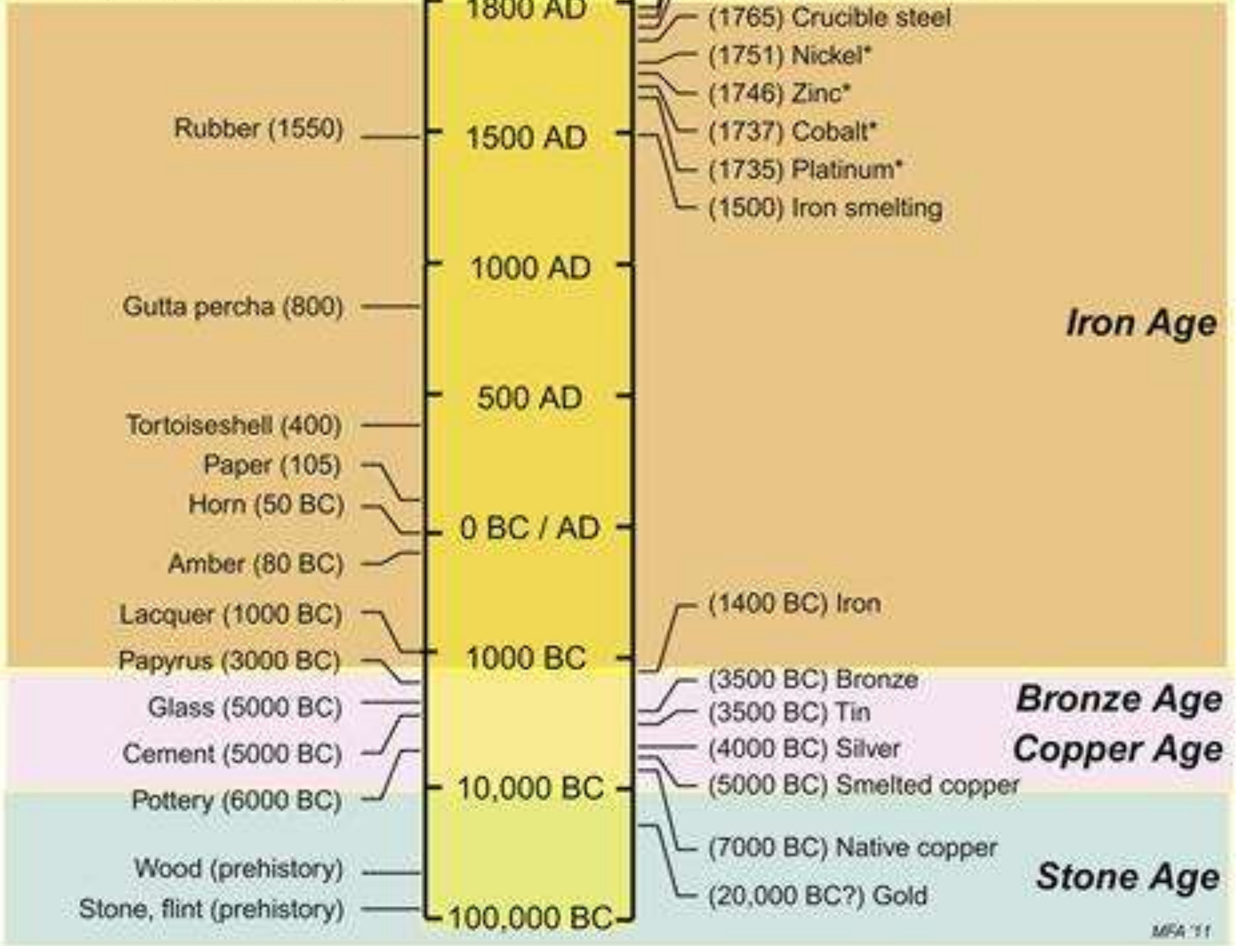
Materials Unit: Critical Materials

CEE 1610/2610: Engineering and Sustainable Development

Special THANK YOU to Cassie Thiel!

How do we

USE MATERIALS?



SOURCE: *Materials and the Environment: Eco-Informed Material Choice* Book by Michael F. Ashby

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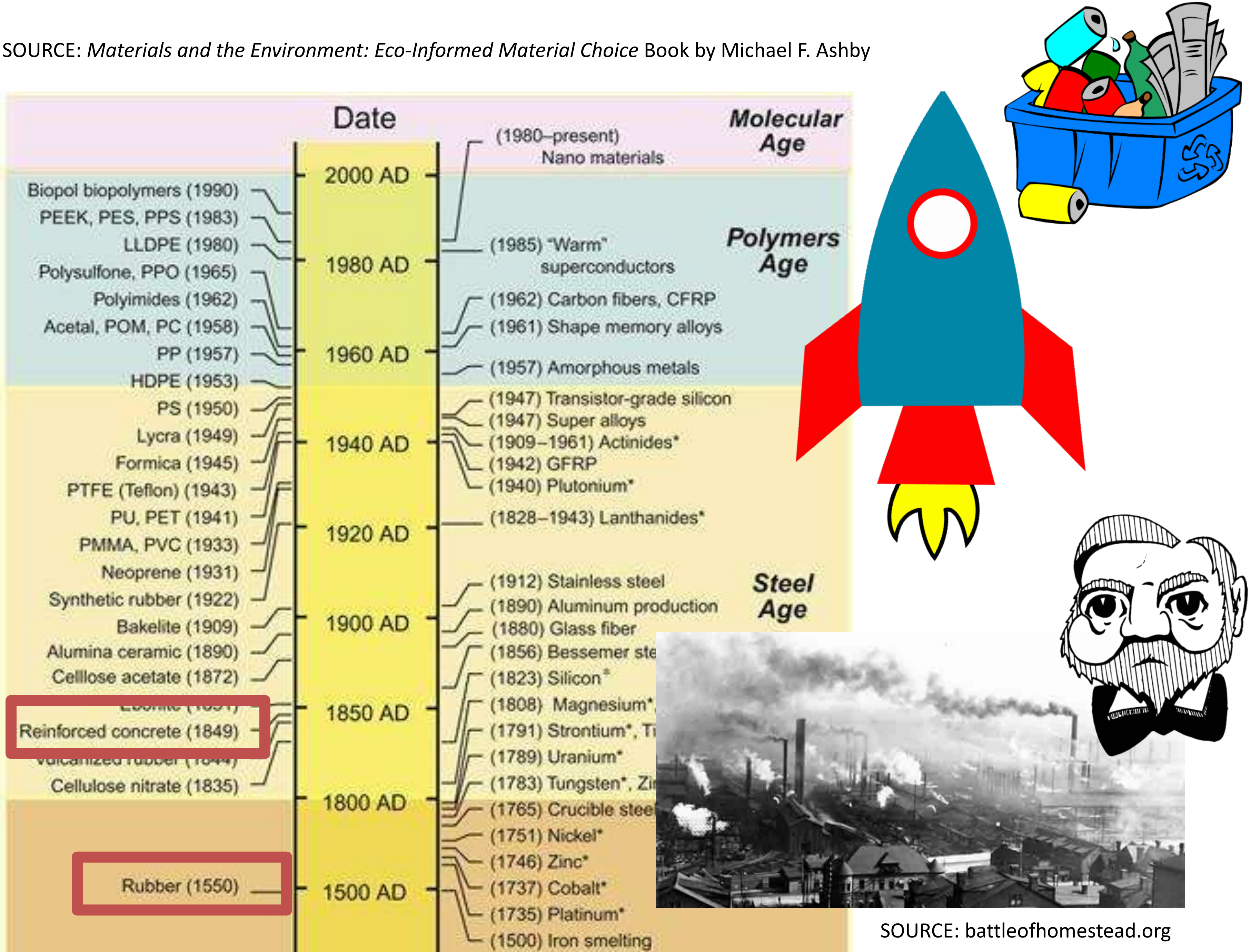
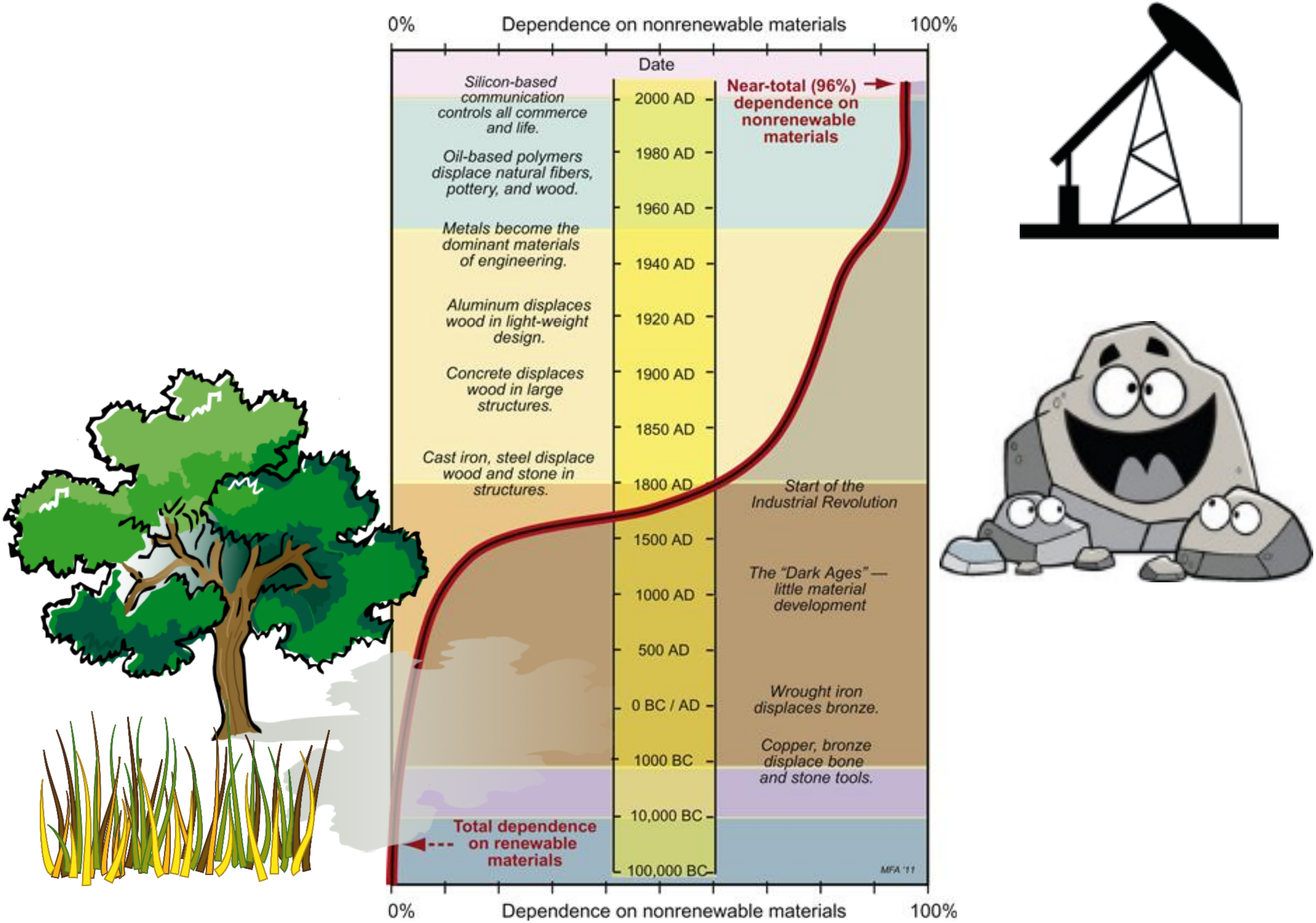


SOURCE: battleofhomestead.org



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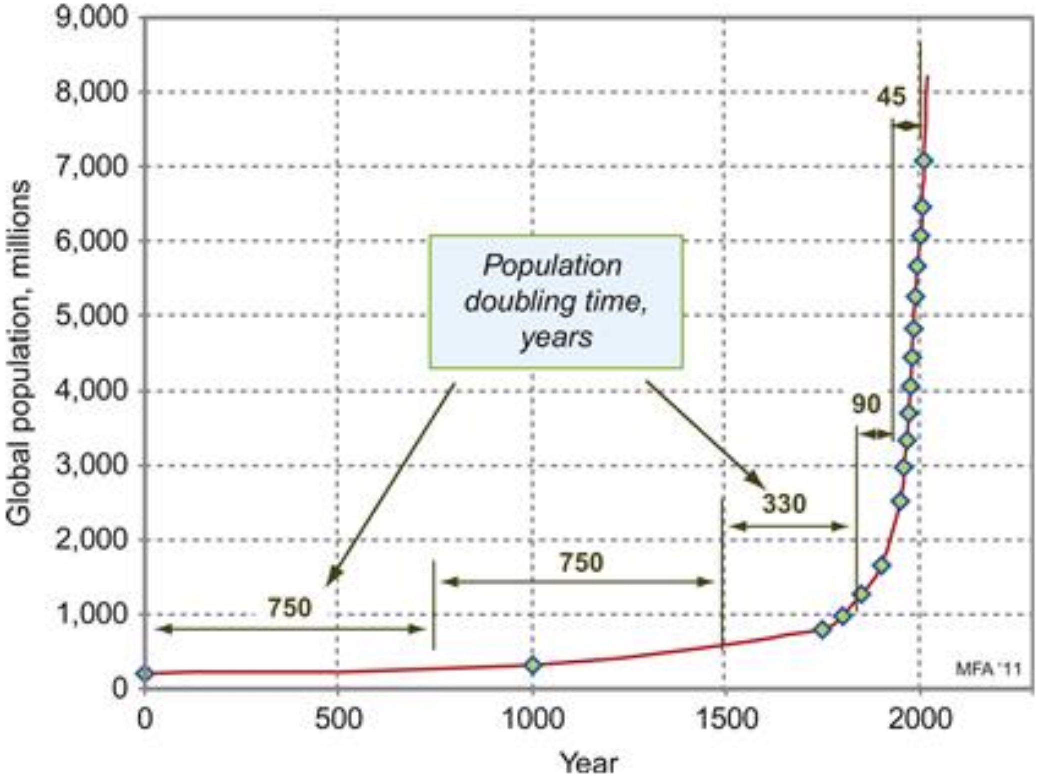


SOURCE: *Materials and the Environment: Eco-Informed Material Choice* Book by Michael F. Ashby

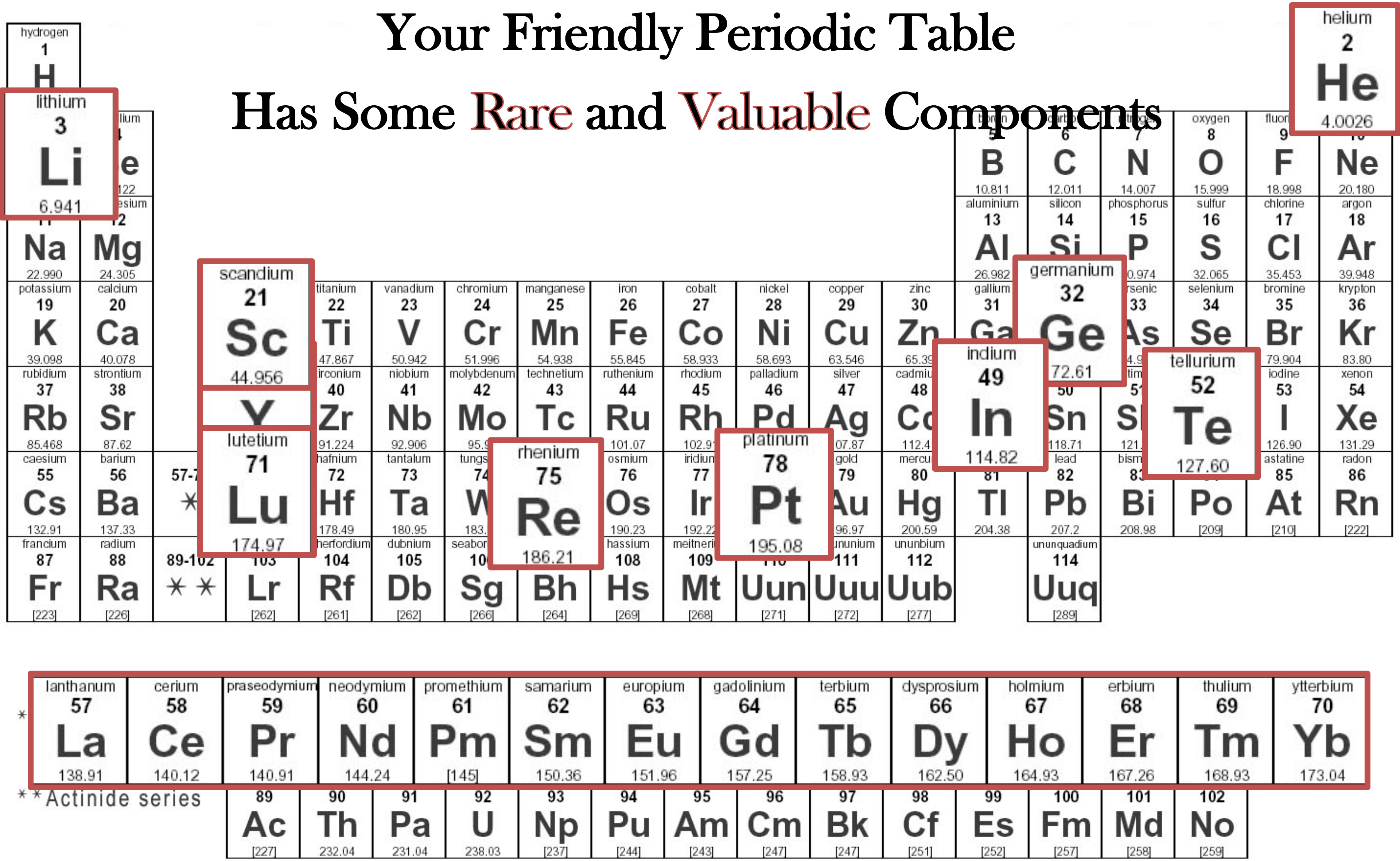
What We’ll Cover in the Materials Unit

- Critical Materials (in the molecular age)
- Material Flow Assessment
- Life Cycle Thinking
- Perspective and Summary

What is a

CRITICAL MATERIAL?

Your Friendly Periodic Table
Has Some Rare and Valuable Components



hydrogen 1 H																		helium 2 He 4.0026
lithium 3 Li 6.941	lium 4 e 122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluori 9 F 18.998	Ne 20.180
11 Na 22.990	esium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si	phosphorus 15 P 0.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga	germanium 32 Ge 72.61	rsenic 33 As 4.9	selenium 34 Se	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		Y	irconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.9	technetium 43 Tc	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd	silver 47 Ag 07.87	cadmiu 48 Cd 112.4	indium 49 In 114.82	50 Sn 118.71	tim 51 Sb 121.	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-7 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungs 74 W 183.	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 96.97	mercu 80 Hg 200.59	81 Tl 204.38	lead 82 Pb 207.2	bism 83 Bi 208.98	Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	103 Lr [262]	herfordium 104 Rf [261]	dubnium 105 Db [262]	seabor 10 Sg [266]	Bh [264]	hassium 108 Hs [269]	meitneri 109 Mt [268]	110 Uun [271]	ununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

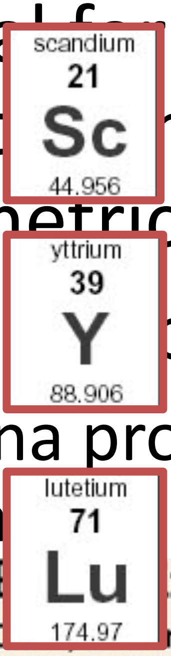
*	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* * Actinide series	89 Ac [227]	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np [237]	94 Pu [244]	95 Am [243]	96 Cm [247]	97 Bk [247]	98 Cf [251]	99 Es [252]	100 Fm [257]	101 Md [258]	102 No [259]

Rare Earth Elements (REEs)

- Critical for functionality in a wide variety of applic ns (not a large market volumetrically)
- China plies 95% of the world's REEs
  - China produced 130,000 tons of rare earth min in 2010 (USGS)

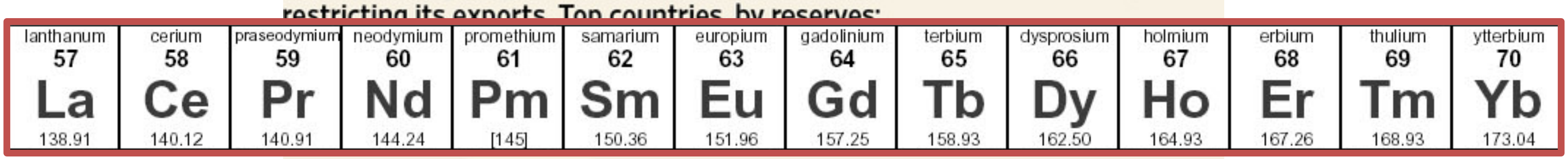
Make up <0.1% of earth's crust

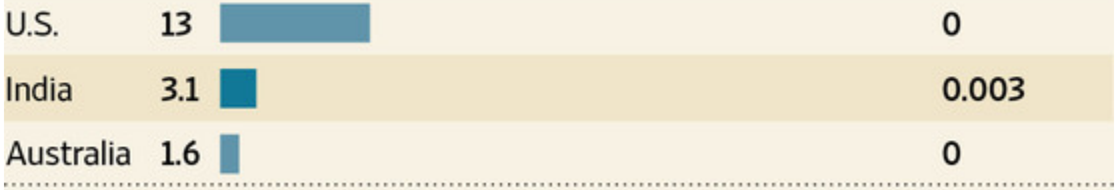
Actually quite common, just widely dispersed



I n

C rgest producer of rare-earth minerals, is accused of unfairly restricting its exports. Top countries, by reserves:





Note: U.S. and Australia plan to boost production; Source: USGS

The Wall Street Journal

http://online.wsj.com/article/SB10000872396390443437504577546772533972202.html

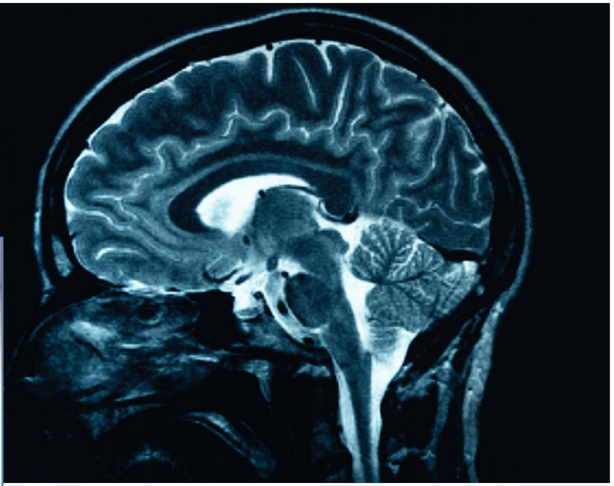
Why do

CRITICAL MATERIALS

matter?


BRAVIA
SONY


GYROSCAN
PHILIPS



Most of the **new technologies** we rely on
to improve our energy consumption and live more sustainably

CONTAIN CRITICAL MATERIALS.

Beyond that, they are
present in many everyday objects.

What are the

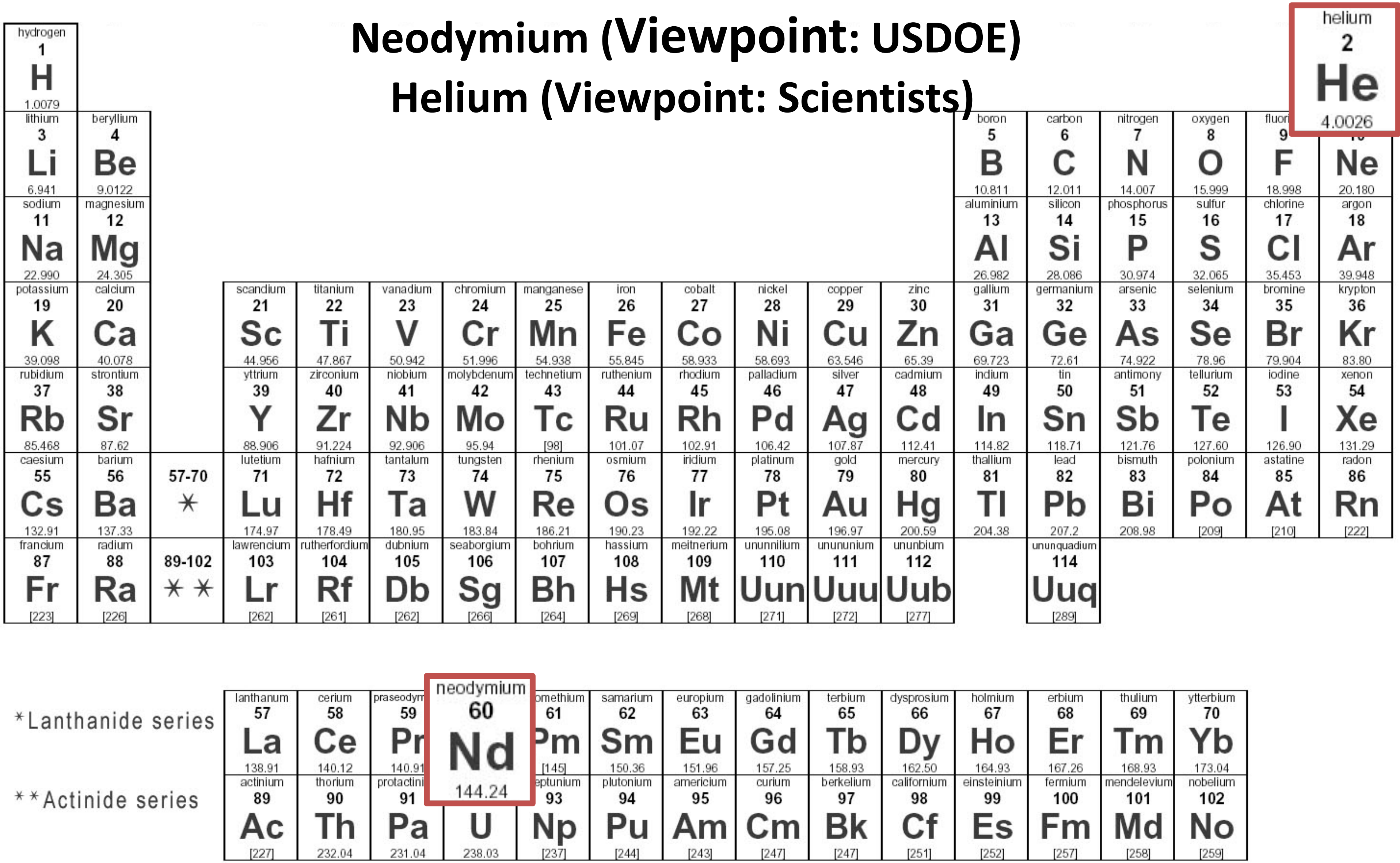
CONCERNS

with critical materials?

Let’s Look at TWO Examples

Neodymium (Viewpoint: USDOE)

Helium (Viewpoint: Scientists)



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Viewpoint: US Department of Energy

- In their “2011 Critical Materials Strategy” report, the DOE identified 16 elements as critical for future energy technologies
- They are especially concerned about: dysprosium, terbium, europium, yttrium, and neodymium

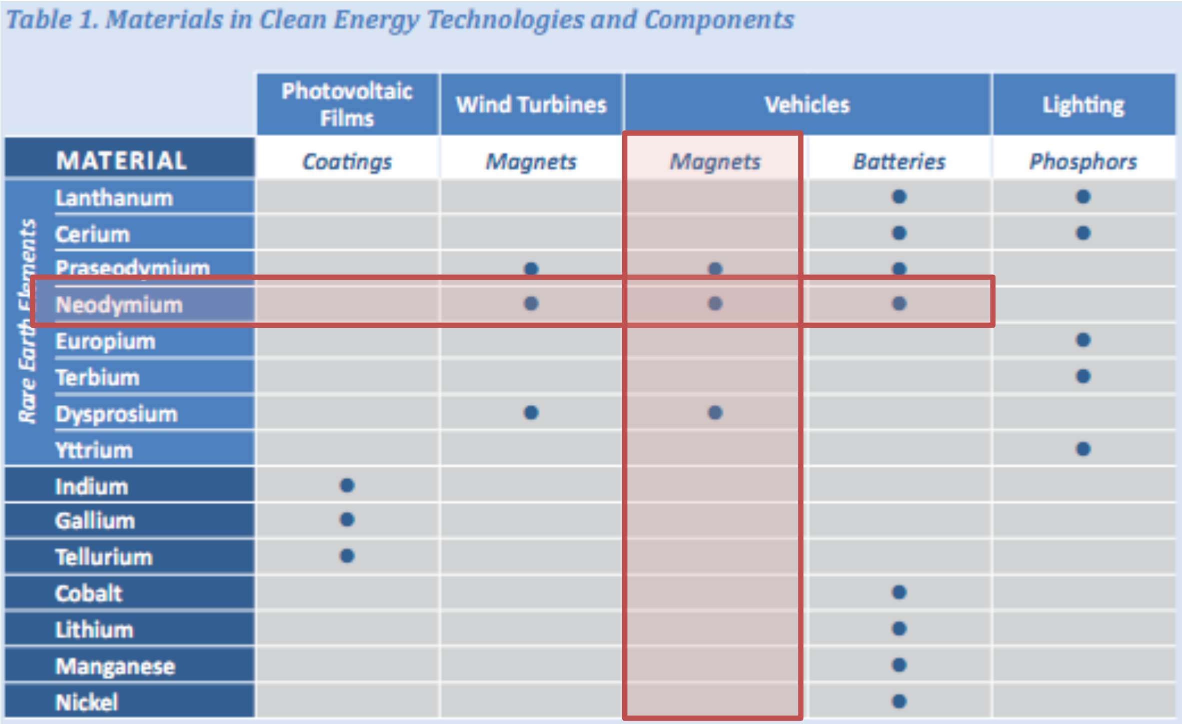


Table 1. Materials in Clean Energy Technologies and Components

		Photovoltaic Films	Wind Turbines	Vehicles		Lighting
	MATERIAL	*Coatings*	*Magnets*	*Magnets*	*Batteries*	*Phosphors*
Rare Earth Elements	Lanthanum				●	●
	Cerium				●	●
	Praseodymium		●	●	●	
	Neodymium		●	●	●	
	Europium					●
	Terbium					●
	Dysprosium		●	●		
	Yttrium					●
	Indium	●				
	Gallium	●				
	Tellurium	●				
	Cobalt				●	
	Lithium				●	
	Manganese				●	
	Nickel				●	

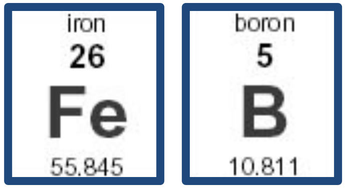
DOE, 2011

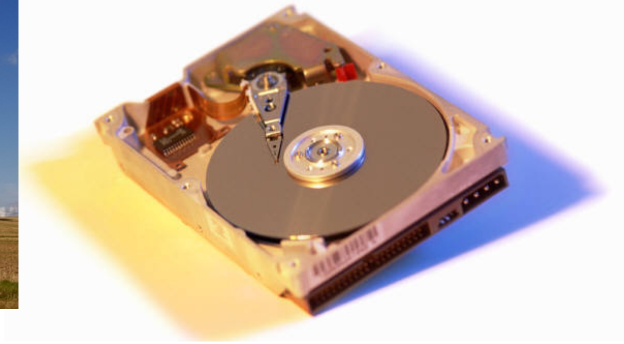
Example:

Permanent Magnets

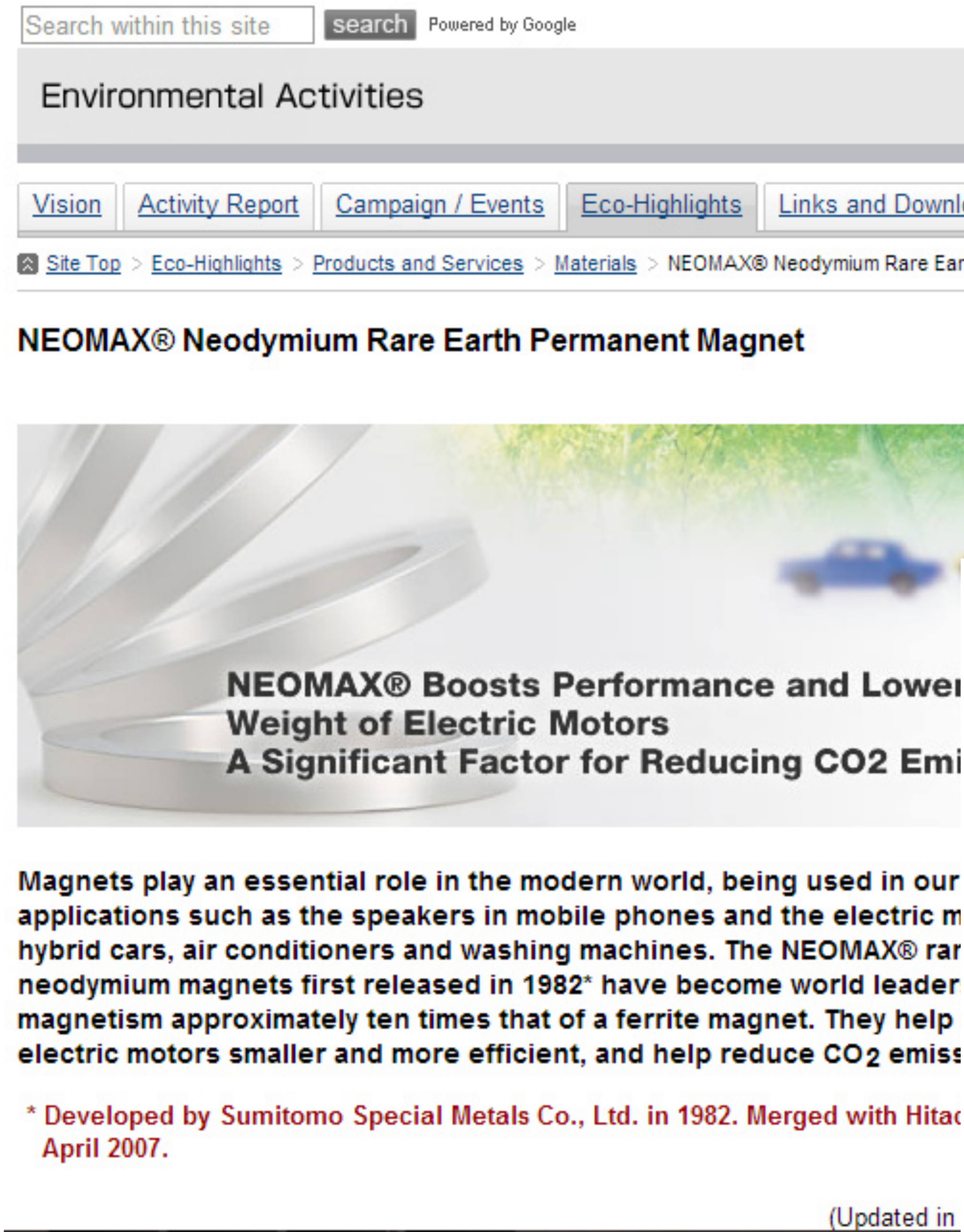
Compact, high-strength magnets made of rare earth elements

- Developed in 1970s and 80s
- Strongest type of permanent magnet (1.4 teslas)
  - Compared to 0.5 – 1.0 teslas of ferrite or ceramic magnets
- Strongest PM is made of **NEODYMIUM**
  - "Neodymium-iron-boron" NIB magnets
  - Substitute **DYSPROSIUM** and **PRASEODYMIUM** for the neodymium
- Used in
  - Hard drives, speakers, electric generators (wind turbines), and motors (power tools to cars **– ESPECIALLY electric cars)**





http://www.hitachi.com/environment/showcase/



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Environmental Activities

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Site Top > Eco-Highlights > Products and Services > Materials > NEOMAX® Neodymium Rare Earth Per

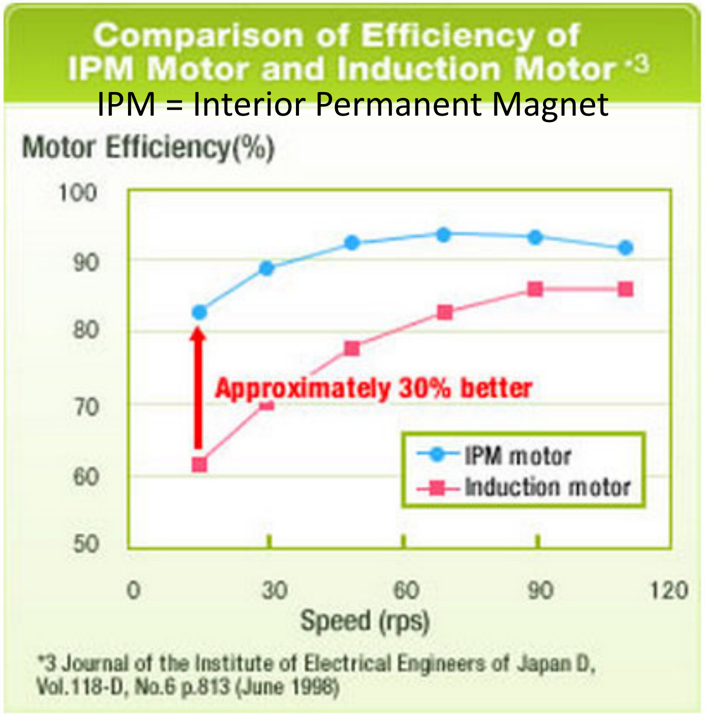
NEOMAX® Neodymium Rare Earth Permanent Magnet

NEOMAX® Boosts Performance and Lowe
Weight of Electric Motors
A Significant Factor for Reducing CO2 Emi

Magnets play an essential role in the modern world, being used in our applications such as the speakers in mobile phones and the electric m hybrid cars, air conditioners and washing machines. The NEOMAX® rar neodymium magnets first released in 1982* have become world leader magnetism approximately ten times that of a ferrite magnet. They help electric motors smaller and more efficient, and help reduce CO_2 emis

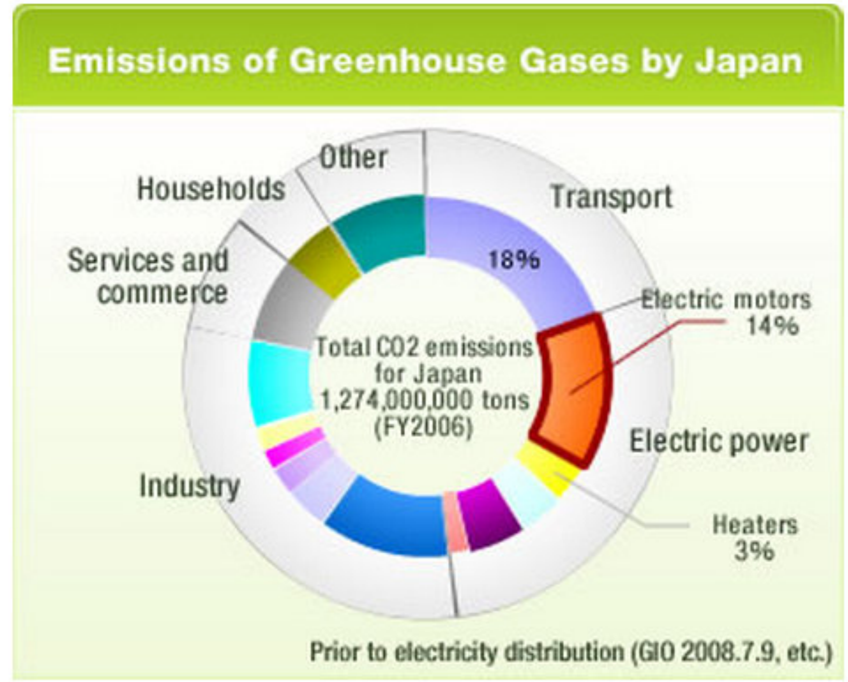
* Developed by Sumitomo Special Metals Co., Ltd. in 1982. Merged with Hita April 2007.

(Updated in



IPM = Interior Permanent Magnet

*3 Journal of the Institute of Electrical Engineers of Japan D, Vol.118-D, No.6 p.813 (June 1998)



Prior to electricity distribution (GIO 2008.7.9, etc.)

Short and Medium Term Criticality

Figure 1. Short-Term (present–2015) Criticality Matrix

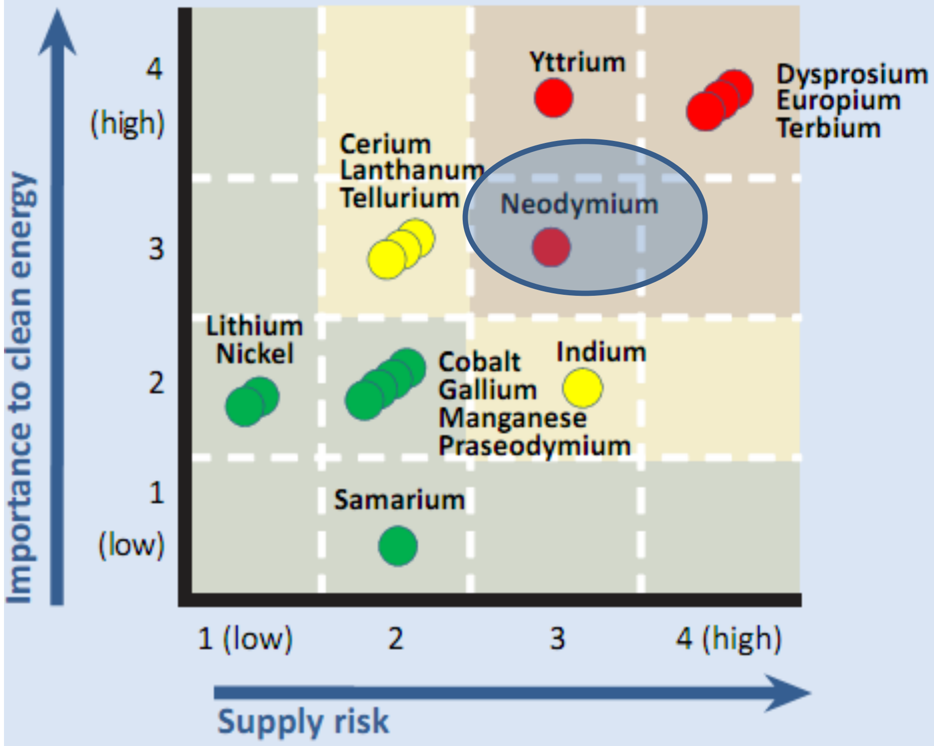
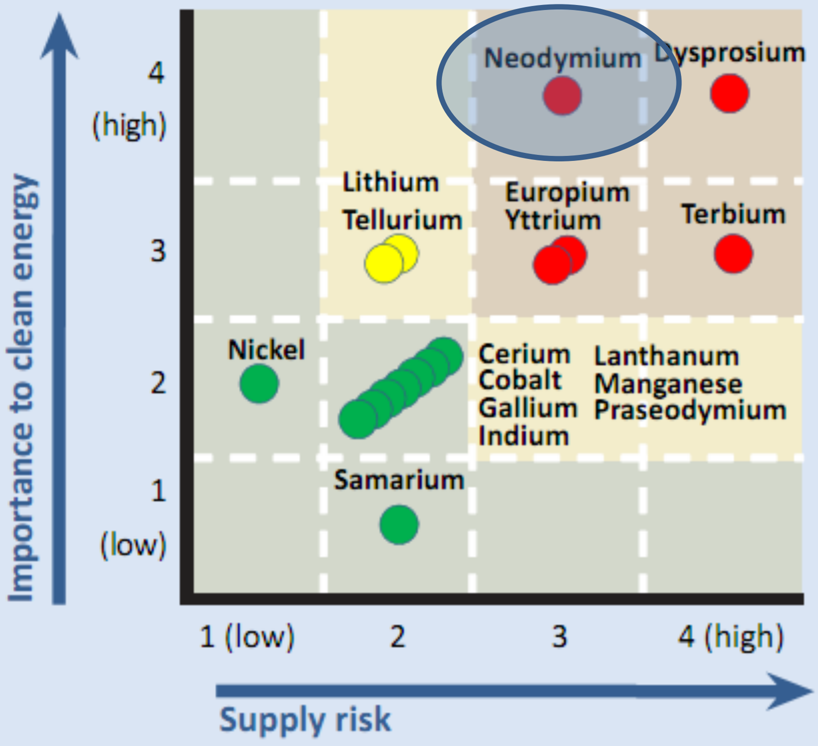


Figure 2. Medium-Term (2015–2025) Criticality Matrix



🟥 Critical 🟨 Near-Critical 🟩 Not Critical

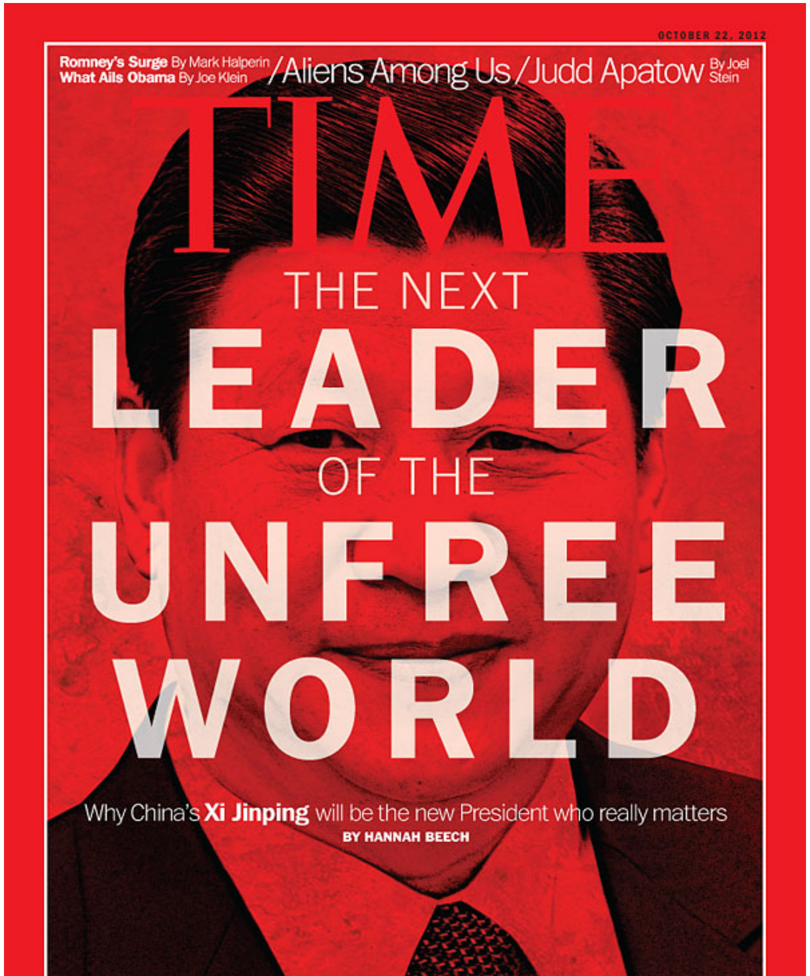
DOE, 2011

Concerns with Neodymium Supply

- China has reduced REE exports

In 2010, China suspended REE exports to Japan over a territorial dispute.

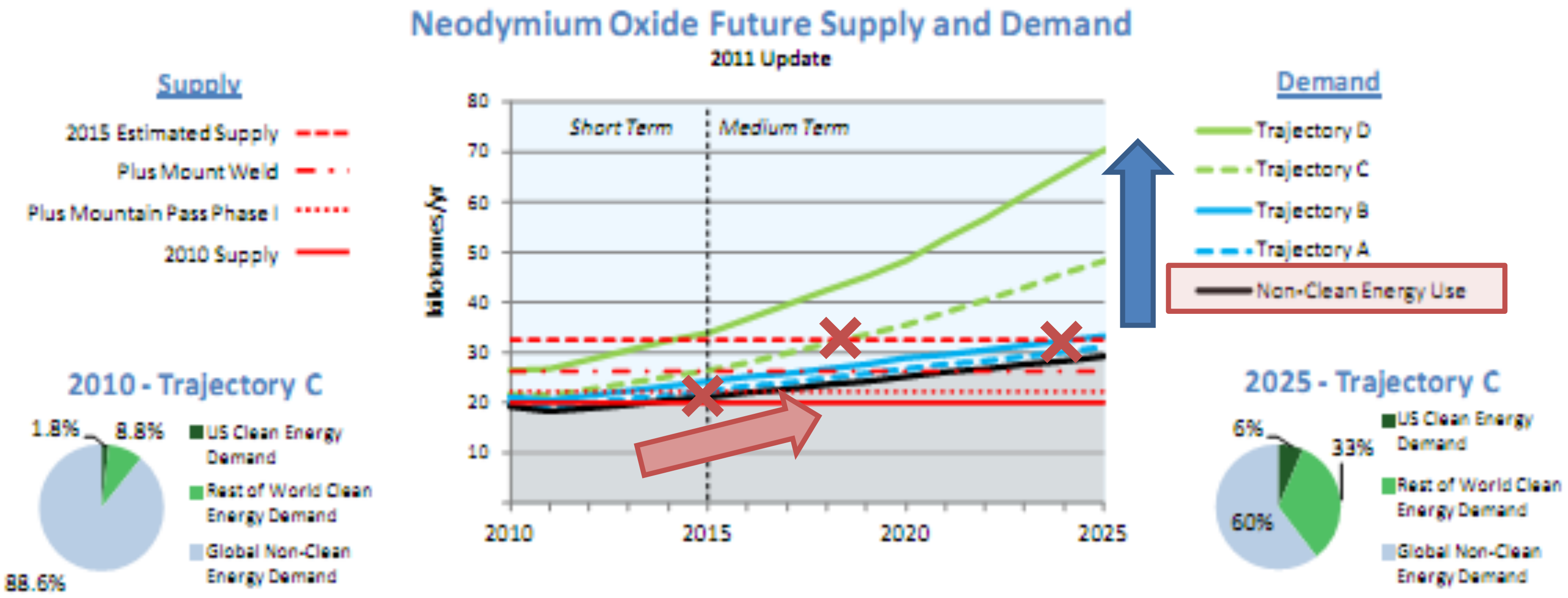
Prices jumped from \$50/kg (early 2010) to \$500/kg by summer 2011



http://www.chinas-global-media-image.net/media/uploads/cover/10/images/121022-Timemagazine.jpg

Concerns with Neodymium Supply

- China has reduced REE exports
- Global demand to increase (PHEVs, EVs, and wind turbines) with slow supply response



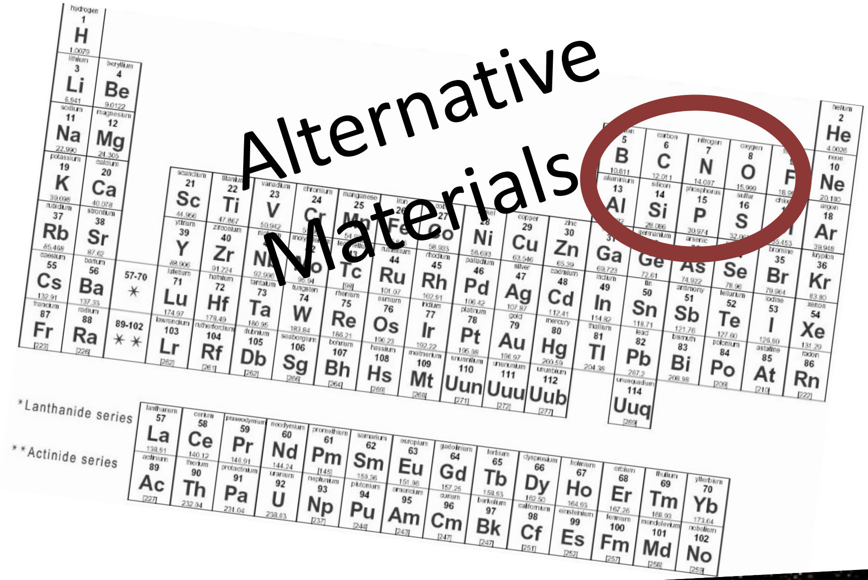
Small Groups (3-5 people)
BRAINSTORM
5 Minutes

What can we do

TO SECURE

critical materials (neodymium specifically)
for the future?

Increased Domestic Production

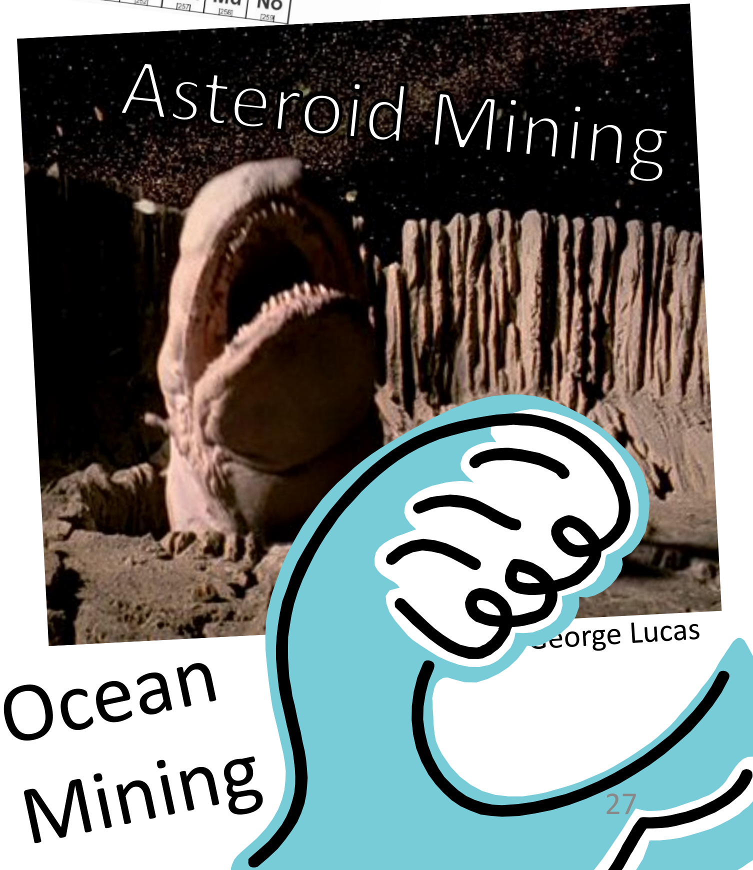


Alternative Materials

Recycling

Efficiency Improvements

Stockpiling



Asteroid Mining

eorge Lucas

Ocean Mining

What the DOE proposes for Nd

1. Diversify global supply chains
    - Risk management
    - Facilitate extraction, processing, and manufacture in the US
    - Molycorp Company reopened its rare-earth mine in Mountain Pass, CA

The Supply Problem

- China has cheap extraction and manufacturing
  - At the cost of the environment and social equity?

health

What It's Like To Take Photos Of A Dying Man

OCTOBER 04, 2015 5:59 AM ET

NADIA WHITEHEAD

http://www.npr.org/sections/goatsandsoda/2015/10/04/439241698/what-its-like-to-take-photos-of-a-dying-man

SHARE

Arriving at a hospital seven hours' drive from his remote village in the mountains, former gold miner He Quangui is finally put in a ward. The doctors proceed to puncture his lungs with a needle to remove syringe after syringe of air. In pain, He Quangui tries to clasp the drip pulley hanging from the ceiling; his brother-in-law Mi Shiliang is at a loss for how to comfort him.

Sim Chi Yin/VII

The Supply Problem

•

(1) Molycorp, (2) Lynas, (3) Indian Rare Earths/Toyota Tsusho/Shin-Etsu, (4) Kazatomprom/Sumitomo, (5) Great Western Minerals, (6) Vietnamese Govt/Toyota Tsusho/Sojitz, (7) Stans Energy, (8) Alkane Resources, (9) Arafura Resources, (10) Greenland Minerals and Energy, (11) Great Western Minerals, (12) Avalon Rare Metals, (13) Rare Element Resources, (14) Pele Mountain Resources, (15) Quest Rare Minerals, (16) Ucore Uranium, (17) US Rare Earths, (18) Matamec Explorations, (19) Tasman Metals, (20) Montero Mining/Korea Resources, (21) Namibia Rare Earths, (22) Frontier Resources/Korea Resources, (23) Hudson Resources, (24) AMR Resources, (25) Neo Material Technologies

•

Figure 4-2. Current and Projected Rare Earth Projects Outside China[87]

The Supply Problem

2012: REE mine owned by Molycorp Minerals LLC reopens in California.

Estimated annual production capacity: 19,050 mt of rare earth oxides

Molycorp 2013 Annual Report

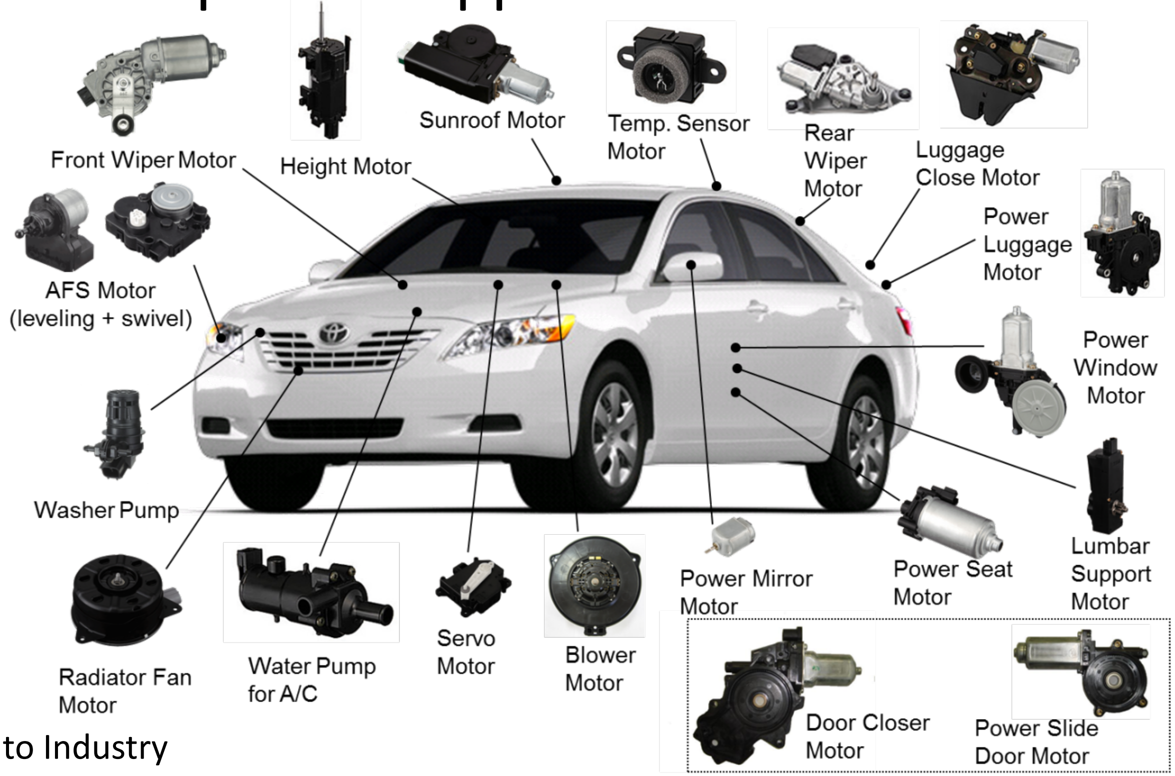
What the DOE proposes for Nd

1. Diversify global supply chains
    - Risk management
    - Facilitate extraction, processing, and manufacture in the US
2. Develop substitutes
    - Material and technology substitutes
    - DOE’s ARPA-E research agency introduced “Rare Earth Alternatives in Critical Technologies program”

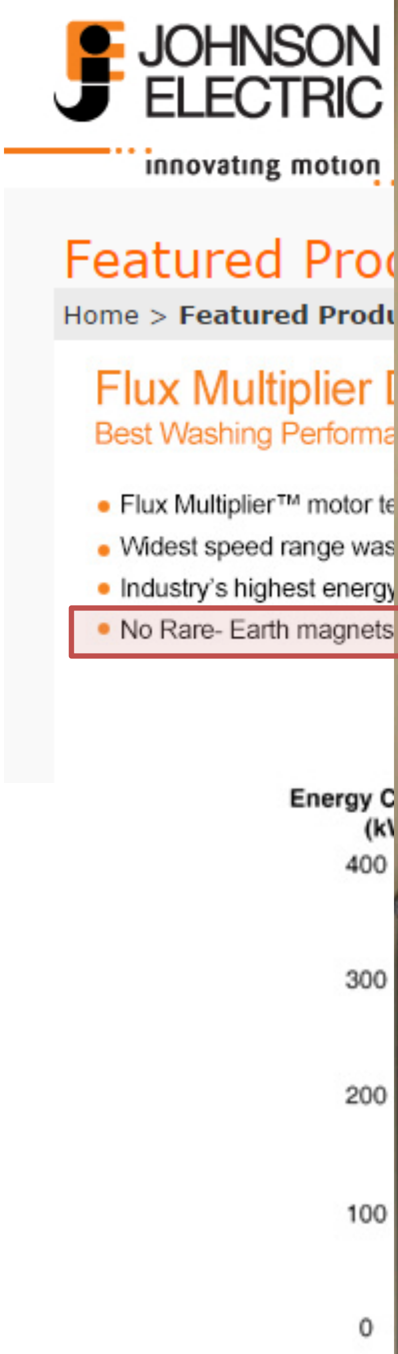
The Wicked Problem

“70 to 120 motors are used in a luxury car”

- Cars need lower weight, maximum passenger volume, and better fuel economy (CAFE standards)
- Neodymium-based motors are smaller and lighter weight for the power supplied.



Source: Friend in the Auto Industry



JOHNSON ELECTRIC

innovating motion

Featured Proc

Home > **Featured Produ**

Flux Multiplier [

Best Washing Performa

- Flux Multiplier™ motor te
- Widest speed range was
- Industry's highest energy
- No Rare- Earth magnets

Conta

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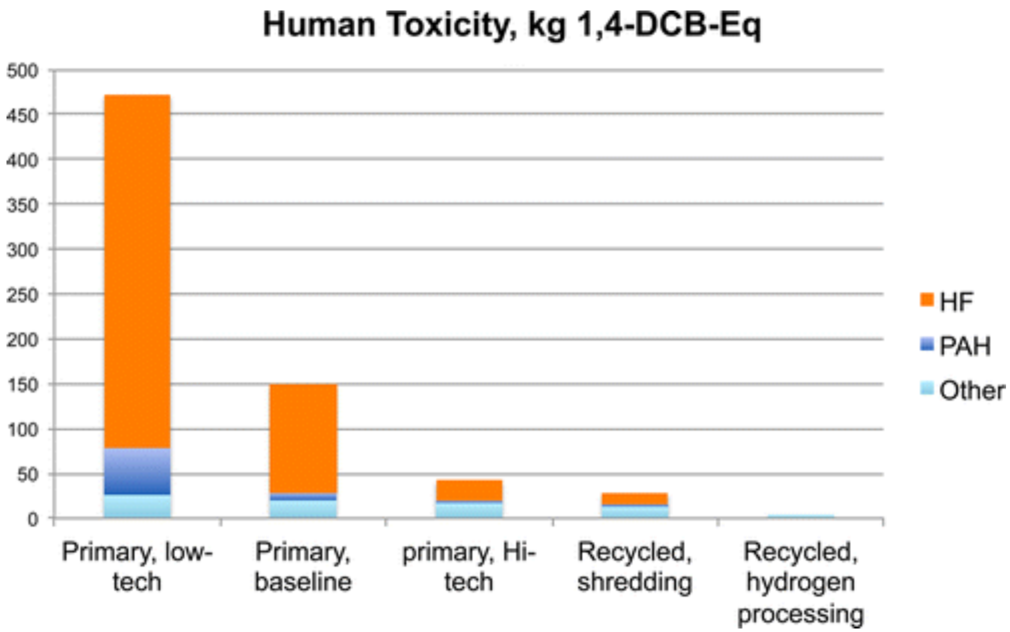
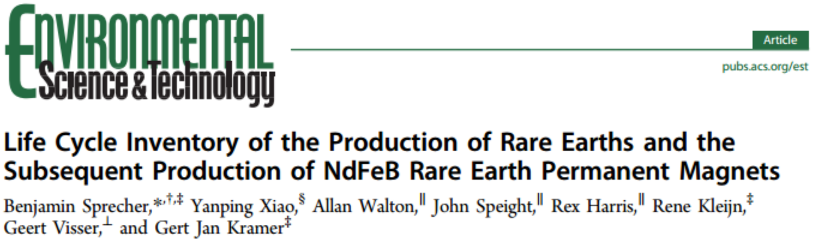
What the DOE proposes for Nd

1. Diversify global supply chains
   - Risk management
   - Facilitate extraction, processing, and manufacture in the US
2. Develop substitutes
   - Material and technology substitutes
3. Recycling, reuse, and efficiency
   - Research and policy for recycling economically
   - Honda has started a recycling program



We conclude that **recycling of neodymium**, especially via manual dismantling**, is preferable to primary production**, with some environmental indicators showing an order of magnitude improvement.

- Sprecher, et. al (2014) ES&T


ENVIRONMENTAL Science & Technology

Article

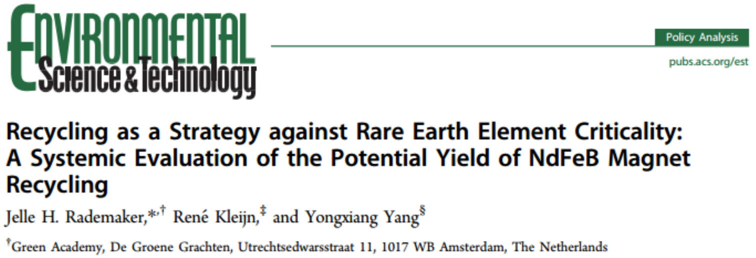
pubs.acs.org/est

Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets

Benjamin Sprecher,*,†,‡ Yanping Xiao,§ Allan Walton,‖ John Speight,‖ Rex Harris,‖ Rene Kleijn,‡ Geert Visser,⊥ and Gert Jan Kramer‡

Waste **flows from permanent magnets will remain small** relative to … growing global REE demand… During the next decade *recycling is unlikely to substantially contribute to global REE supply* security. In the **long term, waste flows will increase sharply** and will meet a substantial part of the total demand for these metals.

- Rademaker, et. al (2013) ES&T


ENVIRONMENTAL Science & Technology

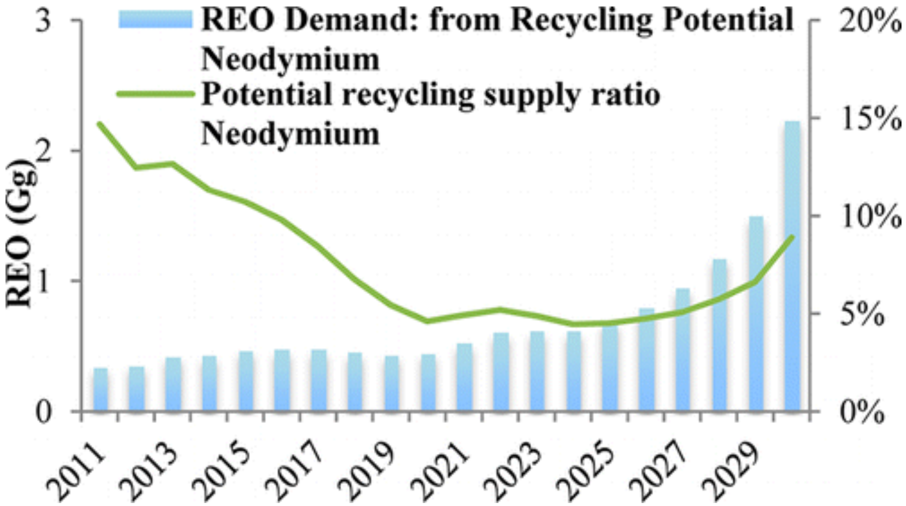
Policy Analysis

pubs.acs.org/est

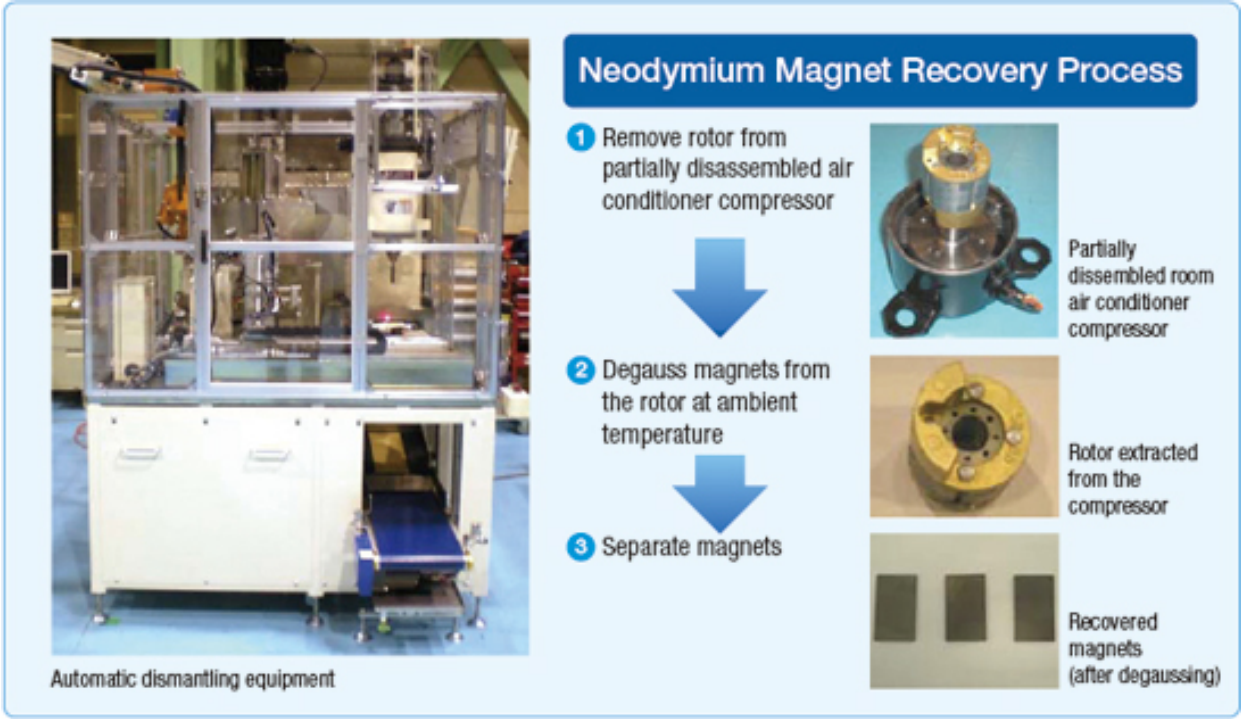
Recycling as a Strategy against Rare Earth Element Criticality: A Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling

Jelle H. Rademaker,*,† René Kleijn,‡ and Yongxiang Yang§

†Green Academy, De Groene Grachten, Utrechtsedwarsstraat 11, 1017 WB Amsterdam, The Netherlands



Mitsubishi Electric Develops Automatic Dismantling Equipment; Removes and Recovers Rare Earth Magnets from AC Compressors in Just 30 Seconds



Automatic dismantling equipment

Neodymium Magnet Recovery Process

① Remove rotor from partially disassembled air conditioner compressor

② Degauss magnets from the rotor at ambient temperature

③ Separate magnets

Partially dissembled room air conditioner compressor

Rotor extracted from the compressor

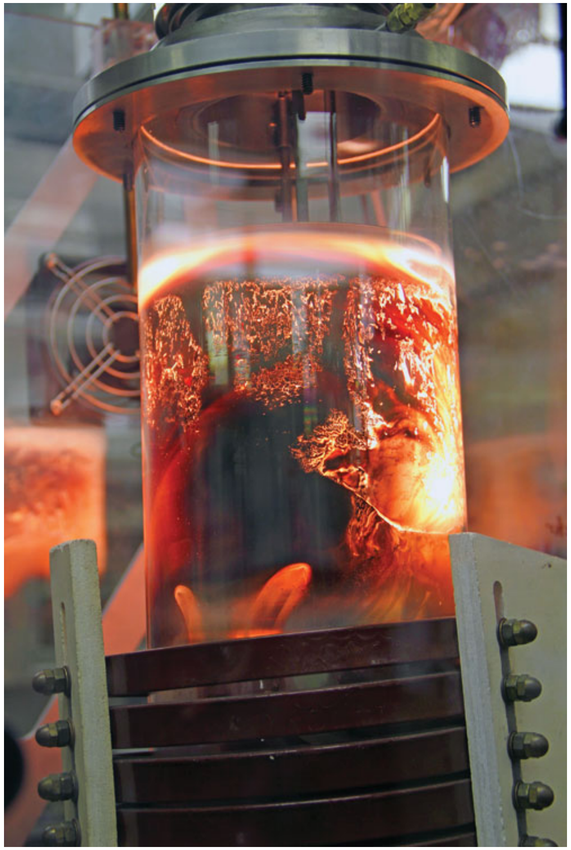
Recovered magnets (after degaussing)

http://www.mitsubishielectric.com/company/environment/ecotopics/rareearth/how/index.html

Ames Laboratory and USDOE Develop Process to Remove Rare Earths from NIB Magnet Scrap

Process: Mill magnets into small pieces, add magnesium, heat material, REEs enter molten magnesium leaving behind iron and boron, molten magnesium cast into an ingot, cooled, then magnesium is boiled off.
Results: REE properties very similar to unprocessed materials

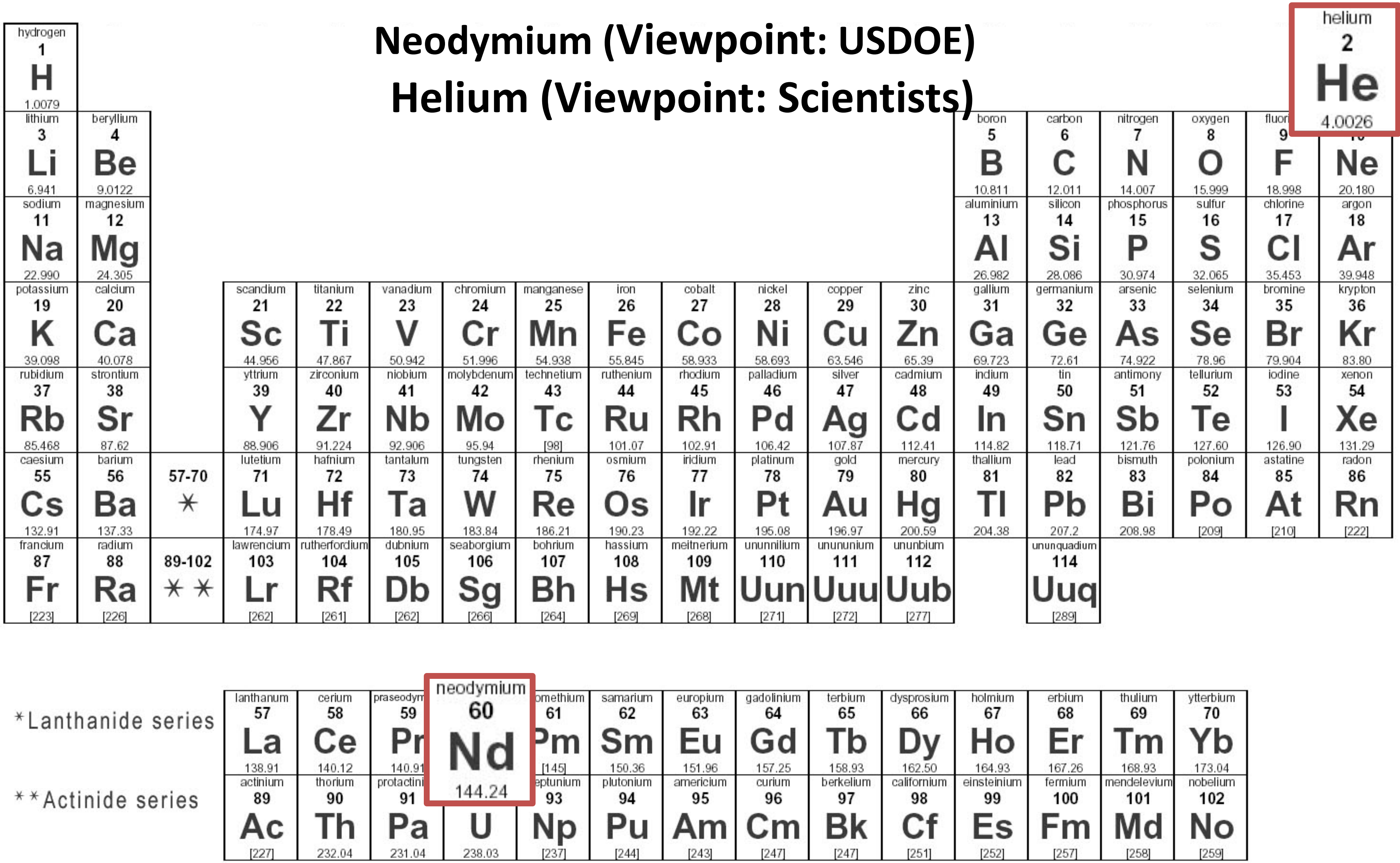
https://www.ameslab.gov/news/inquiry/rare-earth-recycling



Let’s Look at TWO Examples

Neodymium (Viewpoint: USDOE)

Helium (Viewpoint: Scientists)



hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluori 9 F 18.998	Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodym 59 Pr 140.91	neodymium 60 Nd 144.24	omethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* *Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactini 91 Pa 231.04	U 238.03	eptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

Viewpoint: Scientists

- We often think of earth as a closed system for materials. Here’s a secret:

Helium will run out in less than 300 years.

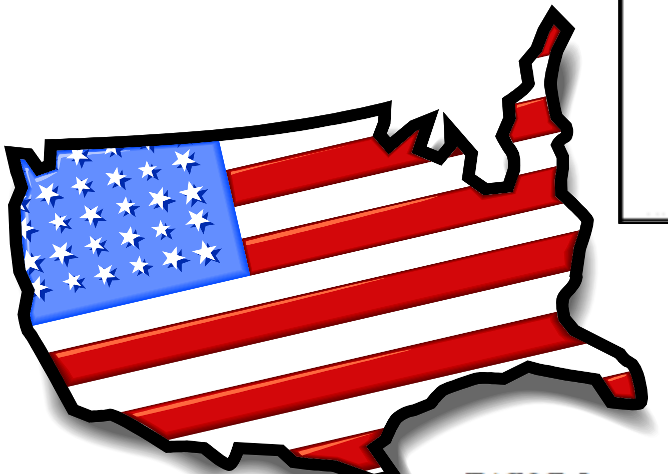
- Based on US Geological Survey

Example:

Helium

(http://minerals.usgs.gov/minerals/pubs/commodity/helium/myb1-2010-heliu.pdf)

- Lowest melting point of any element (-452 degrees Fahrenheit) & inert
- Second most abundant element in the universe (produced when hydrogen atoms fuse together in stars’ cores)
- Rare on earth
    - Generated through radioactive decay in Uranium and Thorium atoms (generates 3.4L/km of earth/year)
    - Exists as an impurity in natural gas fields and is extracted when it’s concentration is >0.3% (economical)
- Produced (and consumed) mostly in the US – 78% of world’s He supply comes from the US
- Other production locations: Algeria, Canada, China, Qatar, Poland and Russia



helium
2
He
4.0026

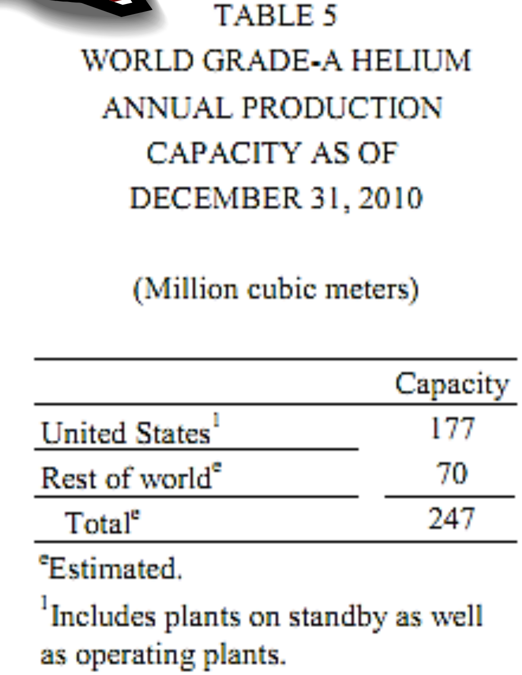


TABLE 5
WORLD GRADE-A HELIUM
ANNUAL PRODUCTION
CAPACITY AS OF
DECEMBER 31, 2010

(Million cubic meters)

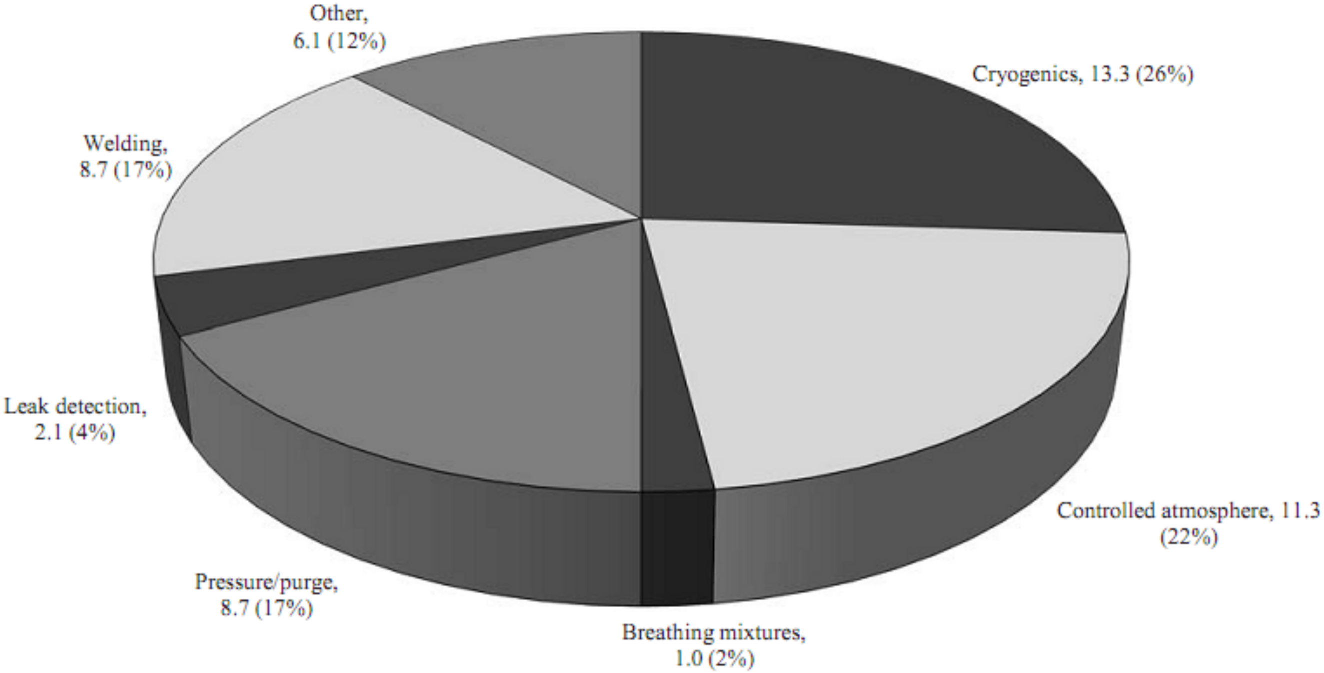
	Capacity
United States[1]	177
Rest of world[e]	70
Total[e]	247

[e] Estimated.

[1] Includes plants on standby as well as operating plants.

US Geological Survey

How Is He Used?

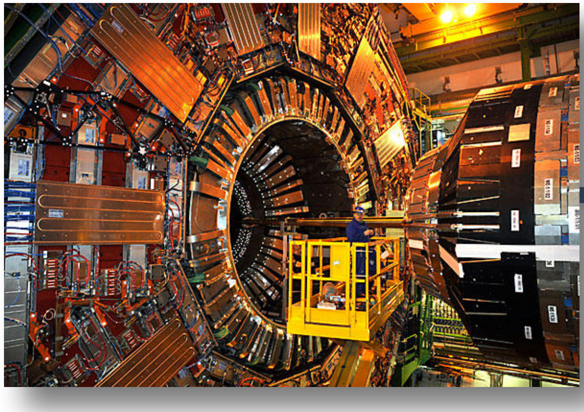


ESTIMATED HELIUM CONSUMPTION, BY END USE, IN THE UNITED STATES IN 2010[1],*

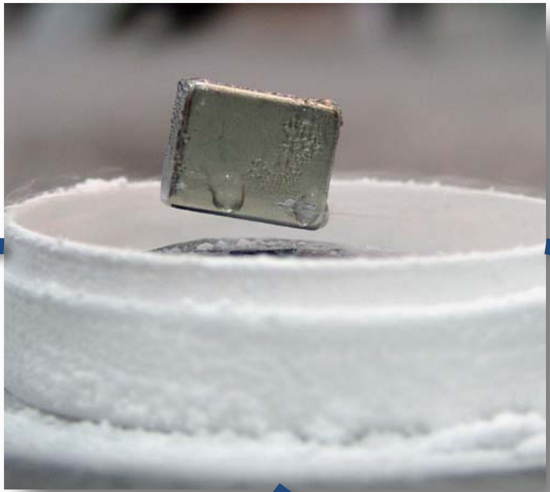
[1] Total helium used in the United States in 2010 was estimated to be 51.2 million cubic meters.

*Correction posted on January 13, 2012.

How Is He Used?

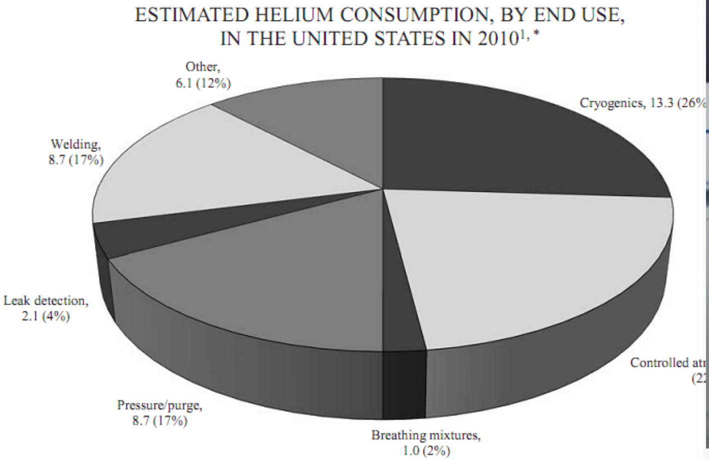


Particle Accelerators



Superconductors
(Superconducting Magnets)

Future Renewable
Energy Generation



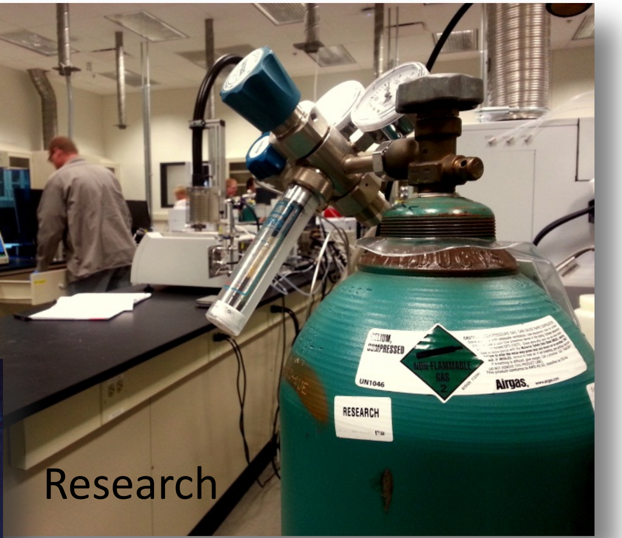
ESTIMATED HELIUM CONSUMPTION, BY END USE,
IN THE UNITED STATES IN 2010[1,*]

[1] Total helium used in the United States in 2010 was estimated to be 51.2 million cubic meters.

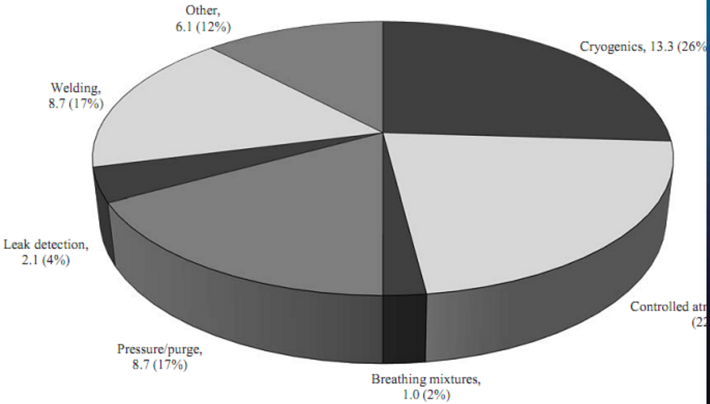
*Correction posted on January 13, 2012.

Medical Testing - MRI Machines

How Is He Used?



ESTIMATED HELIUM CONSUMPTION, BY END USE,
IN THE UNITED STATES IN 2010[1, *]



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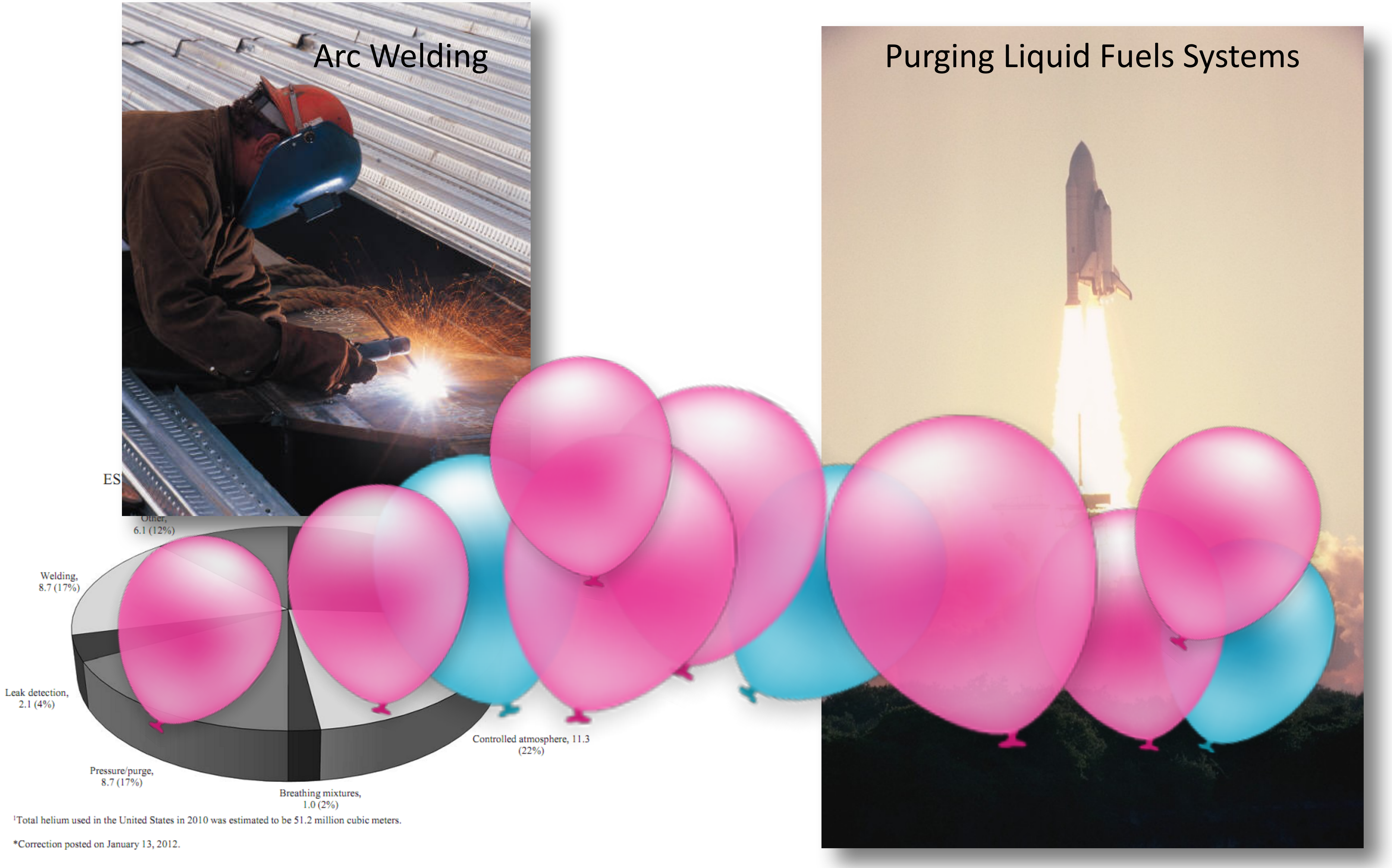
*Correction posted on January 13, 2012.

How Is He Used?



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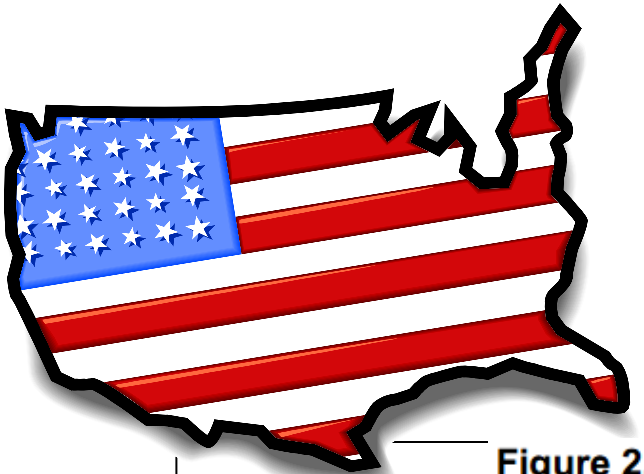


78% of world's helium supply comes from the US

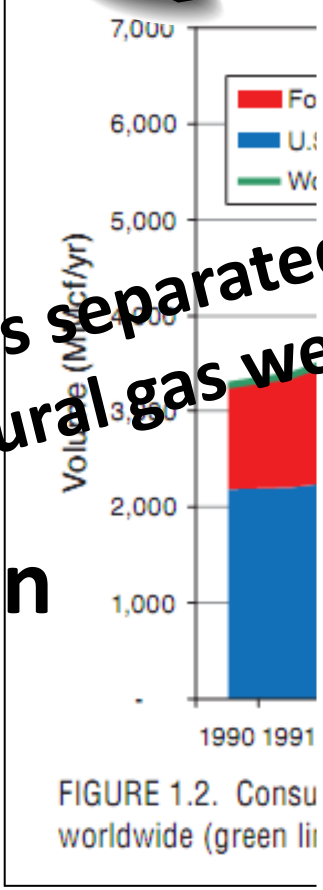
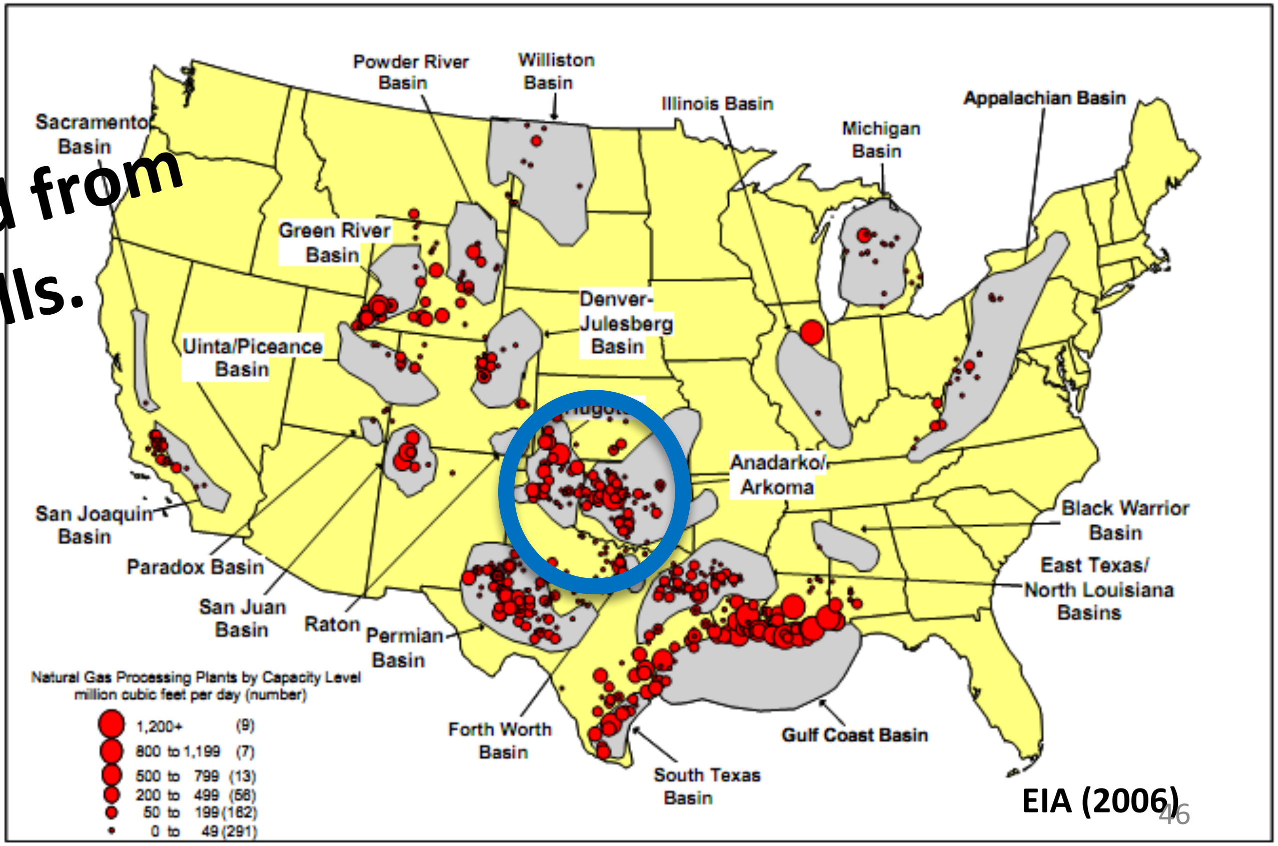


FIGURE 1.2. Consu
worldwide (green li

Helium is separated from ^certain natural gas wells.

Figure 2. Concentrations of Natural Gas Processing Plants, 2004



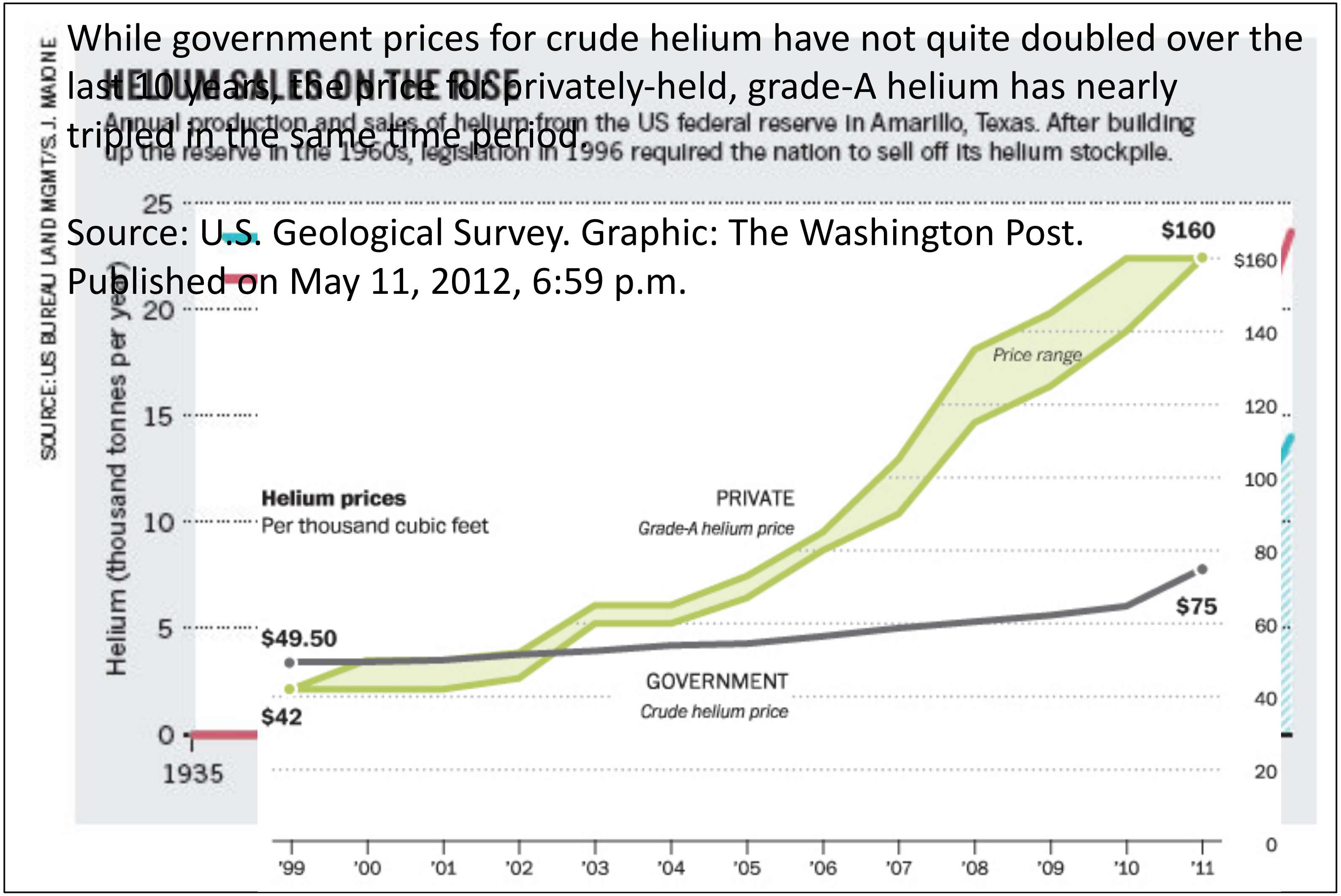
EIA (2006)

Federal Helium Reserve

- In 1996, approximately 1 billion cubic meters
- Cost of $1.4 billion
- 1996 Helium Privatization Act
- Sales of nearly all stored He between 2005-2015
- Non-market rates

While government prices for crude helium have not quite doubled over the last 10 years, the price for privately-held, grade-A helium has nearly tripled in the same time period.

Source: U.S. Geological Survey. Graphic: The Washington Post. Published on May 11, 2012, 6:59 p.m.



Selling the Helium Reserve National Academy Press

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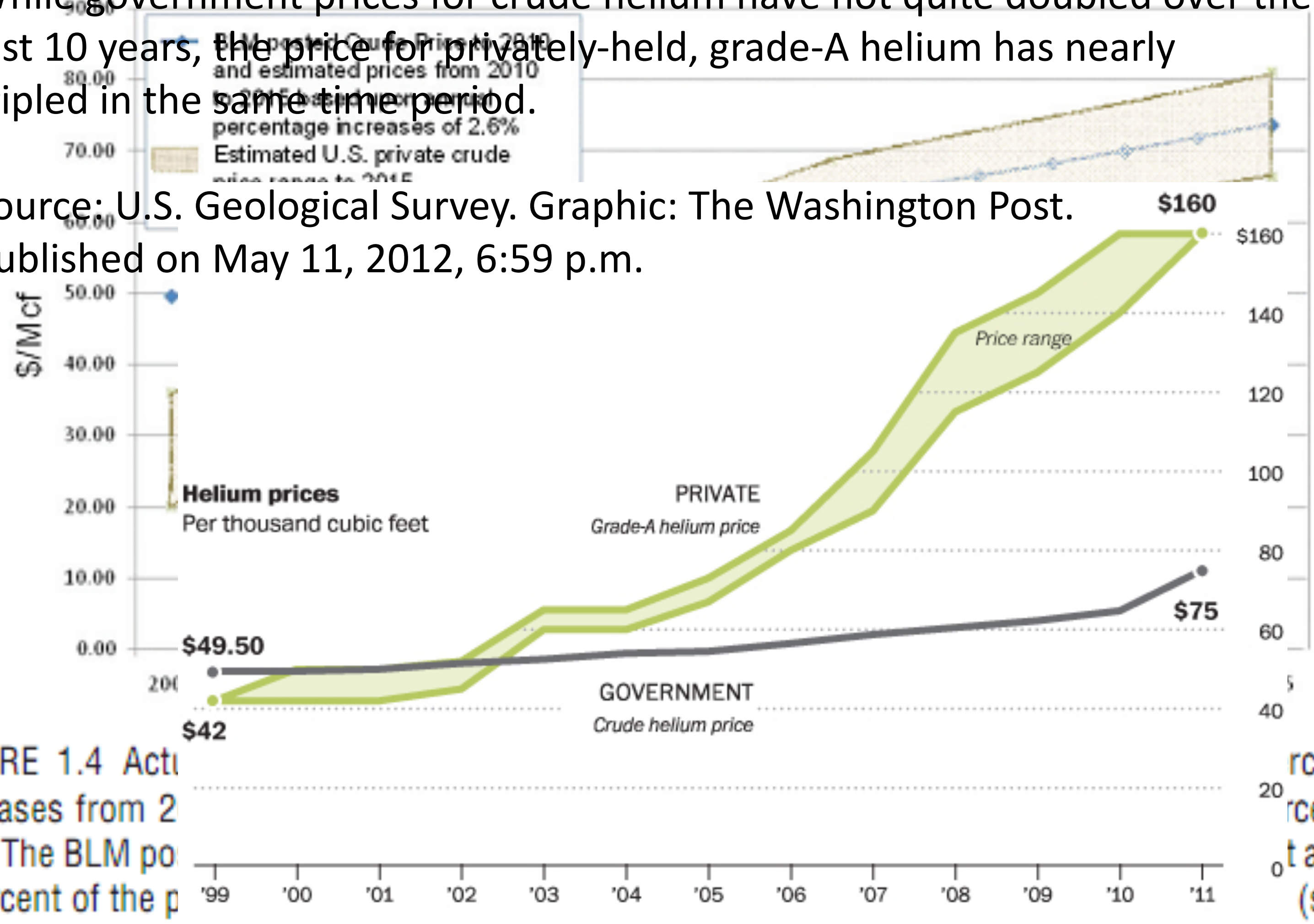


FIGURE 1.4 Actu rcentage
increases from 2 rcent per
year. The BLM po t average
5 percent of the p (shaded
areas). See text for discussion.

Selling the Helium Reserve National Academy Press

What can we do?

Politicians signed a bill (IT'S TRUE!) in 2013 that slowly ended the Helium Reserve's below-market rates.
Helium is now auctioned off to highest bidder (ending price distortion)

Market-driven He may ensure it's efficient and proper use, but we may still need new sources.

Volatility is expected to increase as the federal reserve is depleted.

Short Term

2014: Qatar becomes 2nd largest helium producer with a plant that can produce 60 million m^3 of He per year

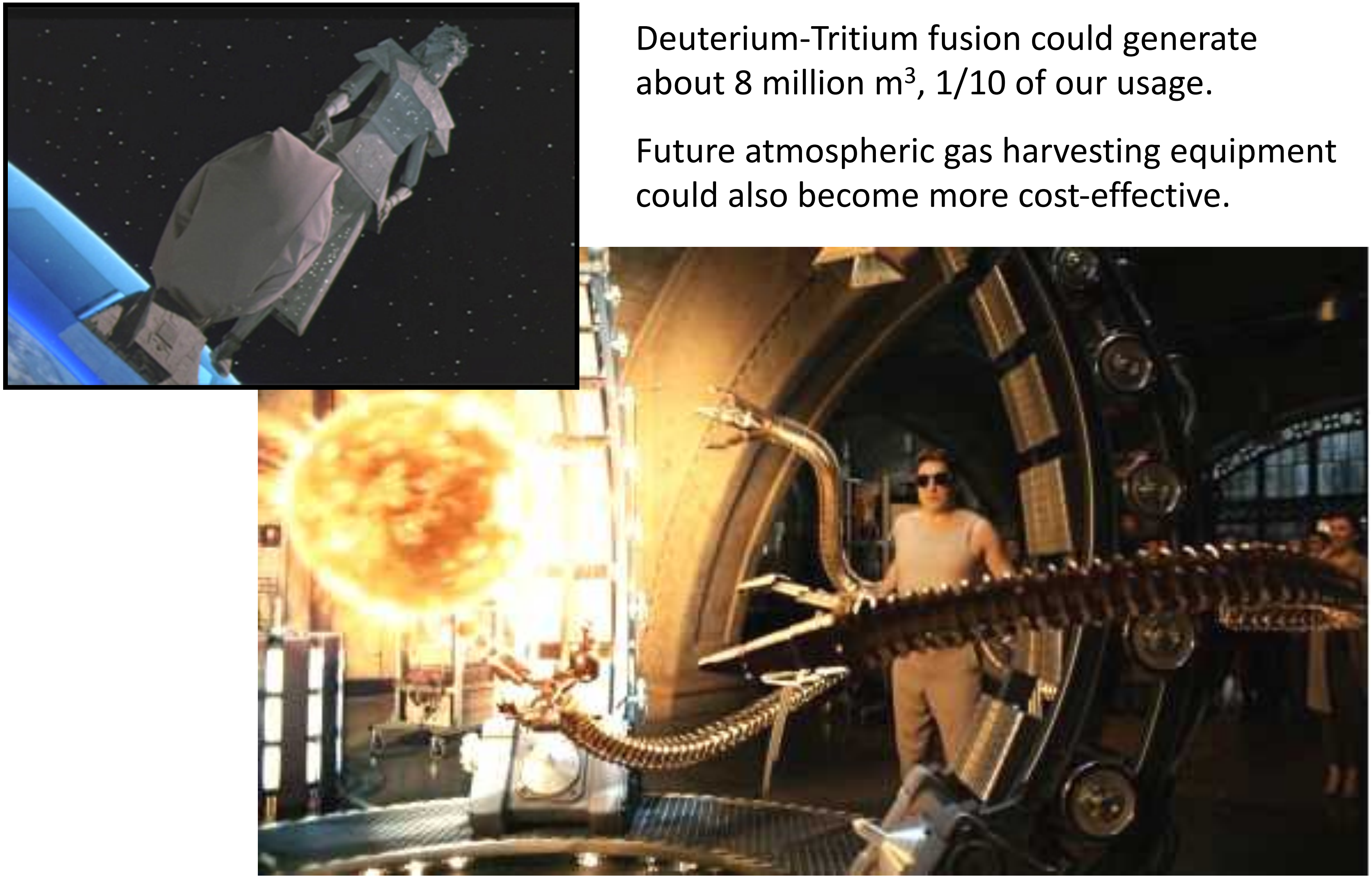
2015: New plant in Colorado set to remove He from a natural CO_2 reserve (CO_2 being used in Texas for enhanced oil recovery)

There is likely to be continued helium shortages and price spikes.
Highly recommended to recover and reuse He, or find alternatives.

Options

Deuterium-Tritium fusion could generate about 8 million m^3, 1/10 of our usage.

Future atmospheric gas harvesting equipment could also become more cost-effective.

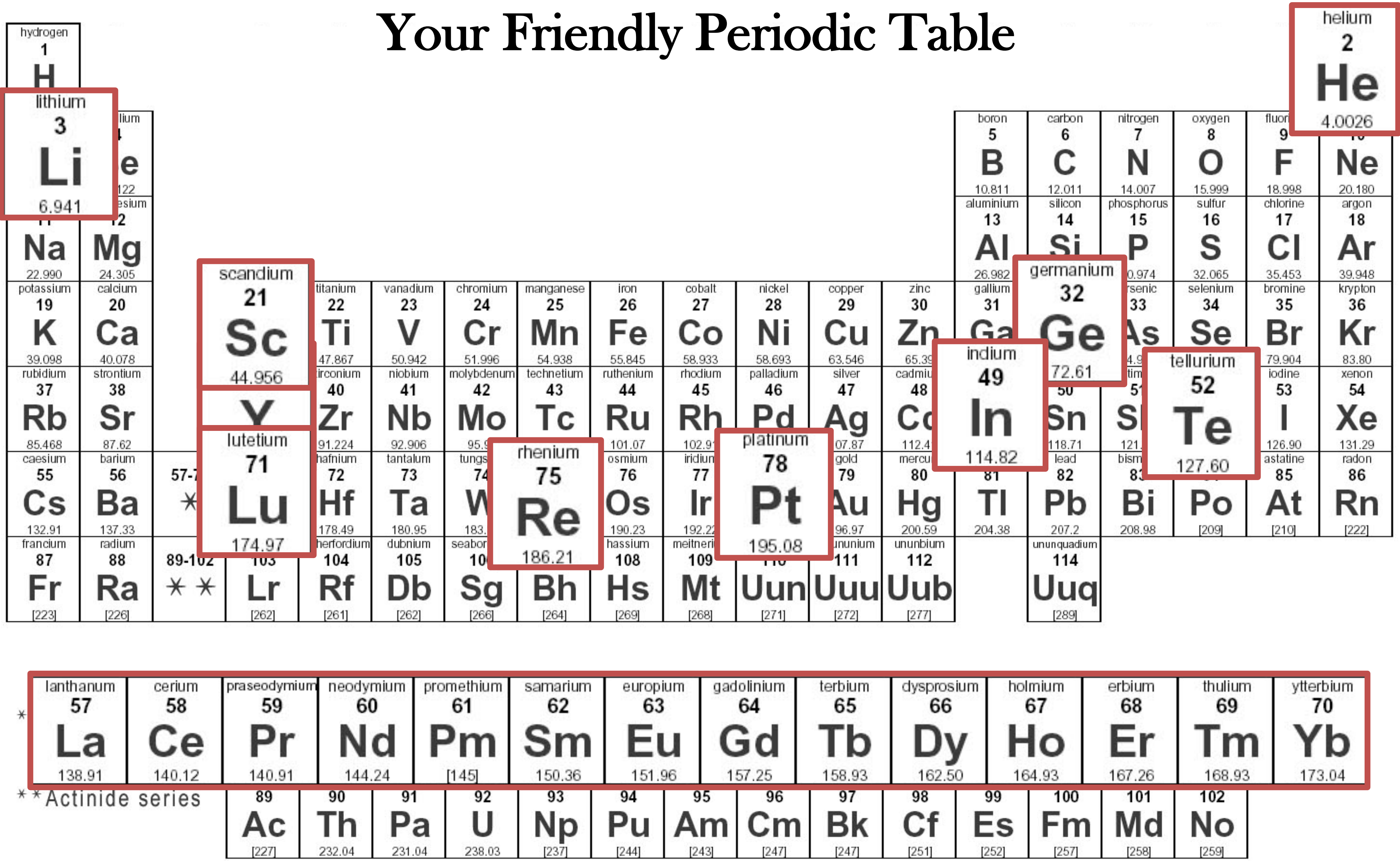


Options

He News Articles for You

- http://www.wired.com/2015/07/feds-created-helium-problem-thats-screwing-science/
- http://www.npr.org/blogs/itsallpolitics/2013/09/30/227772534/congress-reaches-compromise-deal-on-inert-gas
- http://www.washingtonpost.com/blogs/wonkblog/wp/2013/09/27/good-news-congress-just-averted-a-global-helium-crisis/
- http://www.nature.com/nature/journal/v485/n7400/full/485573a.html

Your Friendly Periodic Table



hydrogen 1 H																		helium 2 He 4.0026
lithium 3 Li 6.941	lium e 122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluori 9 F 18.998	Ne 20.180
Na 22.990	esium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si	phosphorus 15 P 0.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga	germanium 32 Ge 72.61	rsenic 33 As 4.9	selenium 34 Se	bromine 35 Br 79.904	krypton 36 Kr 83.80
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caesium 55 Cs 132.91	barium 56 Ba 137.33	57-7 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungs 74 W 183.	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.2	platinum 78 Pt 195.08	gold 79 Au 96.97	mercu 80 Hg 200.59	81 Tl 204.38	lead 82 Pb 207.2	bism 83 Bi 208.98	Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	Lr [262]	herfordium 104 Rf [261]	dubnium 105 Db [262]	seabor 10 Sg [266]	Bh [264]	hassium 108 Hs [269]	meitneri 109 Mt [268]	Uun [271]	ununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

*	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
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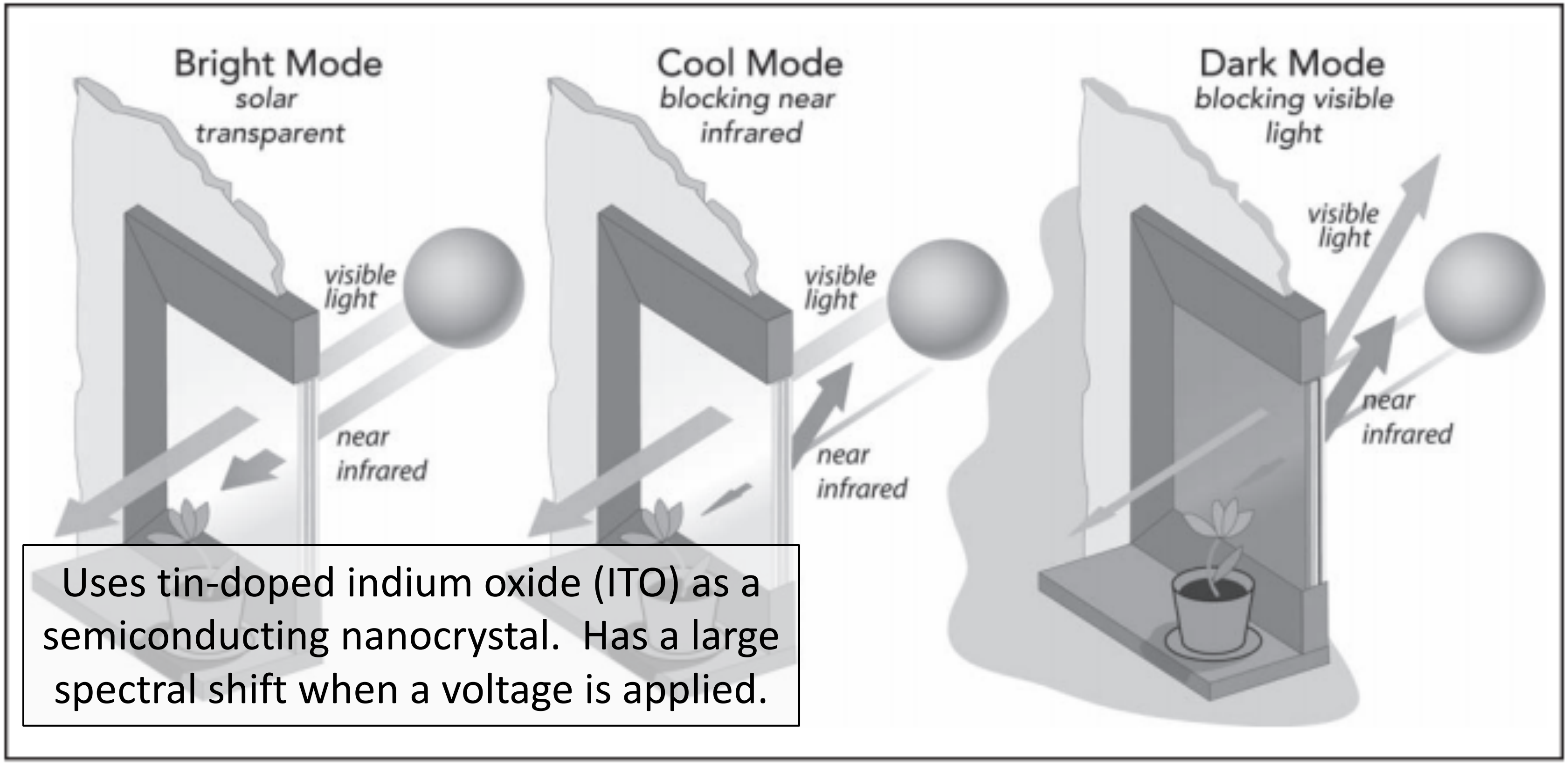
“NOW WE UNDERSTAND THAT THE EARTH IS FINITE, AND WE CAN’T JUST PICK WHATEVER OFF THE SHELF AND BUILD A TECHNOLOGY WITHOUT UNDERSTANDING THE CONSEQUENCES.”

- Frances Houle, Lawrence Berkeley National Laboratory (Berkeley Lab)

http://www.rdmag.com/News/2012/08/Materials-A-Long-Term-View-Of-Critical-Materials/

Assessing Critical Materials: New Technologies Example

8 **Energy Design Update®** **June 2013**



Uses tin-doped indium oxide (ITO) as a semiconducting nanocrystal. Has a large spectral shift when a voltage is applied.

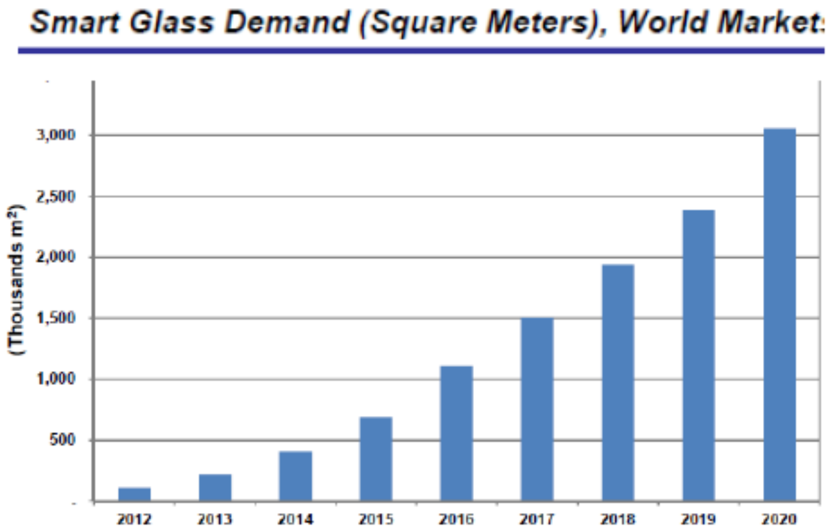
Figure 11. Milliron's team will also investigate coatings that combine the near infrared-selective plasmonic electrochromic effect with conventional electrochromic materials that can also modulate visible light, on demand. Photo courtesy Delia Milliron and Lawrence Berkeley National Laboratory.

http://www.mncee.org/getattachment/ff6fdd50-bba1-4b11-8bd9-74b525a34a57/

Scaling Up Production

- Annual market demands that affect electrochromic windows
  - Current U.S. commercial window demand at 40 million m2
  - Current global window demand at 300 million m2
  - Dynamic window demand currently insignificant, but projected to reach 3 million m2 by 2020
  - Current dynamic window plant capacity at ~0.5 million m2

- Market demand estimates help characterize
  - Impacts from resource use
  - Potential energy savings
  - Projected plant capacity
  - Manufacturing methods
  - Bulk material pricing



Pike Research, 2012

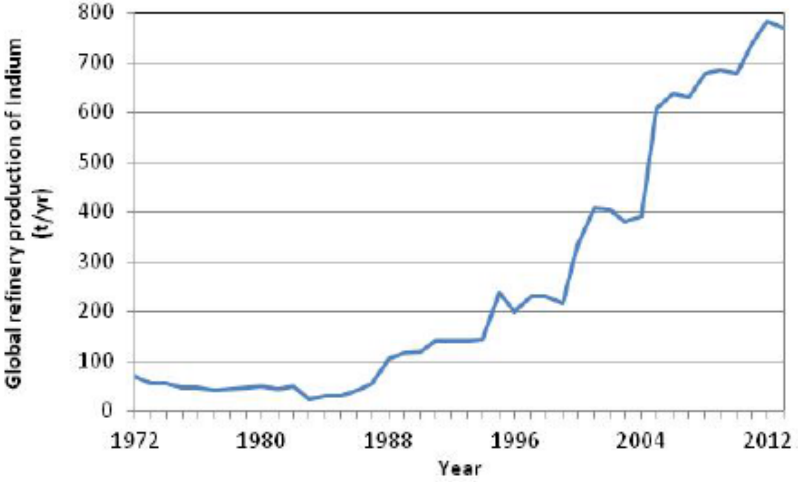
Slide from: Arman Shehabi, et al (Lawrence Berkeley National Lab) 2014; LCA XIV Conference (with permission)

Supply Chain Impacts

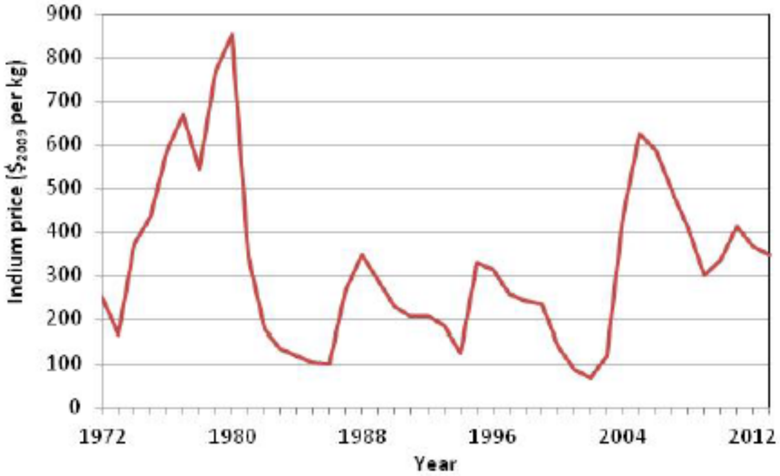
Raw Materials

- Example: Critical material concerns of Indium

Current primary production of Indium ≈ 800 t/yr



Historical price fluctuation: <\$100 to >\$800 per kg



Scenario projections:

- Medium:
  - 30 million ft^2 annual output (1% of total market)
  - Indium demand ≈ 8.3 t/yr (or 1.1% of 2013 production)
- High:
  - 1 billion ft^2 per year (≈global demand in 2020 for architectural glass)
  - Indium demand ≈ 276 t/yr (or 36% of 2013 production)

Slide from: Arman Shehabi, et al (Lawrence Berkeley National Lab) 2014; LCA XIV Conference (with permission)

Indium production and cost data from USGS (2014)

Acknowledgements / Refs

- Karl Dunkle Werner, He aficionado
- Jason Vincenz, MechE extraordinaire
- UIC's Summer Institute for Sustainable Energy
- USDOE (2010). Critical Materials Strategy, US Department of Energy.
- Committee on Understanding the Impact of Selling the Helium Reserve and National Materials Advisory Board (2010). Selling the Nation's Helium Reserve, Natl Academy Pr.
- Arman Shehabi, Lawrence Berkeley National Lab

Good Reads for You

- USDOE (2011). Critical Materials Strategy, US Department of Energy.
- Erdmann, L. and T. E. Graedel (2011). "Criticality of non-fuel minerals: A review of major approaches and analyses." Environmental Science and Technology **45**(18): 7620-7630.
- National Research Council (2000). The Impact of Selling the Federal Helium Reserve, The National Academies Press.