Dimensions of Criticality

Energy Critical Elements

Securing Materials for Emerging Technologies

A report from the

American Physical Society & Materials Research Society

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http://www.aps.org/about/pressreleases/elementsreport.cfm

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Principal take aways I

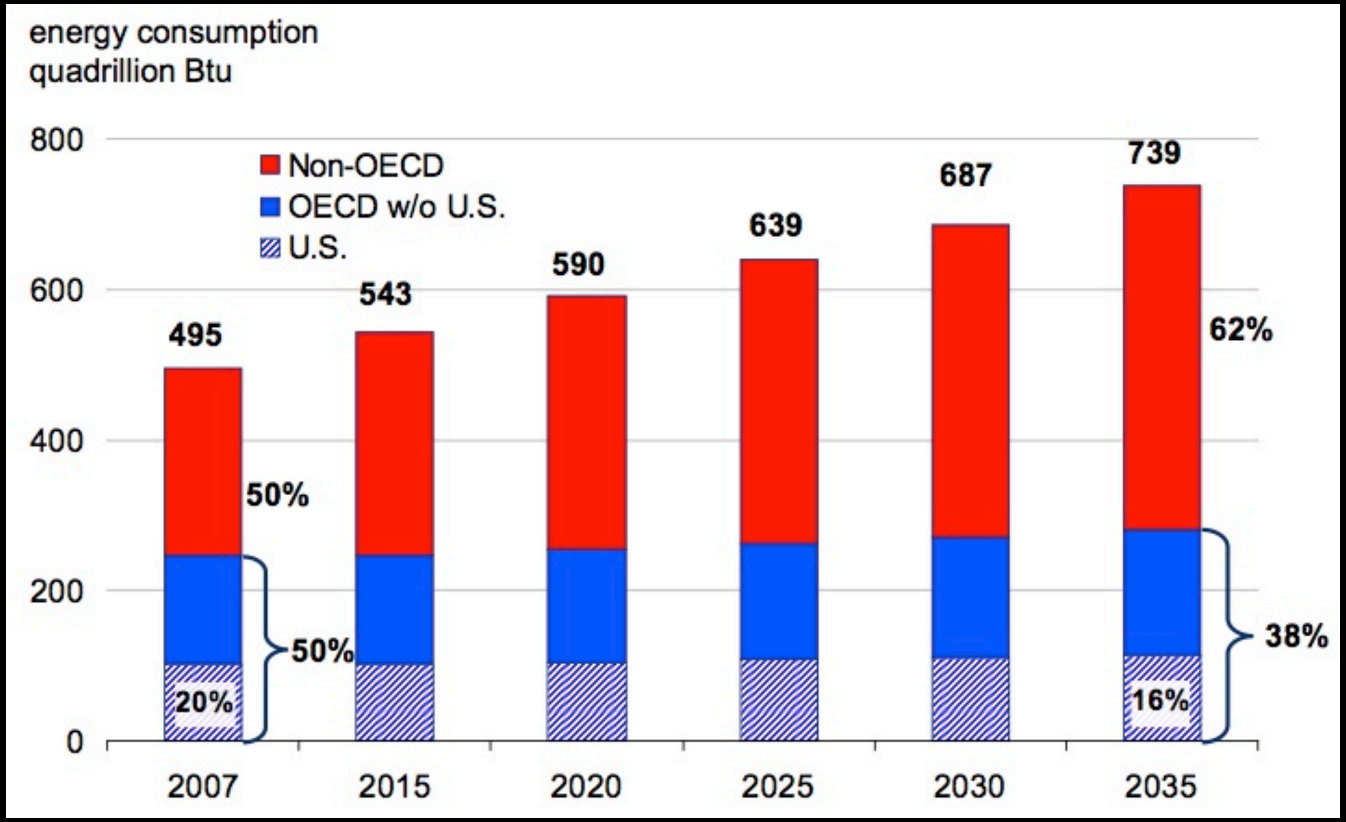
- Energy Critical Elements – common economic & scientific issues that would benefit from a unified policy framework
- Potentially game-changing technologies are susceptible to constraints on availability, interruptions in supply
- Rare Earths are the Flavor of the Month. Next year/decade it may be tellurium, indium, helium,...
- Present "crisis" provides a golden opportunity to address a broader set of issues. We should not let this slip away.

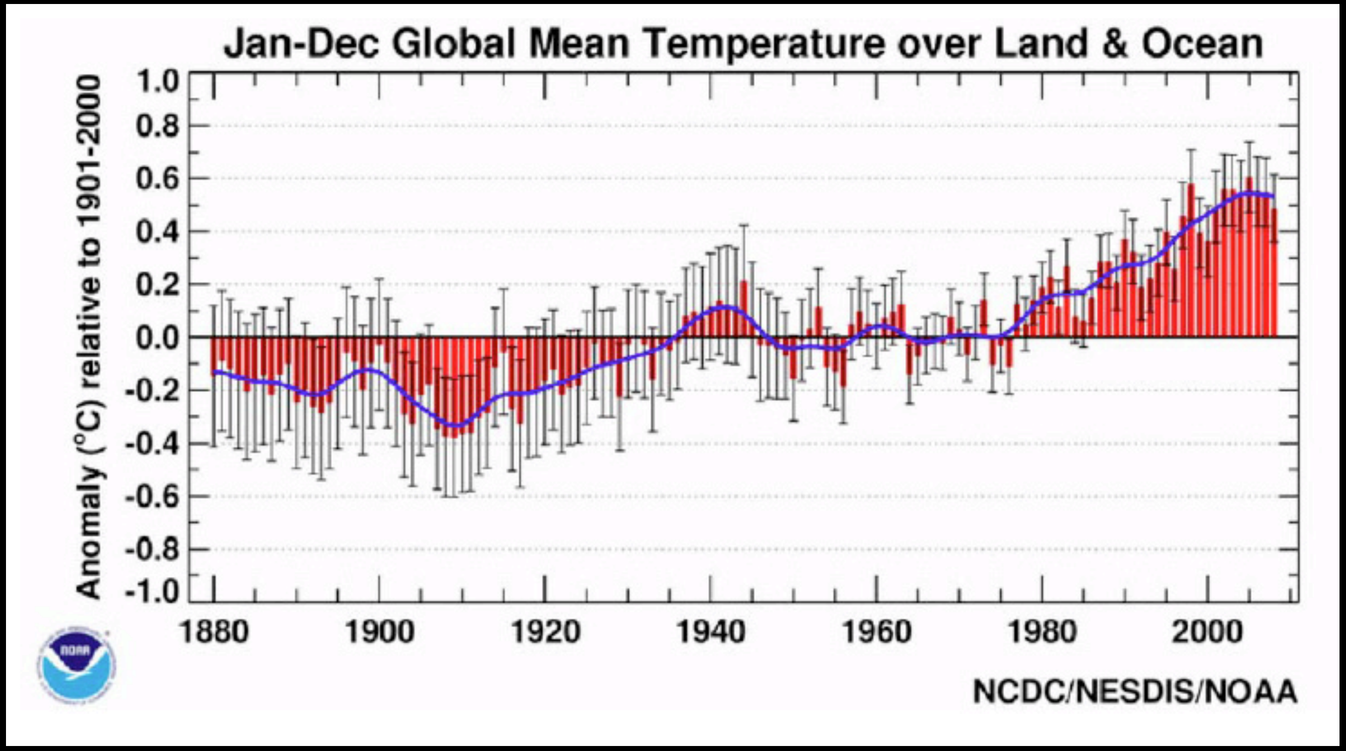
Principal take aways II

- Domestic (US) mining – a component in a rational ECE policy, but no country can/should want to be ECE self-sufficient
- With careful stewardship, and a triad of low-budget-impact, non-interventionist steps: information gathering, research & recycling, present and future ECE problems can be managed.

Energy critical elements?

- Increasing demand for energy
- Quest for energy independence
- Anthropogenic climate change
- New technologies to harvest, transmit, store, conserve & use energy





- **Increasing demand for energy**
- **Anthropogenic climate change**
- **Quest for energy independence**

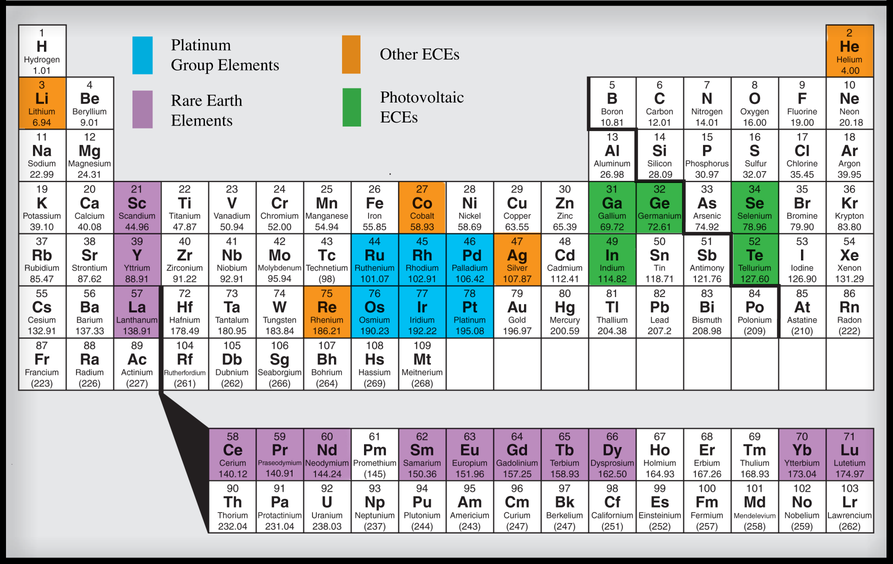
Grand challenge problems for the 21st century

Scientists and engineers in universities, industry, and government labs have responded with new ideas for

Harvesting, Storing, Transmitting, Transforming, Using Energy

- **Search the periodic table**
- **Found often superb technical solutions**
- **Usually without regard to availability**

And there's the rub...



Lab ⇒ Pilot ⇒ Massive Deployment

New energy technologies are typically **materials intensive**

Obstructions to availability? ⇒ Inhibit, derail, otherwise potentially game changing technologies

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

Not the focus of well-established, robust markets.

"Energy critical elements"

ENERGY SCALE

New energy technologies

- Efficient
- Clean, renewable
- Domestic
- CO2 neutral or negative

Neodymium

Dysprosium

Tellurium

Gallium

Praseodymium

Indium

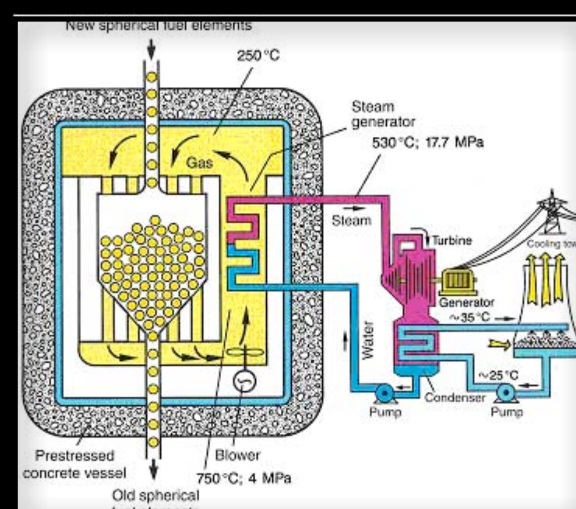
Germanium

Samarium

Rhenium

Cobalt

Lithium



Palladium

Platinum

Ruthenium

Helium

Lanthanum

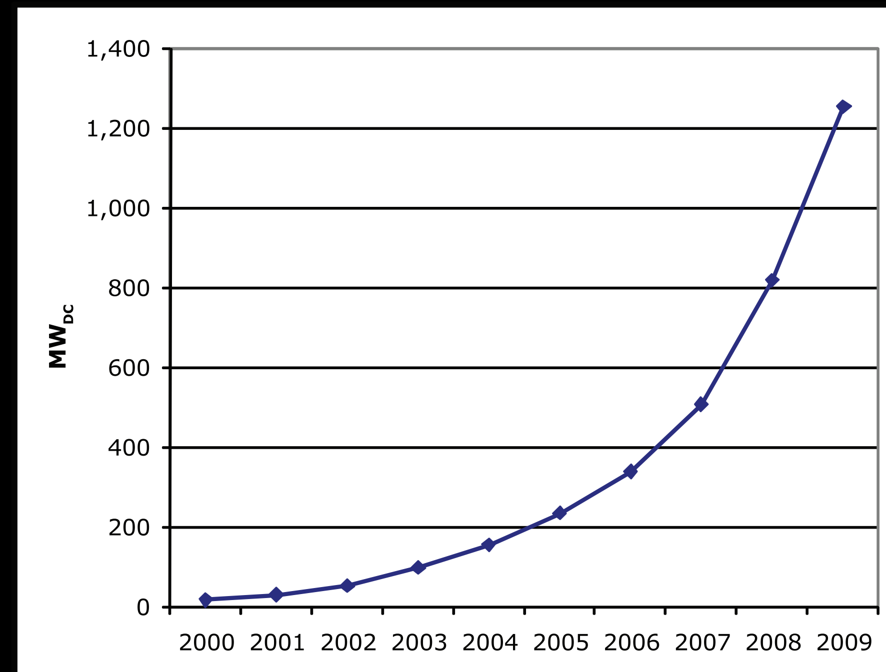
Europium

Terbium

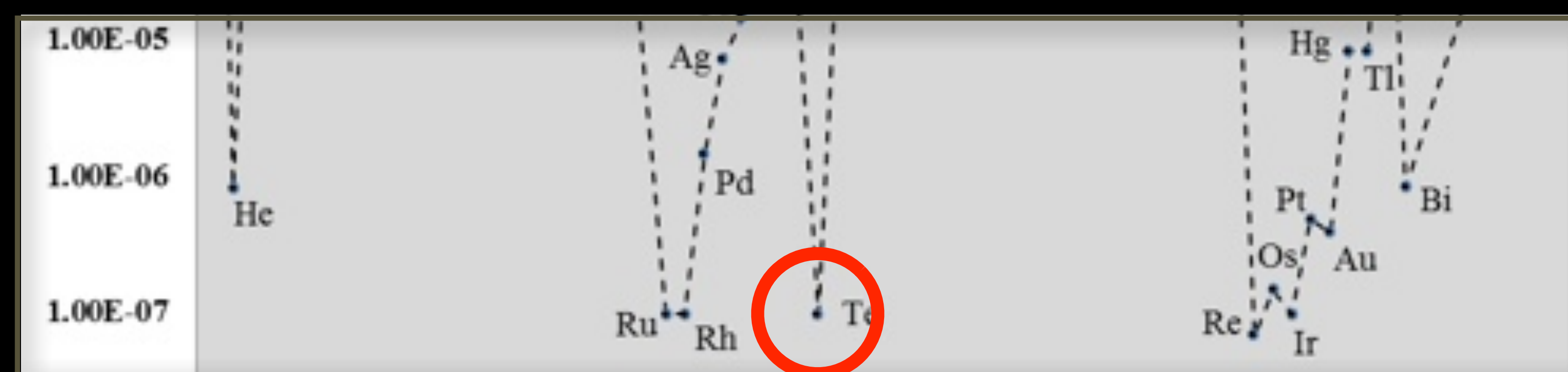
I. Tellurium

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

- With low cost, streamlined production and relatively high efficiency,
- Cd/Te (and CIGS) thin film PV's are gaining attention



First Solar.
Clean.
Affordable.
Sustainable.
Global.



First Solar Passes $1 Per Watt Industry Milestone

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

$0.76 late last year

Platinum Group Elements

Rare Earth Elements

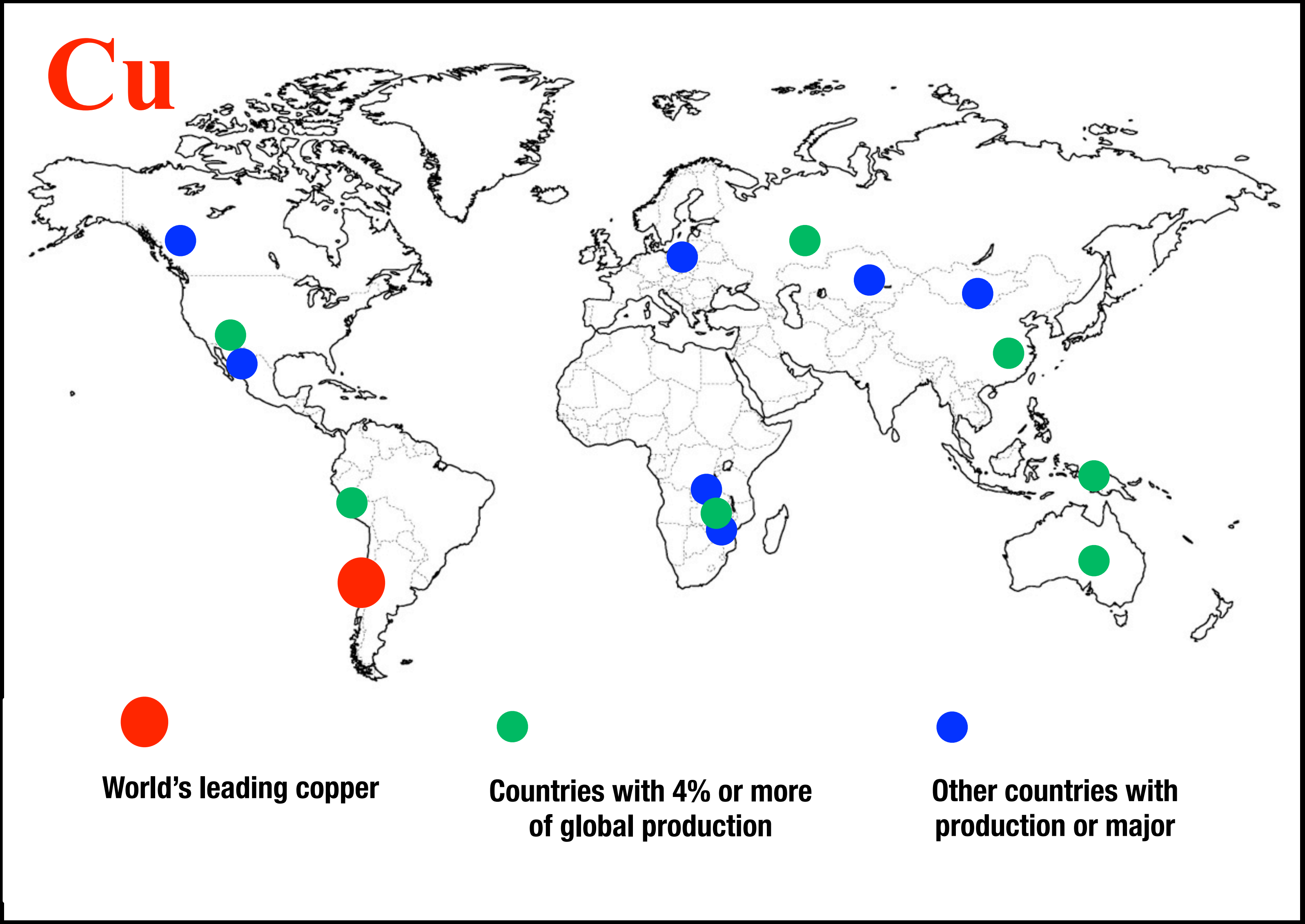
Other ECEs

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)

Why not copper? –

- resources are broadly distributed
- markets are well developed
- many substitutions from non-critical uses



General characteristics of ECEs

- Low crustal abundance ⇒ less concentrated ores, accentuated environmental issues
- Low crustal abundance ⇒ greater geographical fluctuations. Here or there, but not everywhere...
- Traditionally low demand ⇒ coproduction
- Unstable -- yet to reach their "natural" equilibrium level of utilization (see gold or aluminum...)
- Not running out ⇒ Constraints on availability

Constraints on availability

I Absolute abundance & concentration GERMANIUM...

Some are rare, others are not so rare, but they are usually not mineralized efficiently by geological processes, and do not occur in viable ores.

II Geopolitical risks REE & 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.

III 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)

IV Environmental and social concerns — REEs...

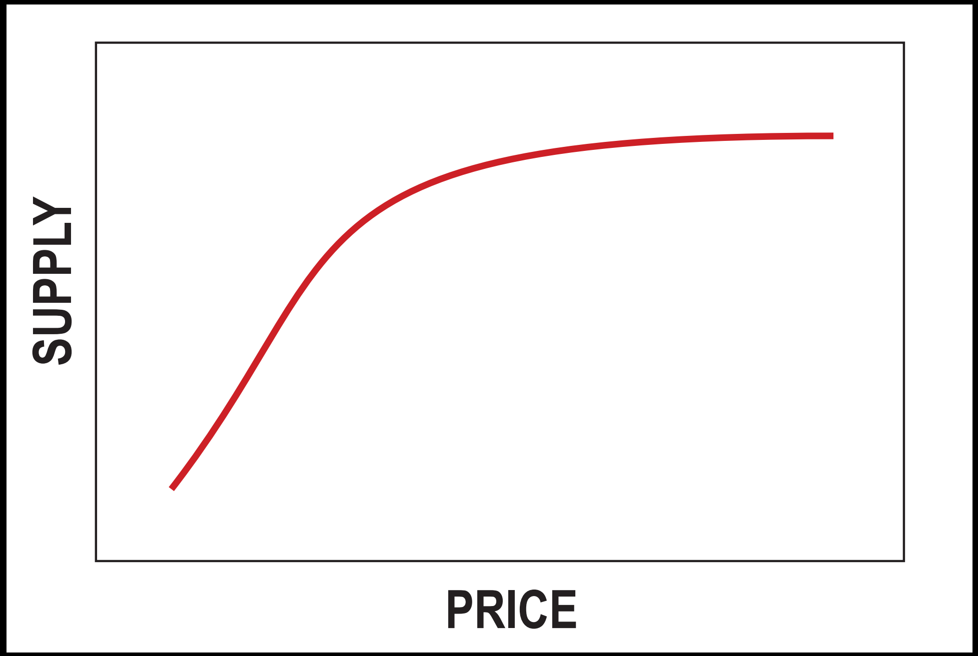
Developed world will not accept environmental disruption. Countries willing to tolerate environmental degradation for short term gain can dominate markets. Rising environmental consciousness renders this unstable.

V Response times in production & utilization — LITHIUM vs. ??

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

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), rhenium (molybdenum), ...
- Prices are artificially low (economy of scope) until the coproduction saturates. By-product does not drive production of main product. Price demand inelasticity.

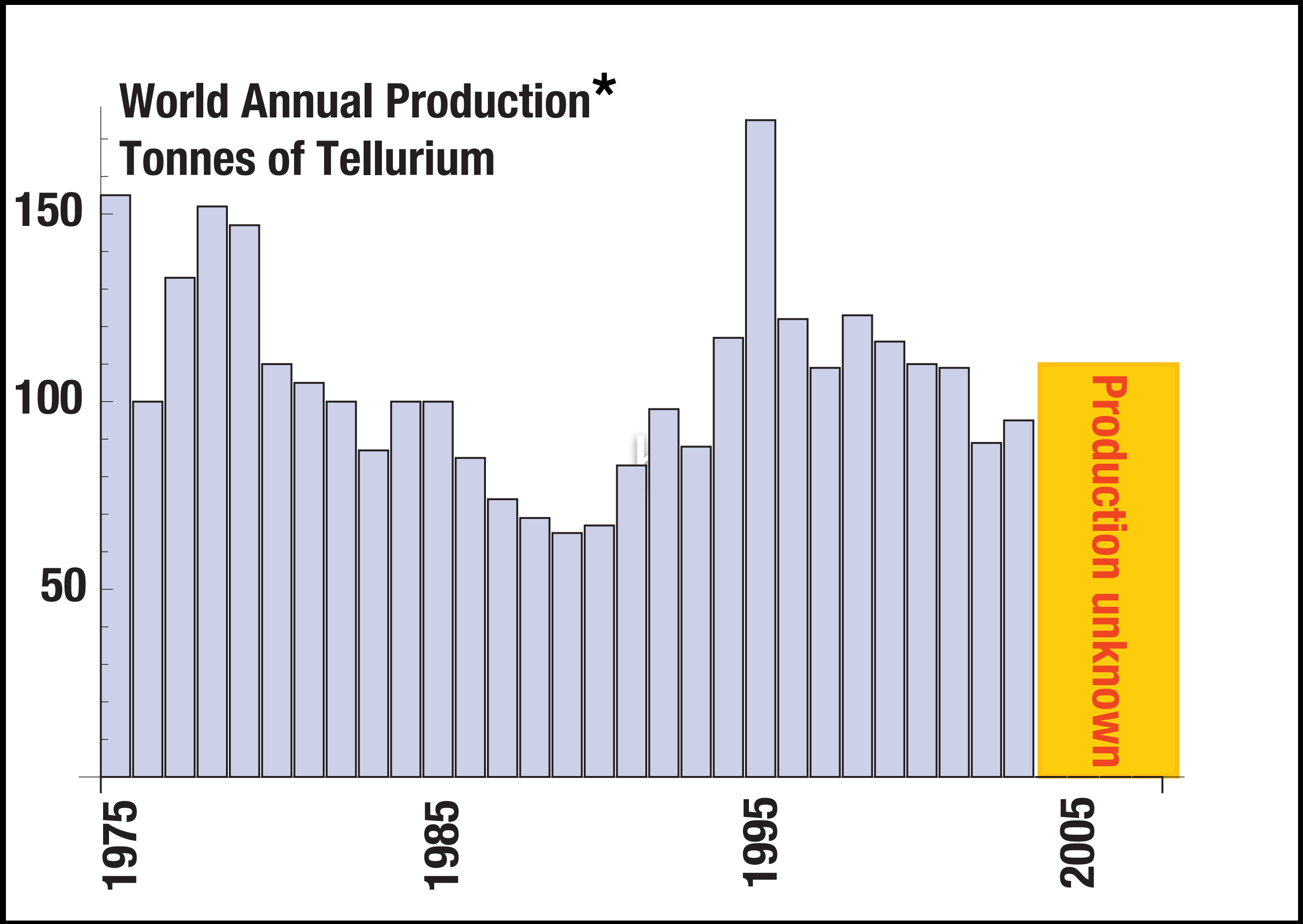


Example: Tellurium in photovoltaics

- 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(capacity)[1]
- ÷ 20 - 25% capacity factor → 400 tonnes(Te)/GW(delivered) [2]

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

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



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

* USGS Mineral Commodity Summary

† USEIA

Well... Produce more tellurium — coproduction with copper

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

What's not the solution?

- Domestic mining alone: (US) ECE independence is not a realistic or even a desirable goal.
  - Global interdependency
  - We're over 90% dependent on foreign sources for ECEs
  - Comparative advantage ⇔ international trade
- (Non-defense) We do not recommend economic stockpiling*
  - Disincentive to innovation
  - Unintended economic consequences

* We did not consider elements or policies critical to national defense

The Rhenium story (GE – 2005/2010)

Thanks to Steve Duclos (GE)

~ 25 kg Re per gas turbine

- Rhenium – critical for high performance turbines (CCGT)
- Rarest of all metals (1/10 of gold)

General electric – major Re consumer

- Anticipated the problem
- Recycled both pre- and post-consumer scrap to forestall shortage
- Mounted a major R&D program to develop new low Re alloys
- Success over 5 years

Rhenium 10 Years On ©Anthony Lipmann (2009)

The moral?

- **Information** ⇒ GE knew the Re market in detail from years of study
- **Recycling** ⇒ GE had the waste stream 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.**
  - **The place for government to step in...**

Policy — thoughts...

- **Window of opportunity** — provided by 'rare earth crisis', to establish long-perspective insurance against eternal repetition of similar events
- **Low budget impact** ⇒ atmosphere in Washington would not support otherwise
- **Non-defense** ⇒ remember, national security was not on our agenda (except as far as energy impacts it)
- **Some progress** ⇒ esp. in Executive Branch initiatives

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.

Already as our report was being printed, OSTP announced the formation of an NSTC subcommittee "Critical & Strategic Mineral Supply Chains", headed by Cyrus Wadia

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 (USGS & DOE?)

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.

Legislative action?

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.

Create national collaborative center(s) including national lab, university, and industrial participants, centered on specific ECE groups — REEs, photovoltaics, ...

Late 2011: DOE announces Critical Materials Energy Innovation Hub (see keynote talk by David Sandalow).

Legislative action?

IV. THE ROLE OF MATERIAL EFFICIENCY

"MORE PRECIOUS THAN GOLD" Consumer-oriented "Critical Materials" designation for ECE-related products. The certification to 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,

Probably should begin with examination of methods being explored and/or implemented in other countries. Looking for best practices....

V. A SPECIAL PLACE FOR HELIUM

HELIUM IS UNIQUE EVEN AMONG ECES

Helium has unique properties: cryogenic, thermal, chemical, and nuclear

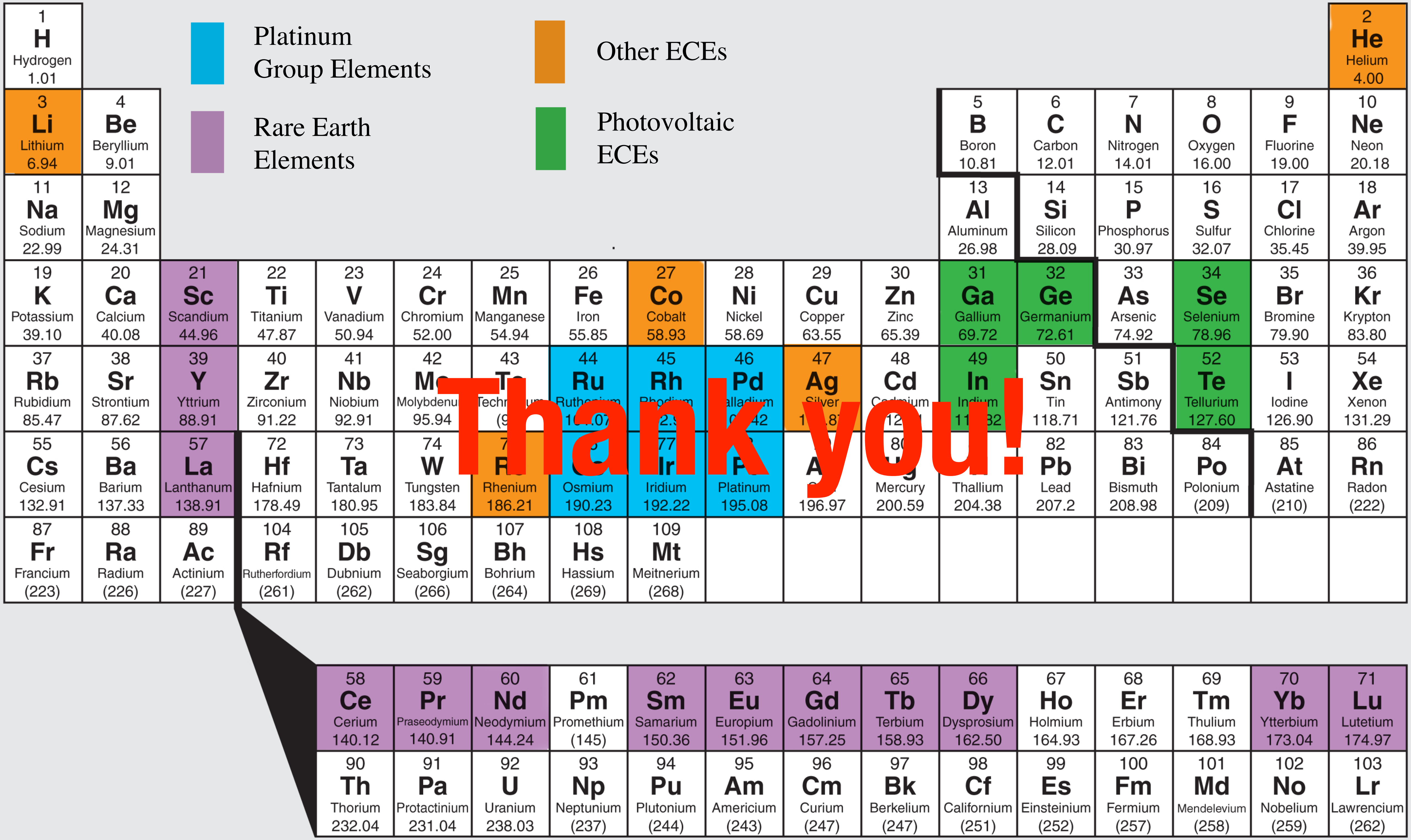
A byproduct of natural gas production, if helium is not recovered at the well-head, it is lost forever to the atmosphere.

"Measures should be adopted that will both conserve and enhance the nation's helium reserves. Failure to do so would not only be wasteful, but would also be economically and technologically shortsighted."

APS Policy Statement

New helium bill in the Senate ....

	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?
HOUSE					PSA								
• 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



Platinum Group Elements
Other ECEs
Rare Earth Elements
Photovoltaic ECEs
Thank you!
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
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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 Molybdenu 95.94
43 Techn
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
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
Rhenium 186.21
Osmium 190.23
77 Ir Iridium 192.22
Platinum 195.08
196.97
Mercury 200.59
Thallium 204.38
82 Pb Lead 207.2
83 Bi Bismuth 208.98
84 Po Polonium (209)
85 At Astatine (210)
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88 Ra Radium (226)
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