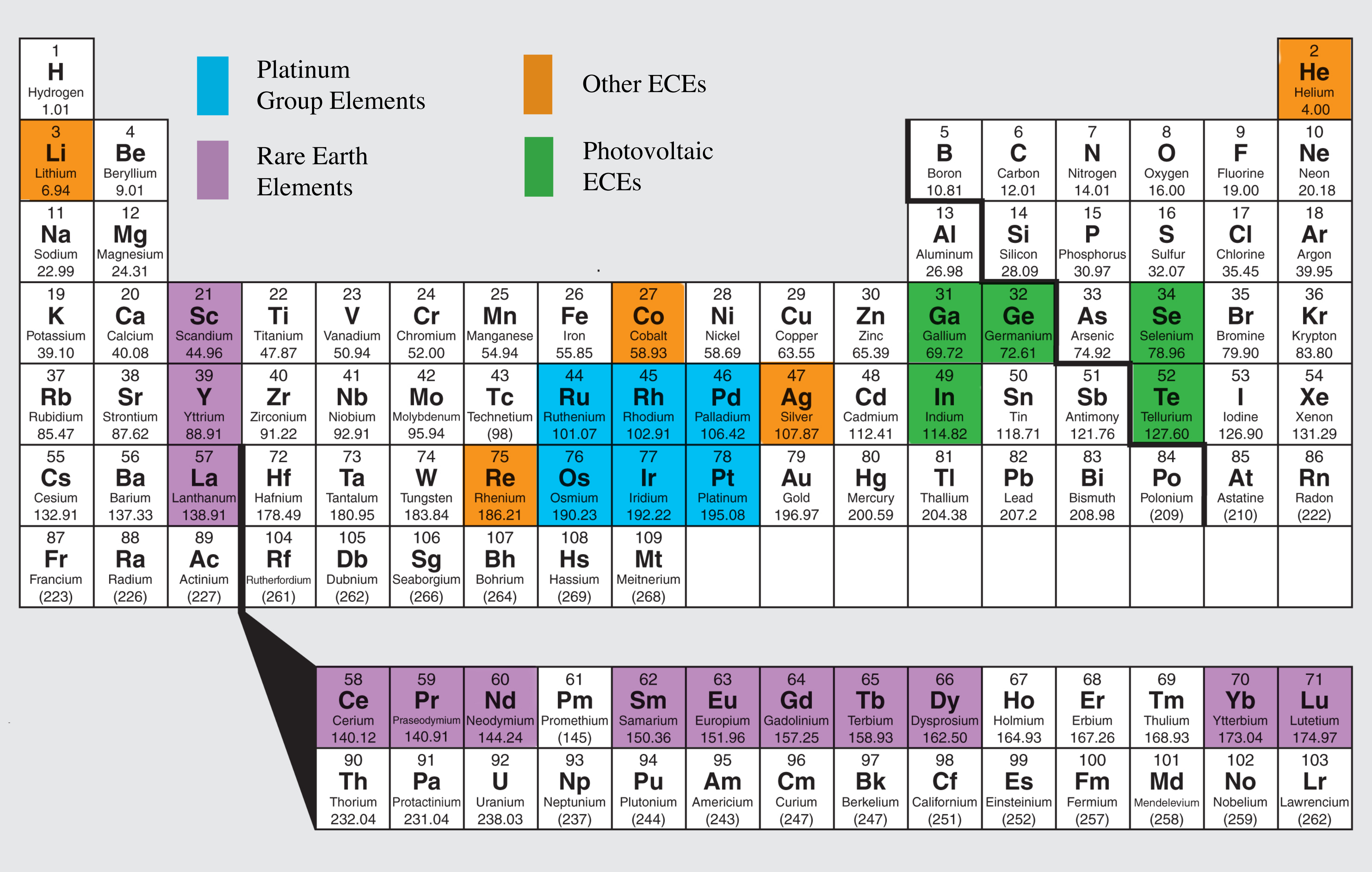
U.S. & other 1st world countries will not accept environmental disruption, leading to off-shore production. Rising environmental consciousness renders this unstable.

Response times in production & utilization **LITHIUM...**

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

Possible ECEs today

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



🟦 Platinum Group Elements

🟪 Rare Earth Elements

🟧 Other ECEs

🟩 Photovoltaic ECEs

1 **H** Hydrogen 1.01																	🟧 2 **He** Helium 4.00
🟧 3 **Li** Lithium 6.94	4 **Be** Beryllium 9.01											5 **B** Boron 10.81	6 **C** Carbon 12.01	7 **N** Nitrogen 14.01	8 **O** Oxygen 16.00	9 **F** Fluorine 19.00	10 **Ne** Neon 20.18
11 **Na** Sodium 22.99	12 **Mg** Magnesium 24.31											13 **Al** Aluminum 26.98	14 **Si** Silicon 28.09	15 **P** Phosphorus 30.97	16 **S** Sulfur 32.07	17 **Cl** Chlorine 35.45	18 **Ar** Argon 39.95
19 **K** Potassium 39.10	20 **Ca** Calcium 40.08	🟪 21 **Sc** Scandium 44.96	22 **Ti** Titanium 47.87	23 **V** Vanadium 50.94	24 **Cr** Chromium 52.00	25 **Mn** Manganese 54.94	26 **Fe** Iron 55.85	🟧 27 **Co** Cobalt 58.93	28 **Ni** Nickel 58.69	29 **Cu** Copper 63.55	30 **Zn** Zinc 65.39	🟩 31 **Ga** Gallium 69.72	🟩 32 **Ge** Germanium 72.61	33 **As** Arsenic 74.92	🟩 34 **Se** Selenium 78.96	35 **Br** Bromine 79.90	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.47	38 **Sr** Strontium 87.62	🟪 39 **Y** Yttrium 88.91	40 **Zr** Zirconium 91.22	41 **Nb** Niobium 92.91	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	🟦 44 **Ru** Ruthenium 101.07	🟦 45 **Rh** Rhodium 102.91	🟦 46 **Pd** Palladium 106.42	🟧 47 **Ag** Silver 107.87	48 **Cd** Cadmium 112.41	🟩 49 **In** Indium 114.82	50 **Sn** Tin 118.71	51 **Sb** Antimony 121.76	🟩 52 **Te** Tellurium 127.60	53 **I** Iodine 126.90	54 **Xe** Xenon 131.29
55 **Cs** Cesium 132.91	56 **Ba** Barium 137.33	🟪 57 **La** Lanthanum 138.91	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.95	74 **W** Tungsten 183.84	🟧 75 **Re** Rhenium 186.21	🟦 76 **Os** Osmium 190.23	🟦 77 **Ir** Iridium 192.22	🟦 78 **Pt** Platinum 195.08	79 **Au** Gold 196.97	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.38	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
87 **Fr** Francium (223)	88 **Ra** Radium (226)	89 **Ac** Actinium (227)	104 **Rf** Rutherfordium (261)	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (266)	107 **Bh** Bohrium (264)	108 **Hs** Hassium (269)	109 **Mt** Meitnerium (268)									
				🟪 58 **Ce** Cerium 140.12	🟪 59 **Pr** Praseodymium 140.91	🟪 60 **Nd** Neodymium 144.24	61 **Pm** Promethium (145)	🟪 62 **Sm** Samarium 150.36	🟪 63 **Eu** Europium 151.96	🟪 64 **Gd** Gadolinium 157.25	🟪 65 **Tb** Terbium 158.93	🟪 66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.93	🟪 70 **Yb** Ytterbium 173.04	🟪 71 **Lu** Lutetium 174.97
				90 **Th** Thorium 232.04	91 **Pa** Protactinium 231.04	92 **U** Uranium 238.03	93 **Np** Neptunium (237)	94 **Pu** Plutonium (244)	95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium (258)	102 **No** Nobelium (259)	103 **Lr** Lawrencium (262)

R. L. Jaffe DOE “Transatlantic Workshop” MIT December 3, 2010

center for
theoretical
physics

Observations

I. The future

In the future essentially the whole periodic table of elements will find important applications, many of them in energy-critical applications.

The problems outlined in this study will not go away.

Minerals policy in general and ECE policy in particular will be an issue for national policy and international cooperation in future years.

II. Coordination

Complex issues that straddle the portfolios of many ministries and agencies within governments and among governments.

Commerce, Defense, Energy, Interior, State, Transportation, Council of Economic Advisors, EPA, U.S. Trade Representative, ...

Coordination at the highest level of the executive needed.

III. Information

Comprehensive, up-to-date information on all aspects of the ECE life-cycle would enable researchers, developers, and investors to plan for materials needs of new technologies.

At present there is no single agency similar to the Energy Information Administration charged with tracking materials

IV. Research, development and the workforce

A focused federal R&D program → expand the availability of ECEs and reduce dependence on ECEs.

Recognize long time scales associated with research and development, esp. for substitutions.

Recognize multidisciplinary and interdependent nature of these activities.

Expertise and manpower follow production and have migrated off-shore.

V. The role of recycling

Recognize special nature of rare elements. Viz. gold, silver, platinum.

Recycling serves many purposes: Displaces virgin production, generates independent supply stream, reduces environmental disruption.

Create consumer awareness of the preciousness of these materials.

But recycling cannot play a primary role in an exponentially expanding market.

V. Possible market interventions

Stockpiling for economic purposes does not seem to be a good option. Free trade works to the benefit of all parties.

Helium is an exception that needs special consideration.

STAY TUNED
APS/MRS Study report due out in early January