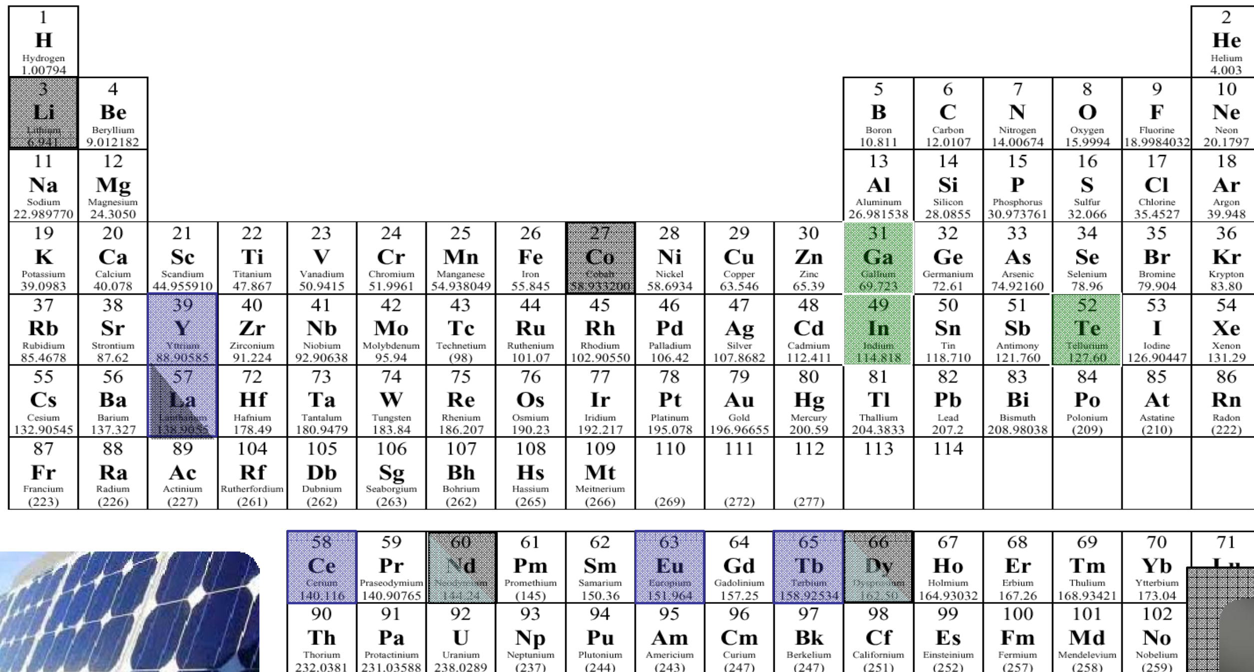
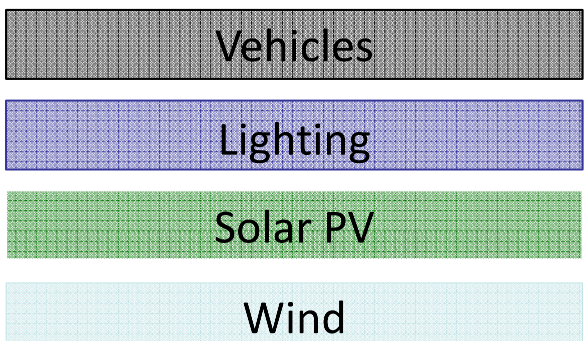
Critical Materials: Rare Earth & Related Elements

Mark Johnson

March 11, 2011

Critical Materials in Clean Energy





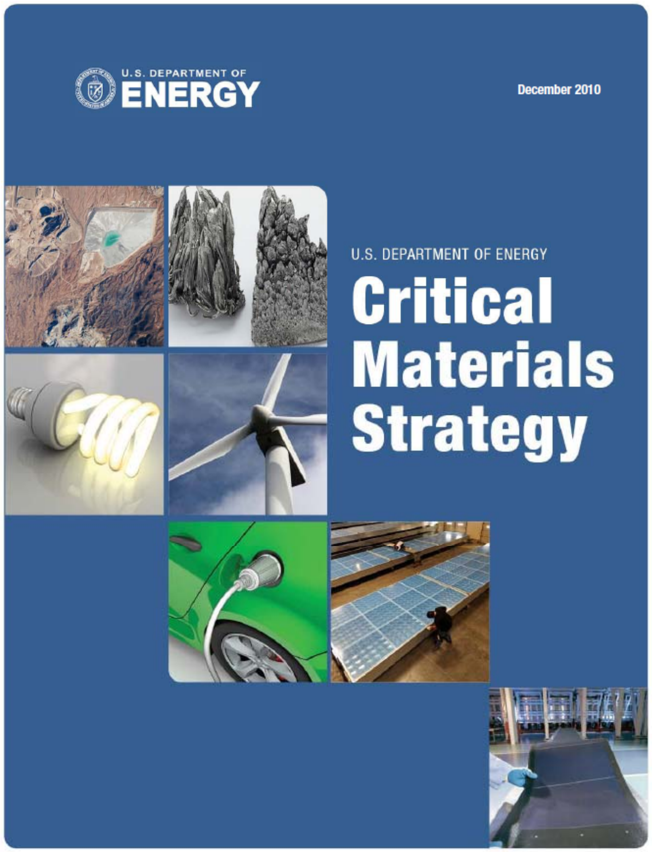
US DOE: Critical Materials Strategy (Dec 2010)

Coordinated Critical Materials Effort

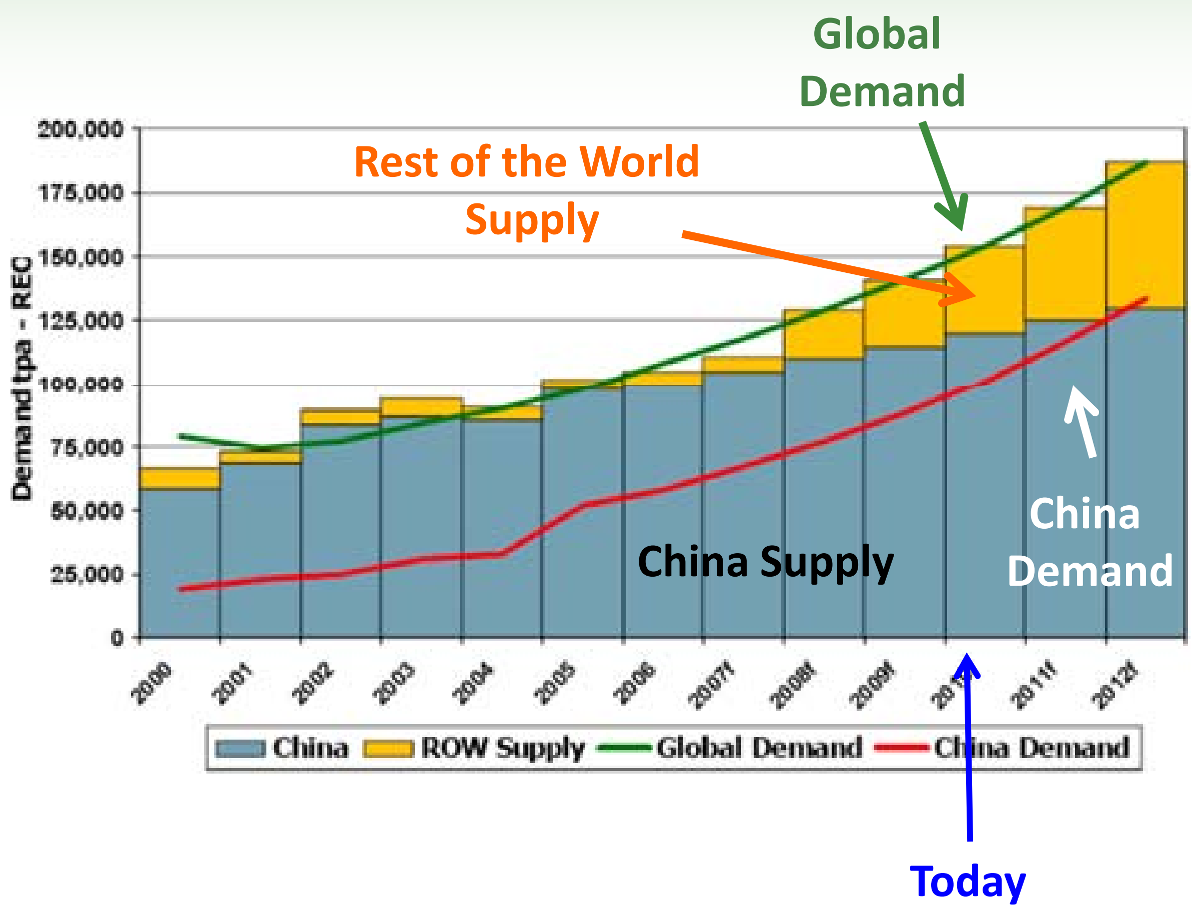
- Policy and International Affairs (PI) led Department-wide Critical Materials Strategy Study

  [David Sandalow, Assistant Secretary, PI]

- US-Japan Roundtable (LLNL) on Rare Earths (Nov 2010)
- US-EU Workshop on Rare Earths Research (Dec 2010)
- ARPA-E Workshop on Critical Materials Technology (Dec 2010)



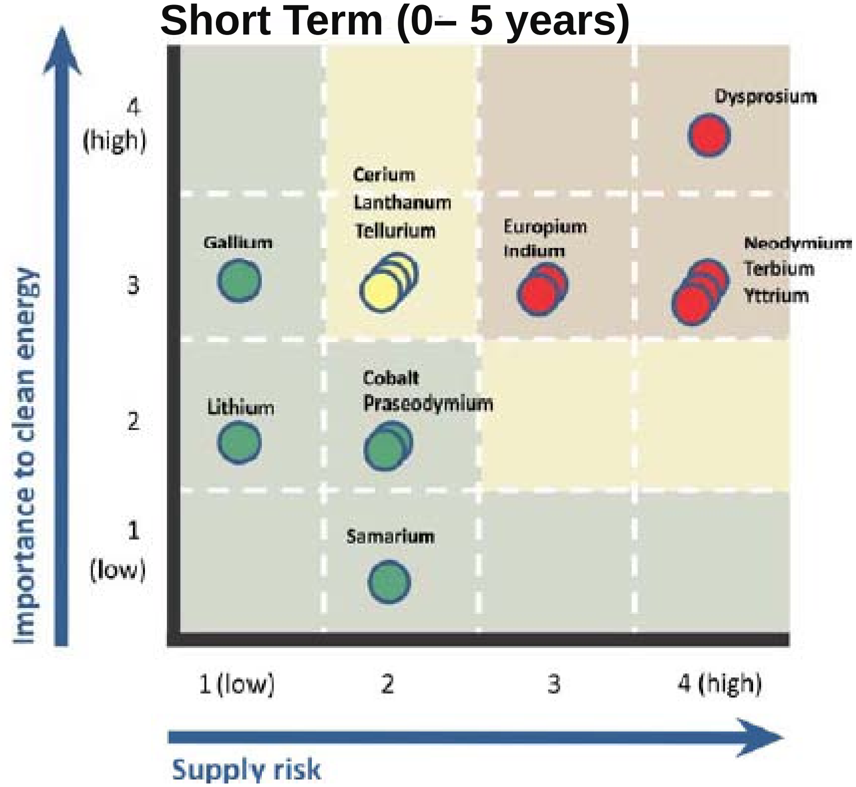
Shifting Economics Of Rare Earth Materials



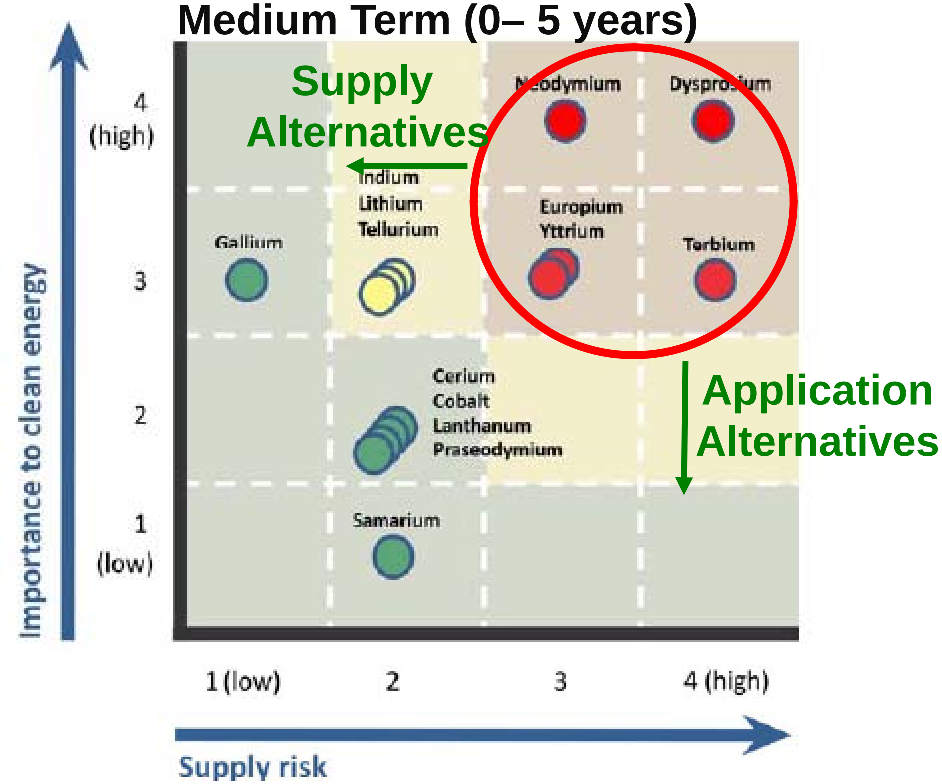
Within 5 Years: World's Dominant Supplier of Rare Earth Materials May Switch From a Net Exporter to a Net Importer

Rare Earth Criticality by Element

Short Term (0– 5 years)

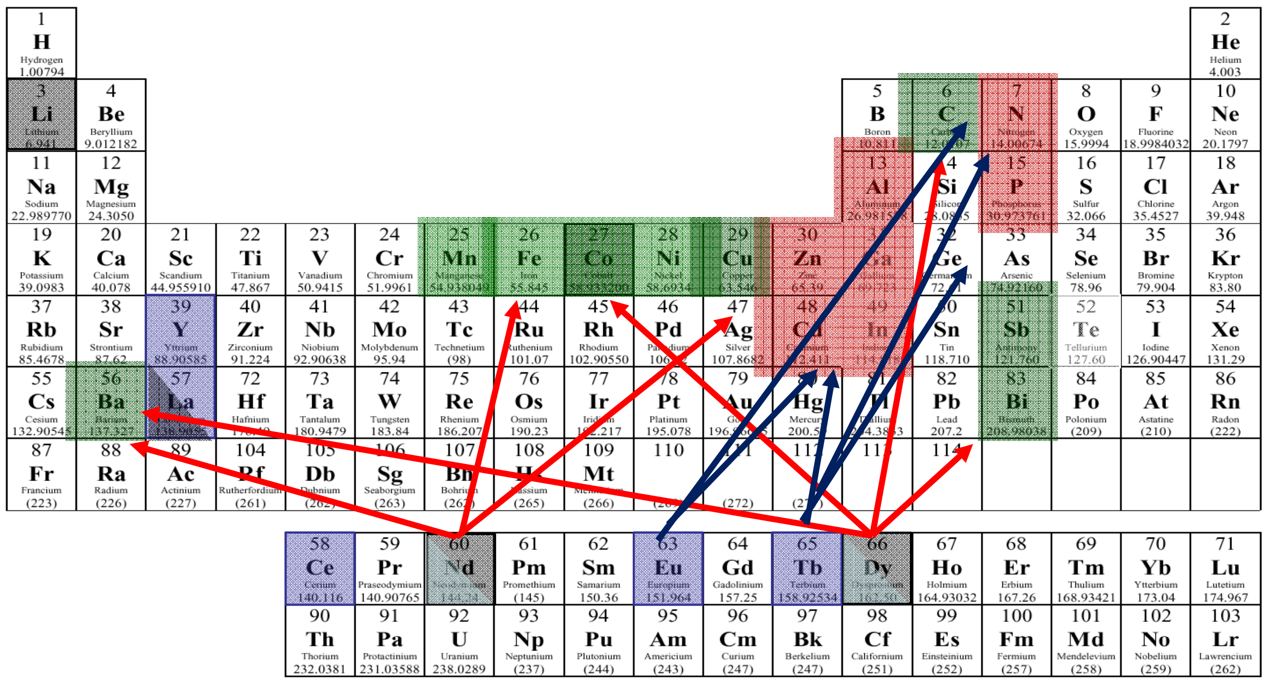


Medium Term (0– 5 years)

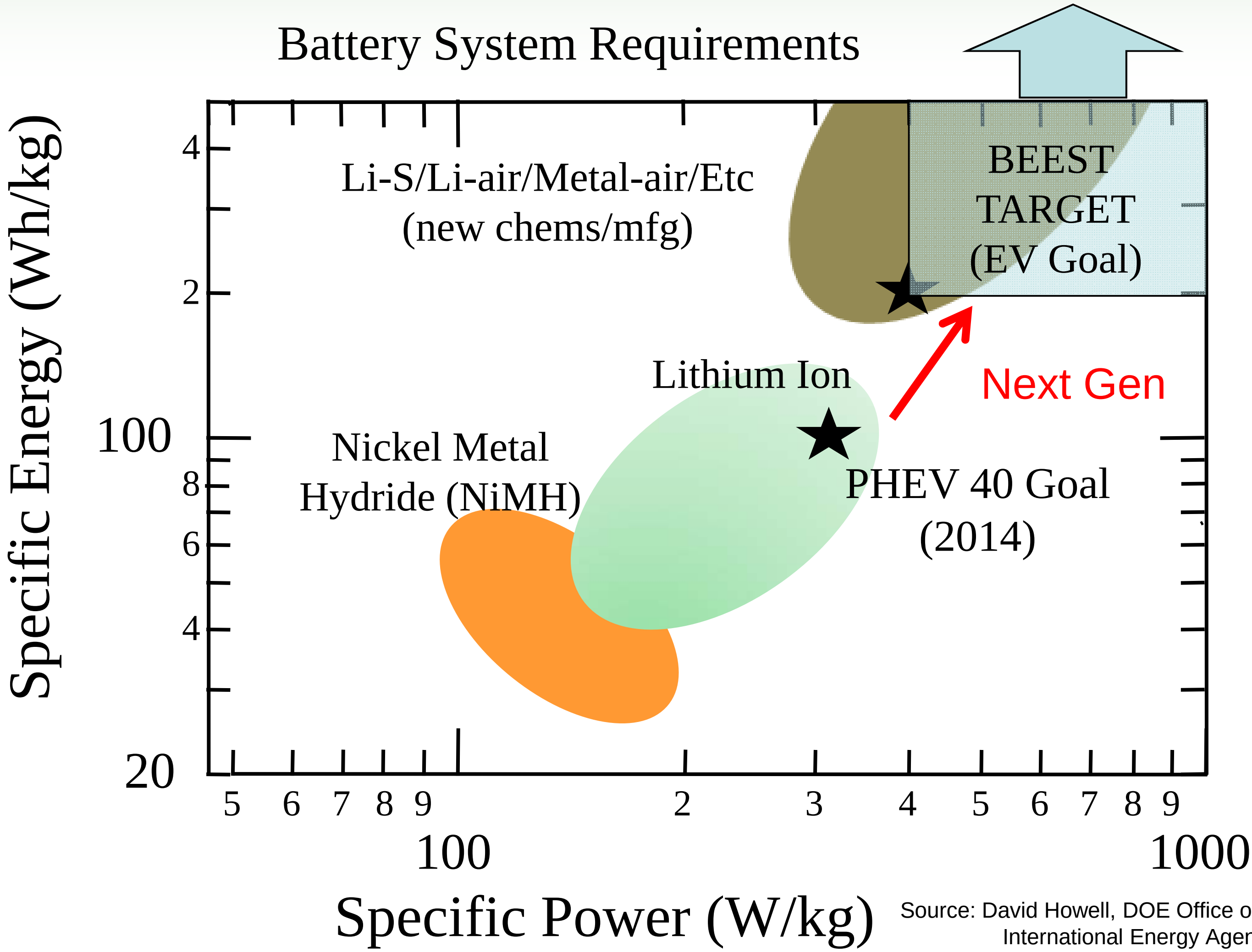


US DOE: Critical Materials Strategy (Dec 2010)

Possible Approach: Eliminate Need for Material



Batteries for Electrical Energy Storage in Transportation (BEEST) Program

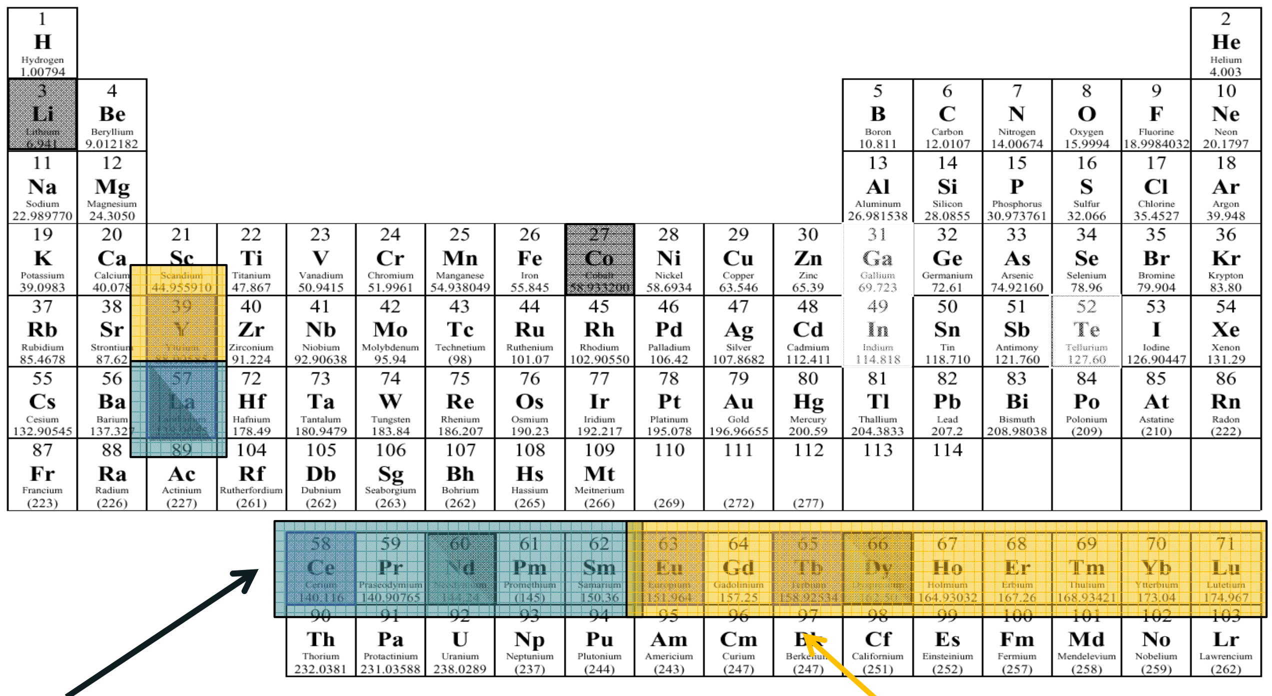


Storage Cost
Current Target: $1,000/kWh

BEEST Target: $250/kWh

Source: David Howell, DOE Office of Vehicle Technologies, 2009.
International Energy Agency, *Technology Roadmaps: Electric and Plug-in Hybrid Electric Vehicles*

Possible Approach: Get Most From Available Supply

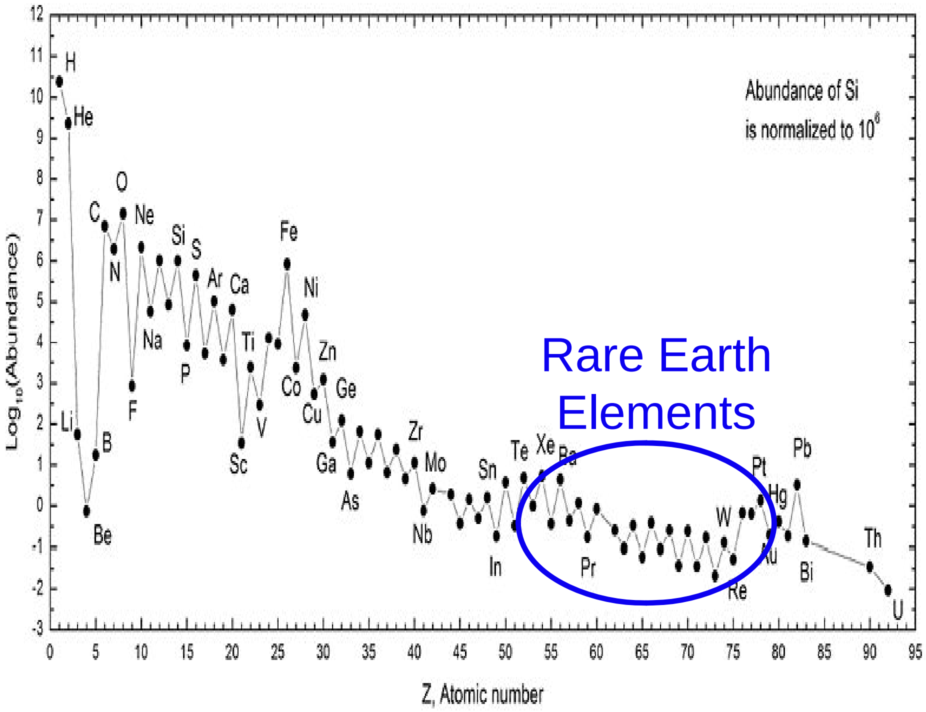


Light Rare Earth Elements

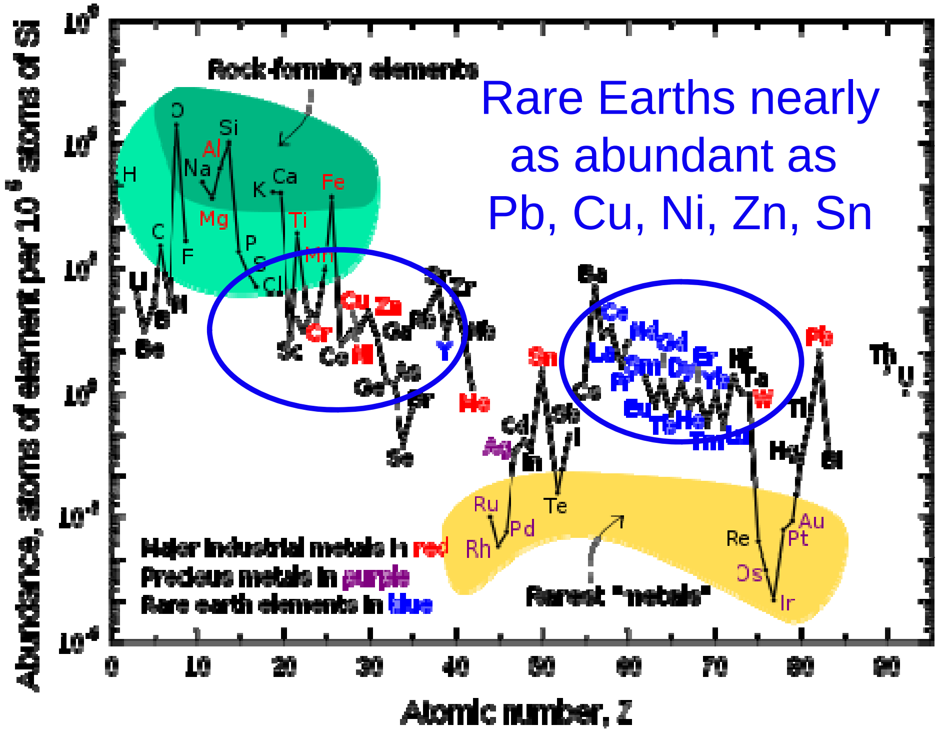
Heavy Rare Earth Elements

Rare Earth Elements Are Not That Rare

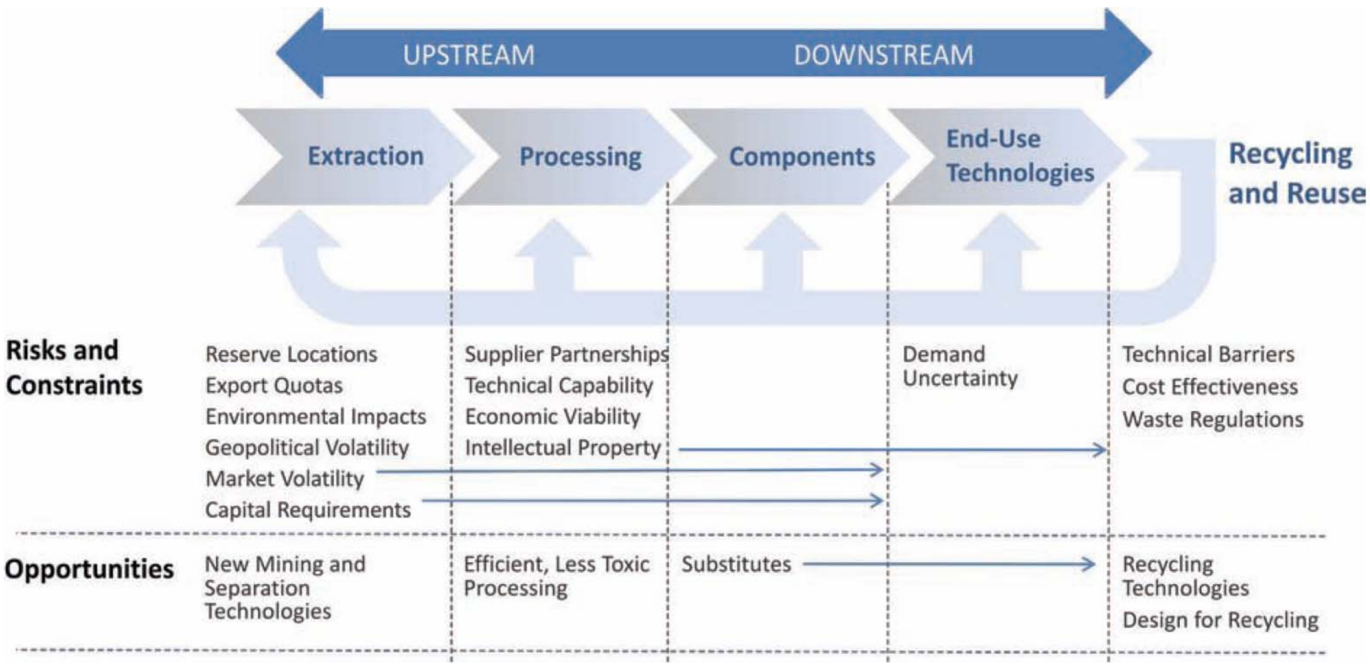
Solar System Abundance

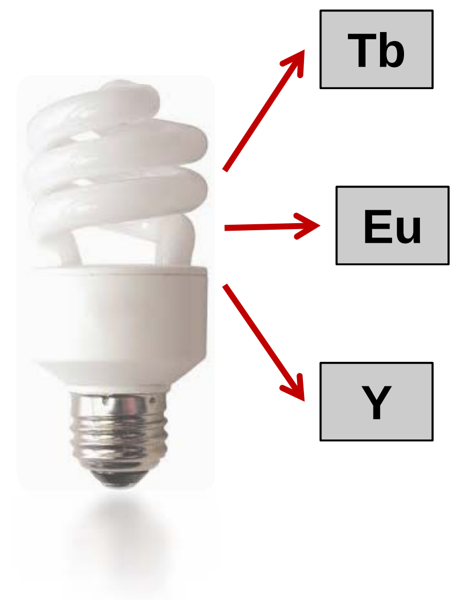


Upper Crust Abundance



Developing Technology Alternatives Across Supply Chain





Critical Materials in Clean Energy from DOE-Wide Study

1 H Hydrogen 1.00794																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.9055	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	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 (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				
				58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu
				90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	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)	

Vehicles

Lighting

Solar PV

Wind

Key Elements in Energy-Wide Supply Chain

Traditional Energy

Smart Grid

Vehicles

Lighting

Solar PV

Wind

Technology Opportunity Areas for Study

Vehicles

Lighting

Solar PV

Wind

Traditional Energy

Smart Grid

Batteries

Phosphors

Transparent Contacts

Permanent Magnets

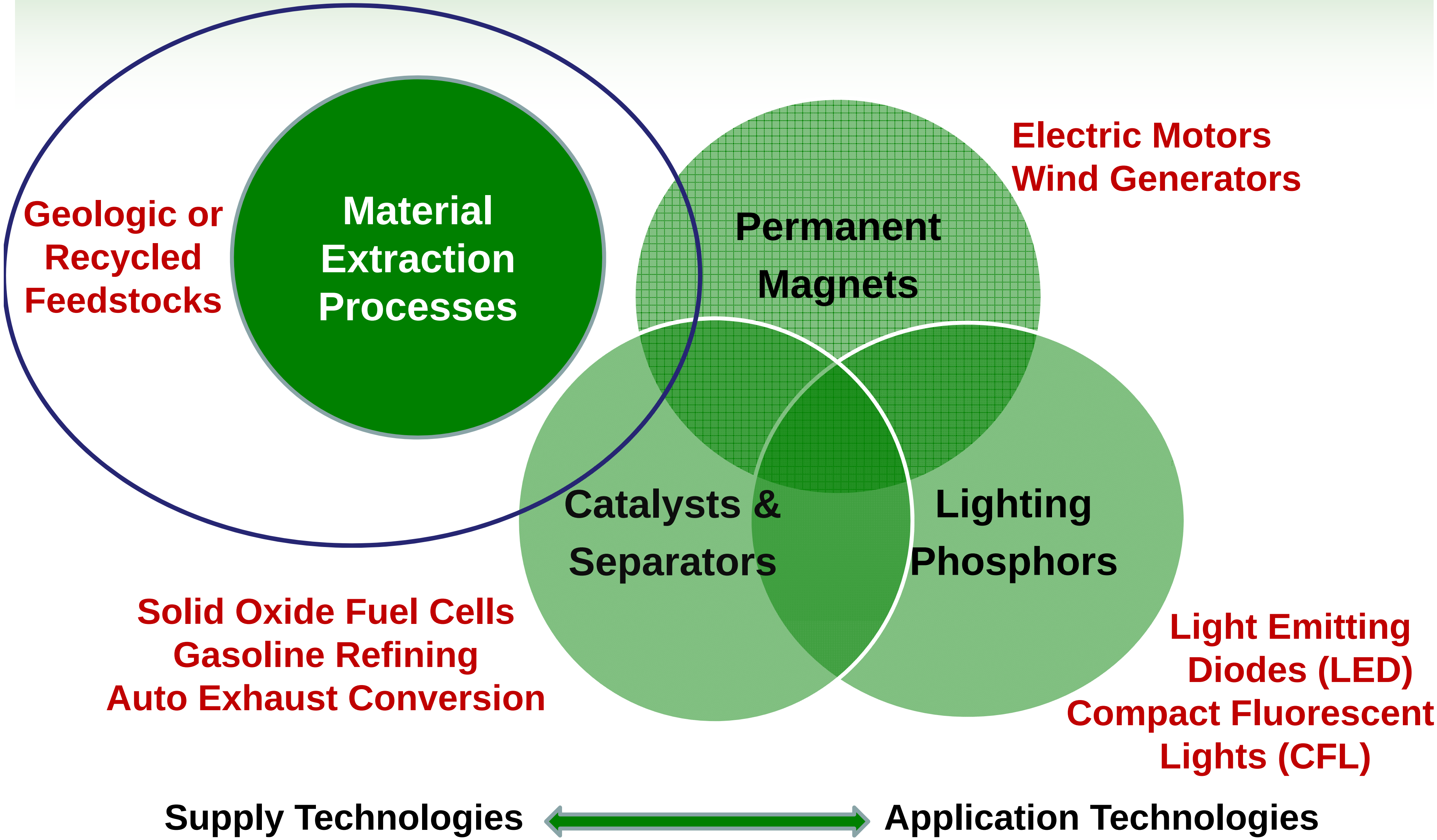
Oxygen Separators

Catalysts

Opportunities
For New, Disruptive
Approaches to
Technology Needs

Metrics to Drive
New Learning
Curves and
Approaches

ARPA-E Workshop: Critical Materials Technology



45% of Global Rare-Earth Production
Bayan Obo, China

<u>Primary Ore</u>:
Bastnasite: RE-(CO_3)F
800 million metric tons; 6% REO

<u>Secondary Ore</u>:
Monazite: RE-PO_4

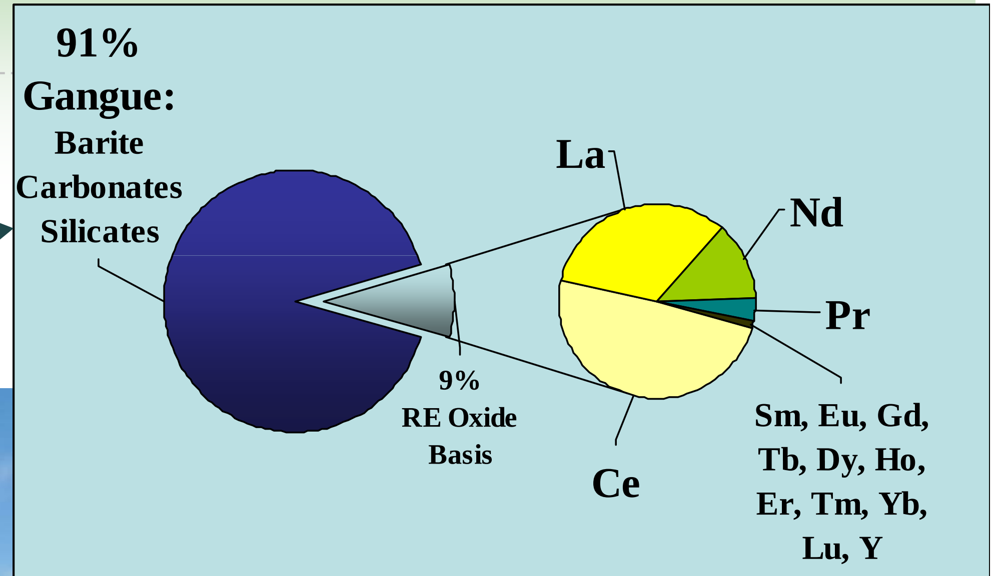
Photos: Google Maps

US Rare-Earth Production Capability
Mountain Pass, CA (re-opened by Molycorp)

<u>Primary Ore</u>:
Bastnasite: RE-$(CO_3)F$
3.3 million metric tons:
7-9% REO

Photos: Google Maps

Molycorp Rare Earth Facility
Mountain Pass, CA



Different Types of Rare Earths

Heavy and Light Rare Earths are from different Ores

<u>Light Rare Earths</u>

Neodymium – Magnets

<u>Heavy Rare Earths</u>

Dysprosium - High Temp Magnets

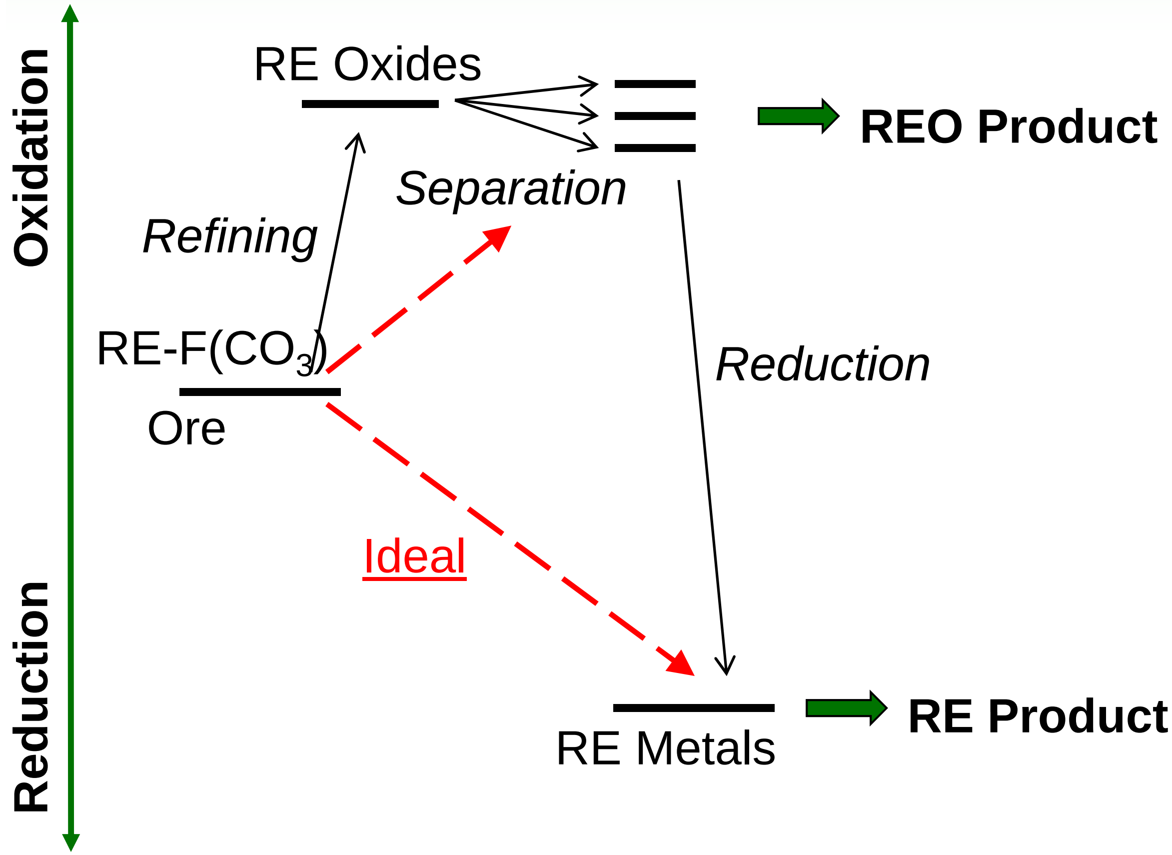
Yttrium – SOFCs and Phosphors

Terbium – Phosphors

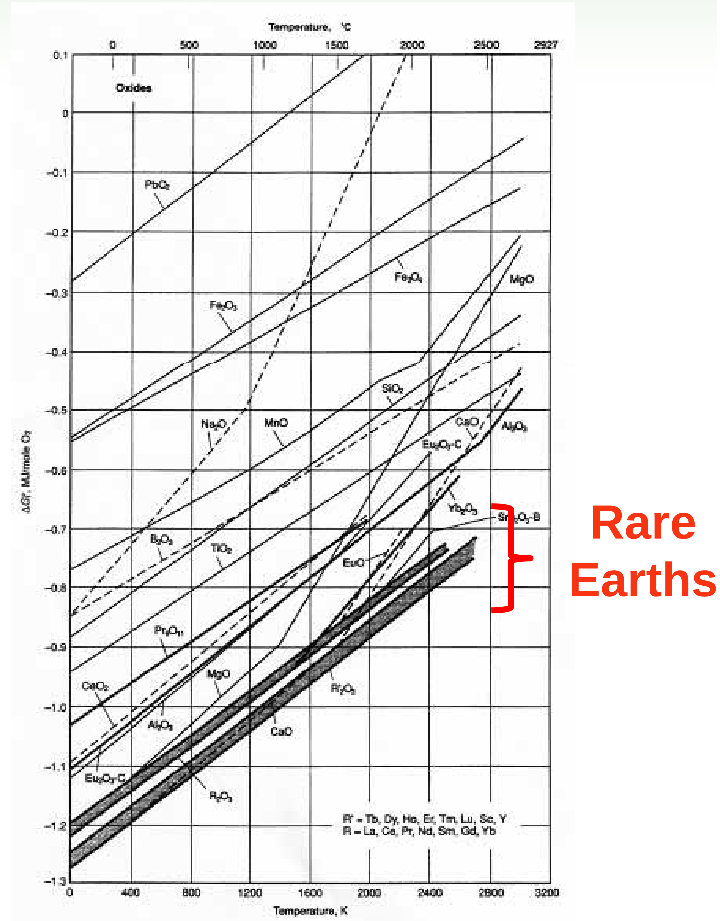
Europium - Phosphors

TYPE	LOCATION (S)	LIGHT				MEDIUM			HEAVY							
		Lanthanum (La)	Cerium (Ce)	Praseodymium (Pr)	Neodymium (Nd)	Samarium (Sm)	Europium (Eu)	Gadolinium (Gd)	Terbium (Tb)	Dysprosium (Dy)	Holmium (Ho)	Erbium (Er)	Thulium (Tm)	Ytterbium (Yb)	Lutetium(Lu)	Yttrium(Y)
Currently active:																
Bastnäsite	Bayan Obo, Inner Mongolia	23.0	50.0	6.2	18.5	0.8	0.2	0.7	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Xenotime	Lahat, Perak, Malaysia	1.2	3.1	0.5	1.6	1.1	0.0	3.5	0.9	8.3	2.0	6.4	1.1	6.8	1.0	61.0
Rare earth laterite	Xunwu, Jiangxi Province, China	43.4	2.4	9.0	31.7	3.9	0.5	3.0	0.0	0.0	0.0	0.0	0.0	0.3	0.1	8.0
Ion adsorption clays	Longnan, Jiangxi Province, China	1.8	0.4	0.7	3.0	2.8	0.1	6.9	1.3	6.7	1.6	4.9	0.7	2.5	0.4	65.0
Loparite	Lovozerskaya, Russia	28	57.5	3.8	8.8	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Various	India	23	46	5	20	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Various	Brazil	N.A.														
Possible to come online in the next 5 years:																
Bastnäsite [22]	Mountain Pass, California, United States	33.2	49.1	4.3	12.0	0.8	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Monazite	Mount Weld, Australia	26.0	51.0	4.0	15.0	1.8	0.4	1.0	0.1	0.2	0.1	0.2	0.0	0.1	0.0	0.0
	Eastern coast [23], Brazil	24.0	47.0	4.5	18.5	3.0	0.1	1.0	0.1	0.4	0.0	0.1	0.0	0.0	0.0	1.4
Apatite	Nolans bore, Australia	20.0	48.2	5.9	21.5	2.4	0.4	1.0	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Fergusonite [24]	Nechalaco, Canada	16.9	41.4	4.8	18.7	3.5	0.4	2.9	1.8	0.7	0.0	0.0	0.0	0.0	0.0	7.4
Bastnäsite & Parisite	Dong Pao, Vietnam	32.4	50.4	4.0	10.7	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.007
Alanite & apatite	Hoidas Lake, Canada	19.8	45.6	5.8	21.9	2.9	0.6	1.3	0.1	0.4	0.0	0.0	0.0	0.0	0.0	1.3
Trachyte	Dubbo Zirconia, Australia	19.5	36.7	4.0	14.1	2.5	0.1	2.1	0.3	2.0	0.0	0.0	0.0	0.0	0.0	15.8

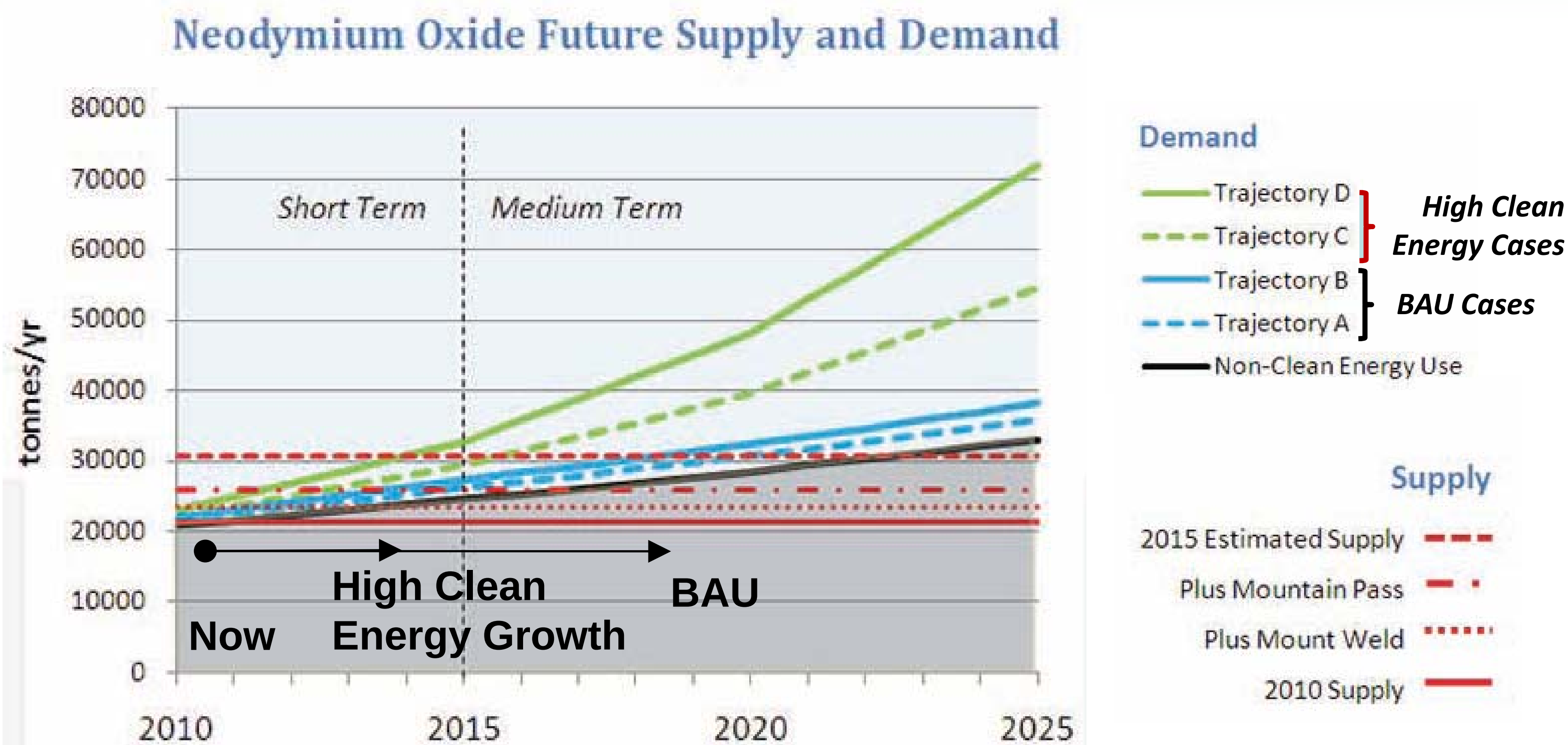
Rare Earth Oxide and Metal Extraction Process



Rare-Earth Processing Cycle



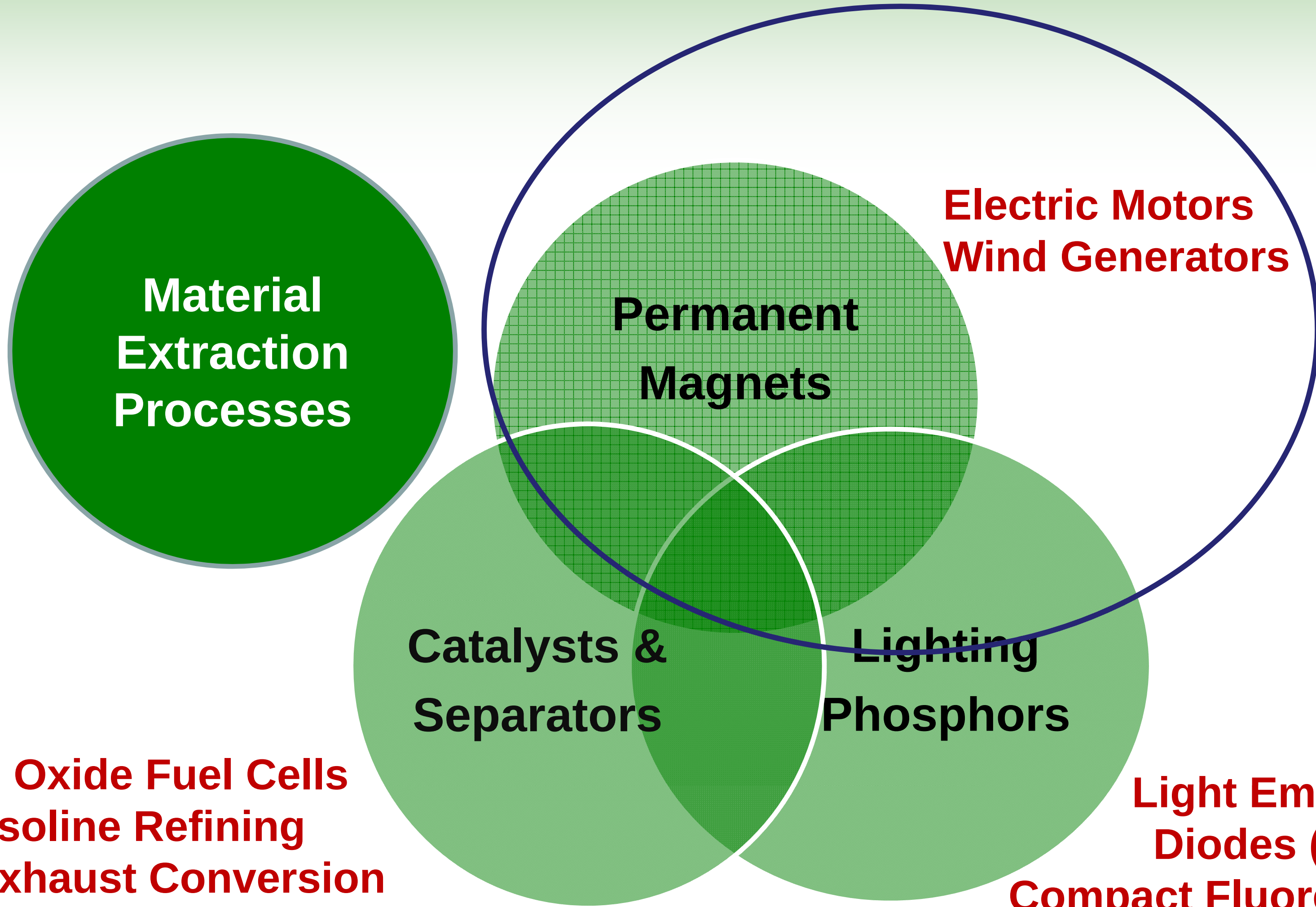
Supply and Demand Scenarios Neodymium (Permanent Magnets)



ARPA-E Workshop: Critical Materials Technology

Geologic or Recycled Feedstocks

Electric Motors
Wind Generators

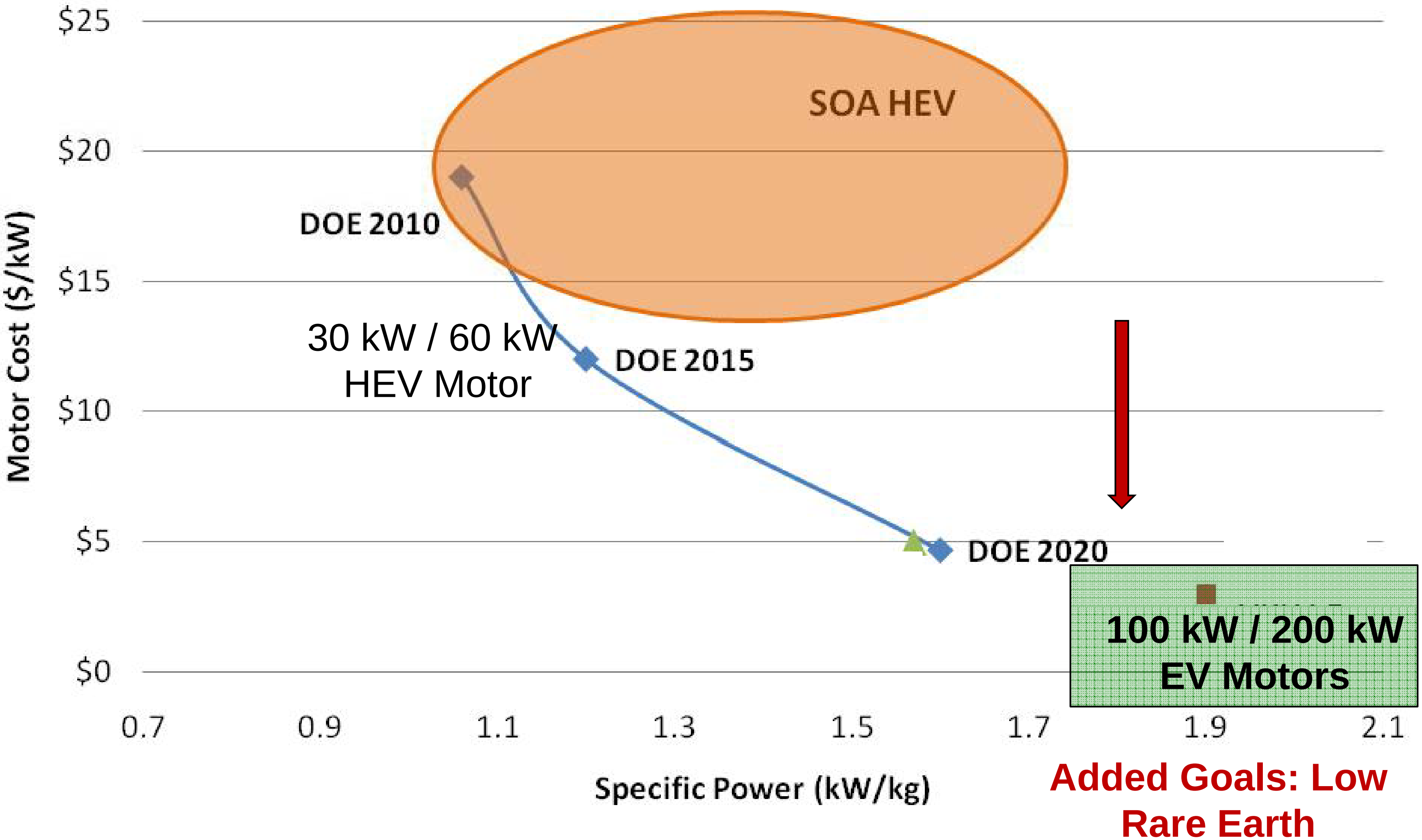


Solid Oxide Fuel Cells
Gasoline Refining
Auto Exhaust Conversion

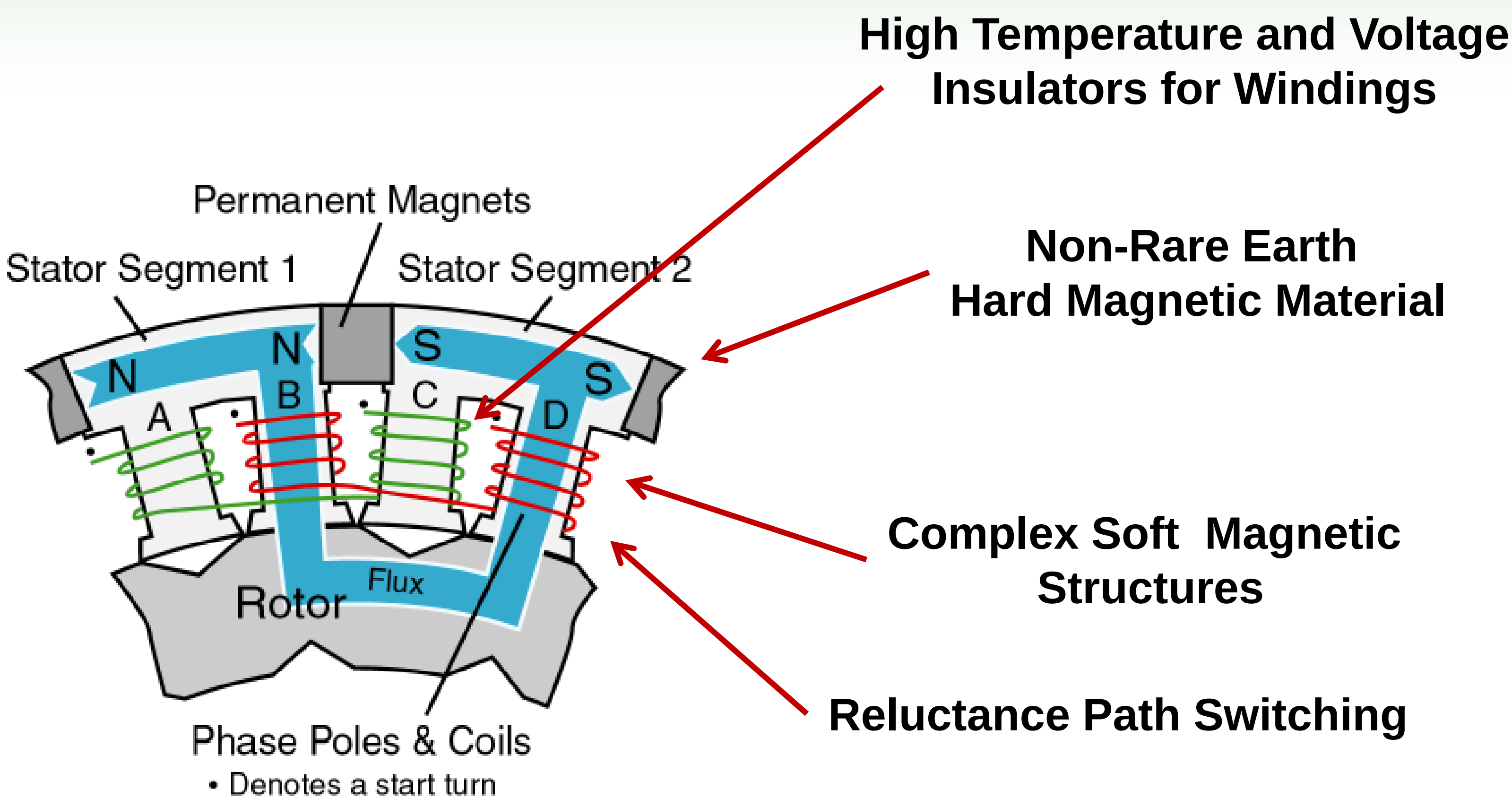
Light Emitting Diodes (LED)
Compact Fluorescent Lights (CFL)

Supply Technologies ⟷ **Application Technologies**

Magnetic Systems: Motors for Electric Vehicle (EV) 2020 Roadmap Goals with Low Rare Earth Content

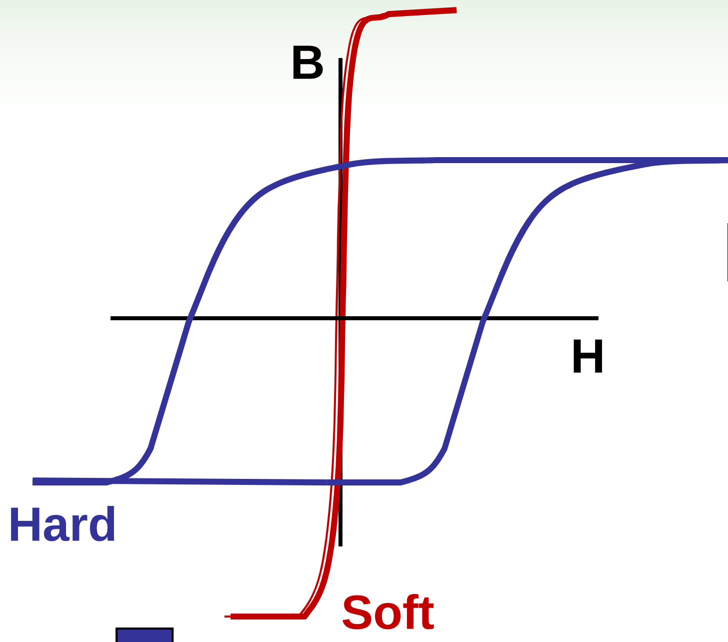


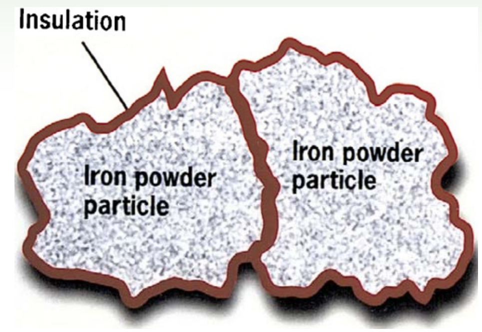
Advanced Electric Motor Concepts



Example: Parallel Path Magnetic Motor Technology

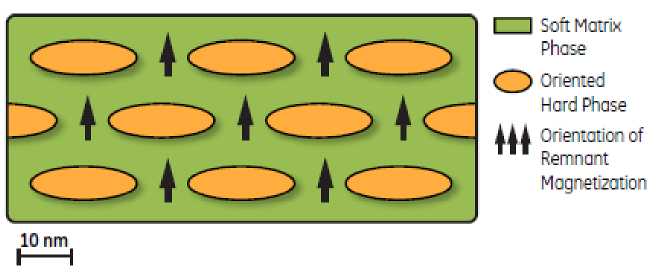
Needed Enabling Magnetic Materials





Soft Magnetic Nanocomposite

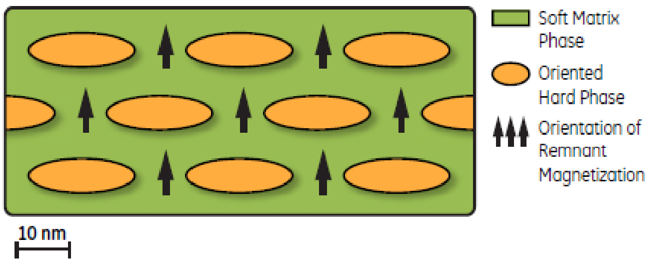
High Permeability (Fe, Fe-Si, Fe-Co)
Low Eddy Current Loss
Isotropic Permeability (ideal)
Manufacture-able / Moldable
Enables Novel Structures



Hard Magnetic Nanocomposite

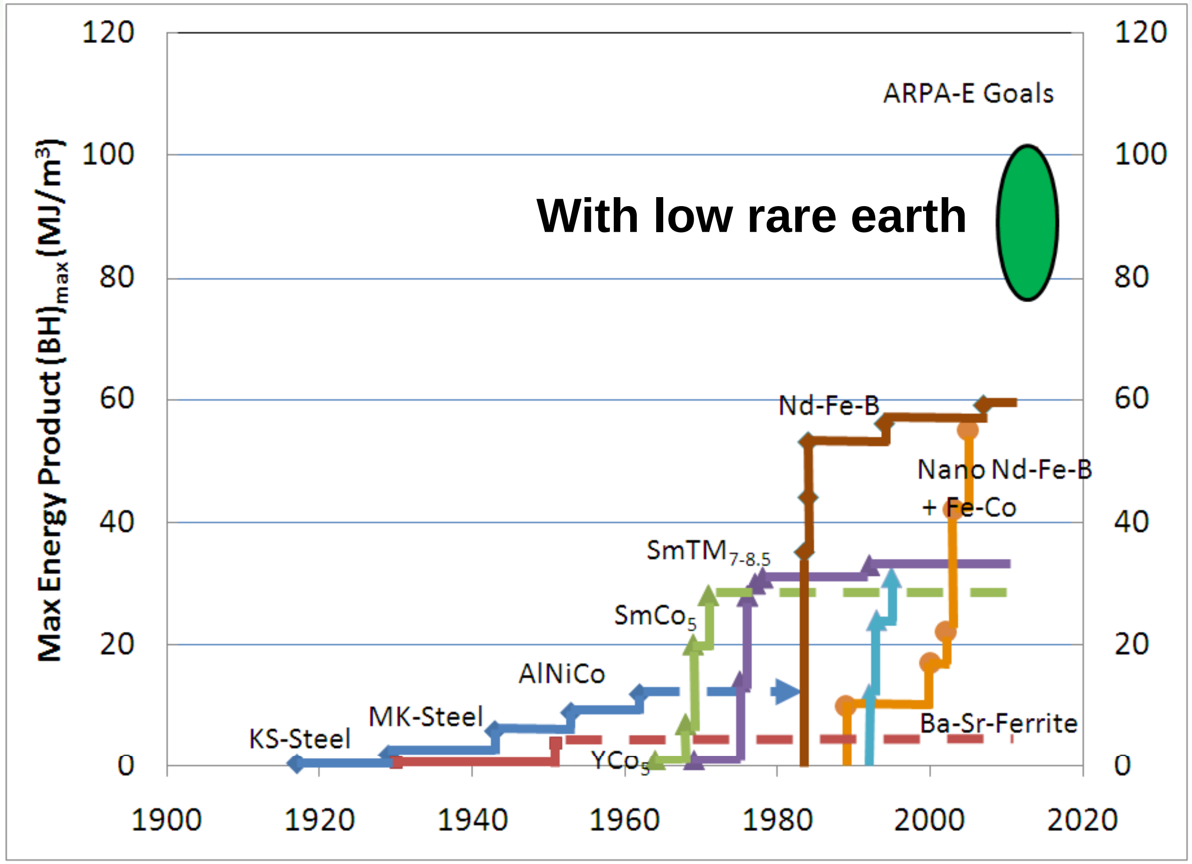
Spring Exchange Coupling
Coercivity of Hard Phase (SmCo, NdFeB)
Remnance of Soft Phase (Fe, Fe-Co)
High Energy Density
Reduced Rare Earth Content
Current: U Del. & GE

Nanocomposite Permanent Magnets



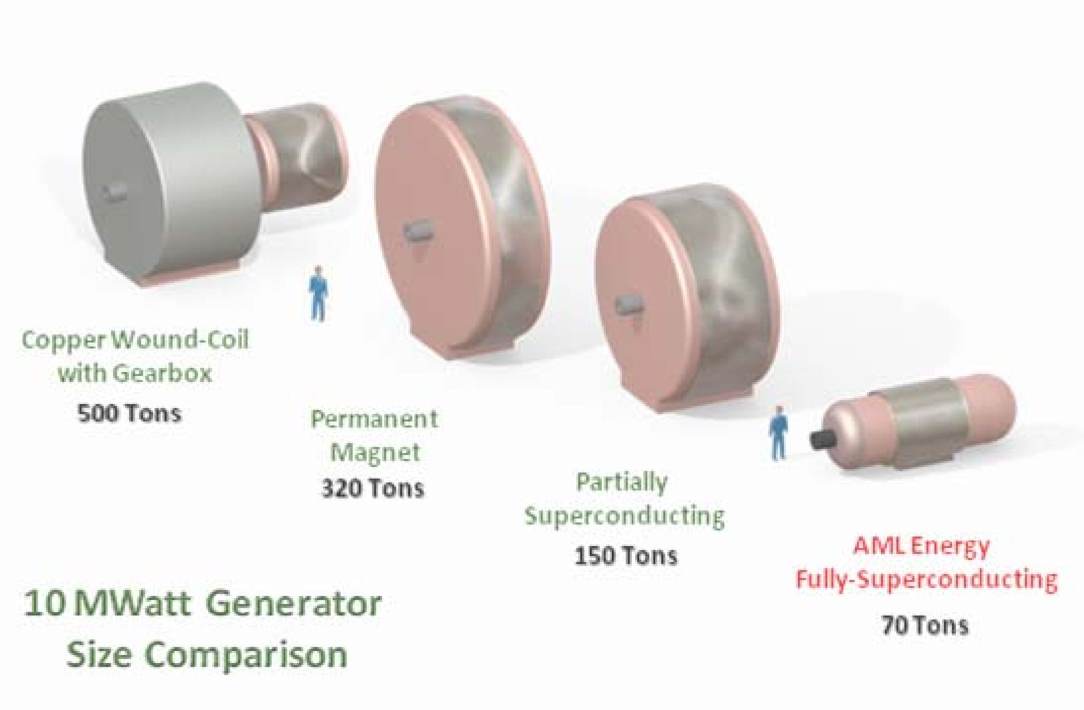
Core@Shell Hard/Soft Exchange Spring Coupled Nanocomposite Magnets with:

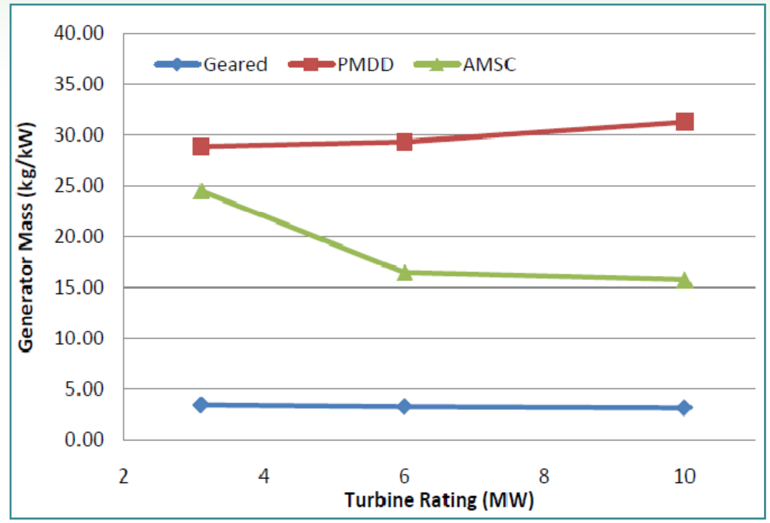
- 80 MGOe (vs 59 MGOe NdFeB)
- 59 MGOe with 80% less rare earth

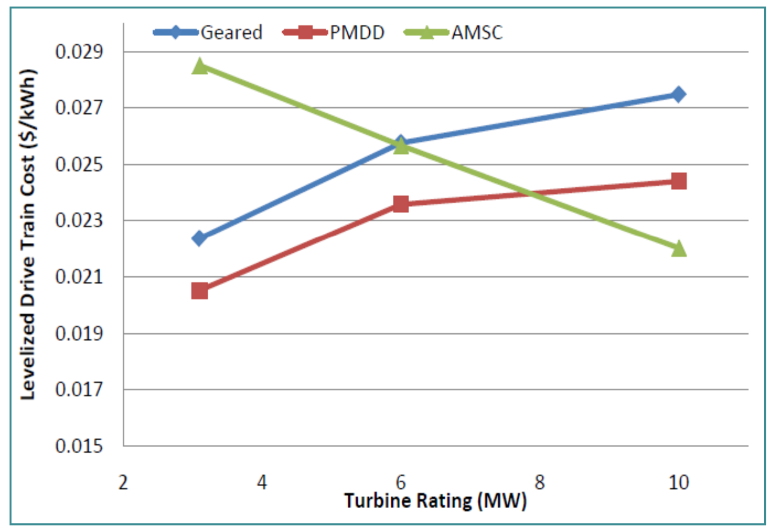


Nanocomposite exchange spring coupled permanent magnets with high energy product and less rare earths

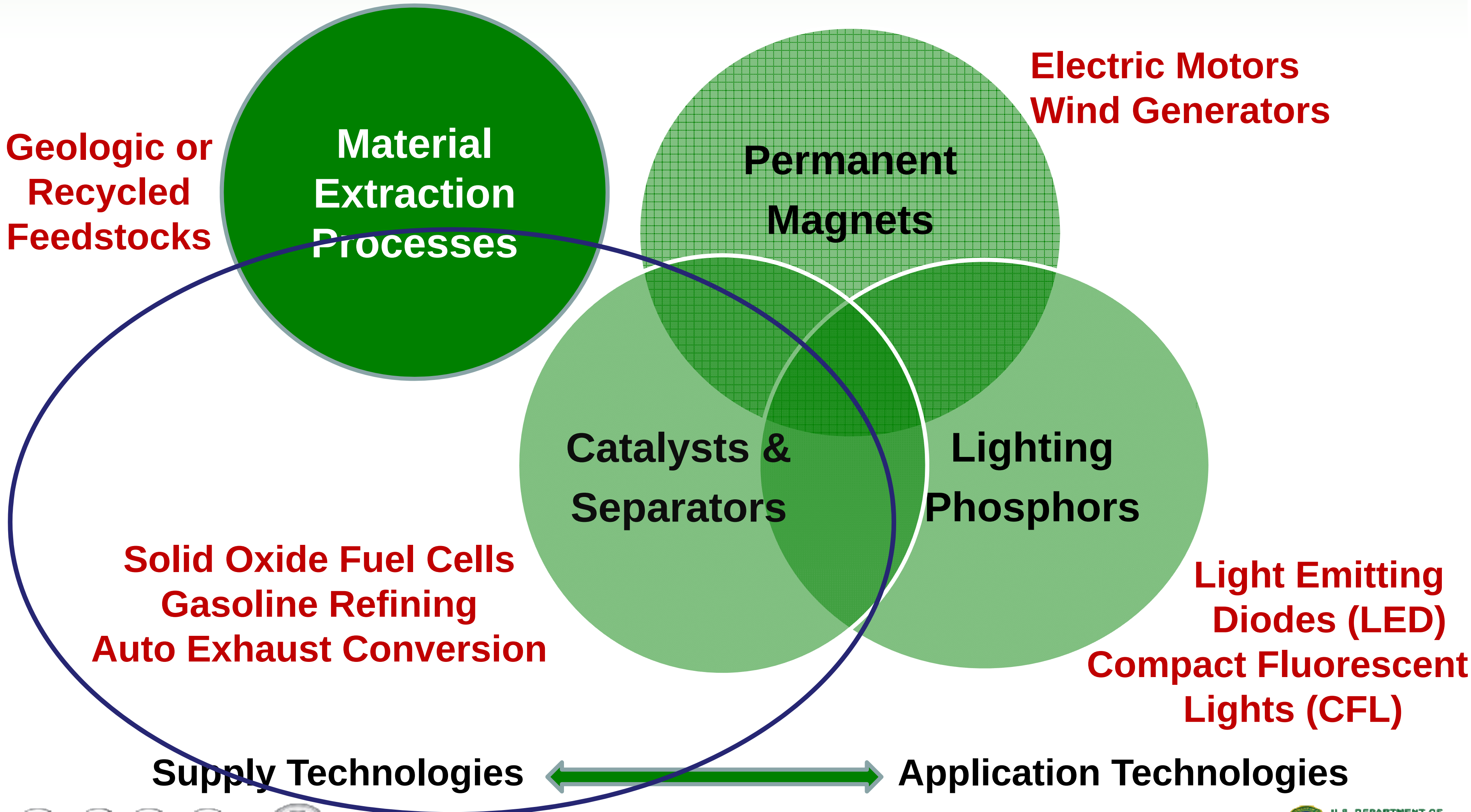
Large Scale Wind Generator (>10MW) Systems



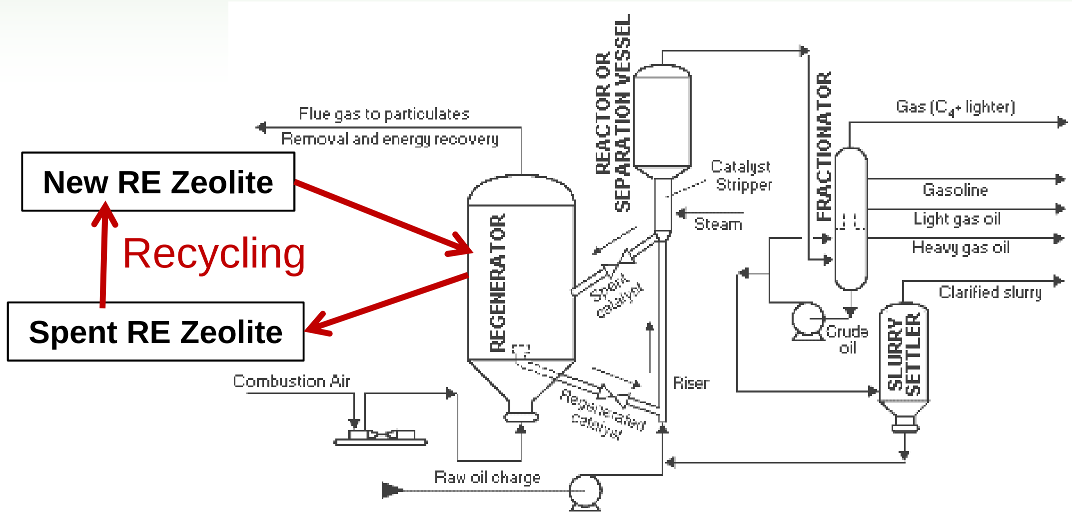




ARPA-E Workshop: Critical Materials Technology



Catalysts: Fluid Catalytic Cracking



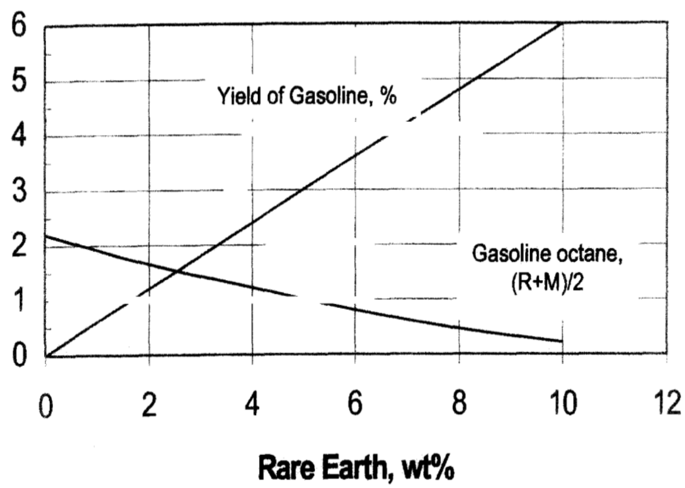
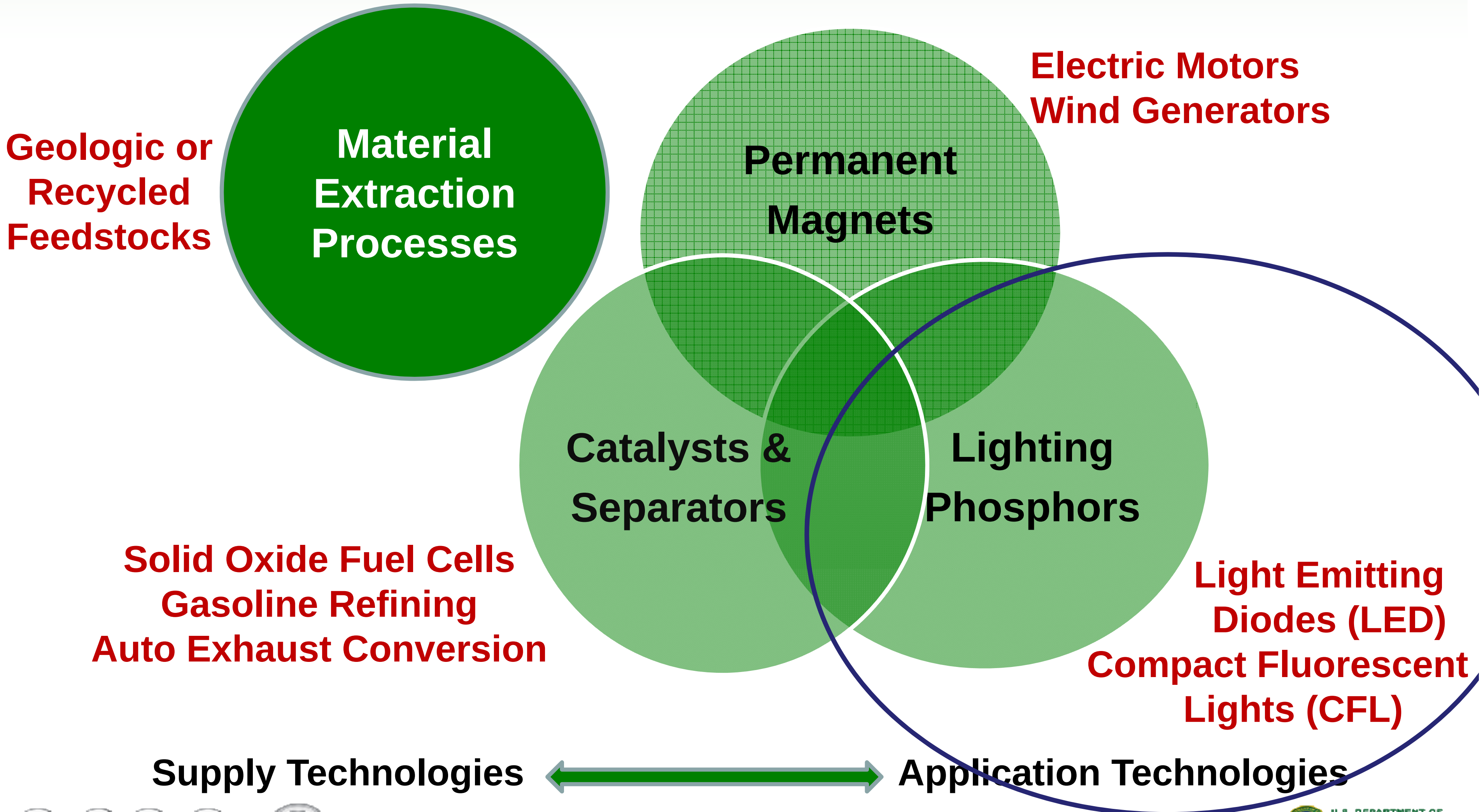


Figure 3-6. Effects of rare earth on gasoline octane and yield.

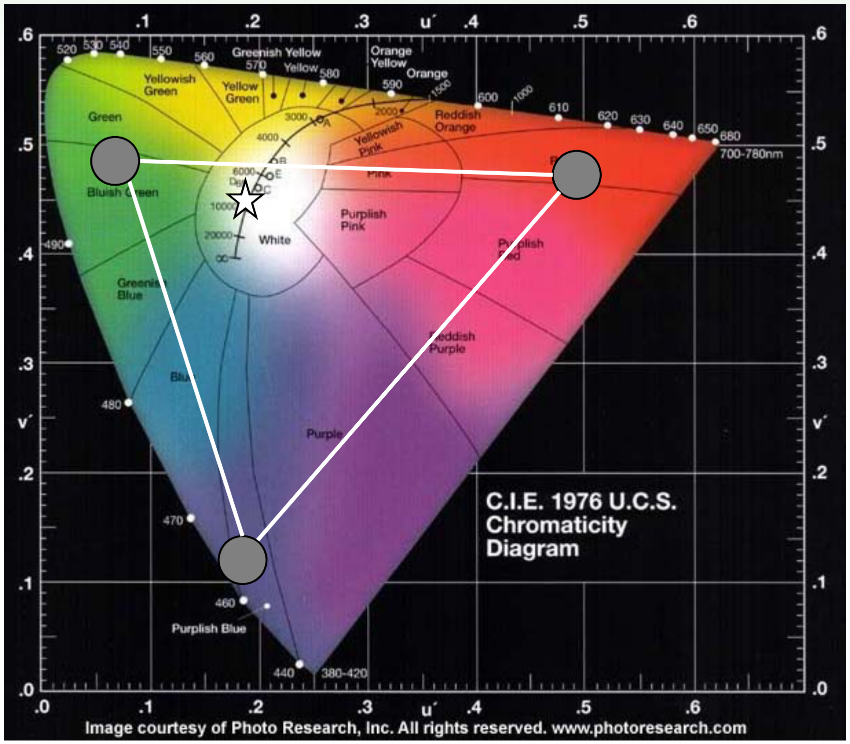
1-2% catalysts replaced per day.
All catalyst replaced every 2 months due to loss of aluminum.
Old catalyst is landfilled.

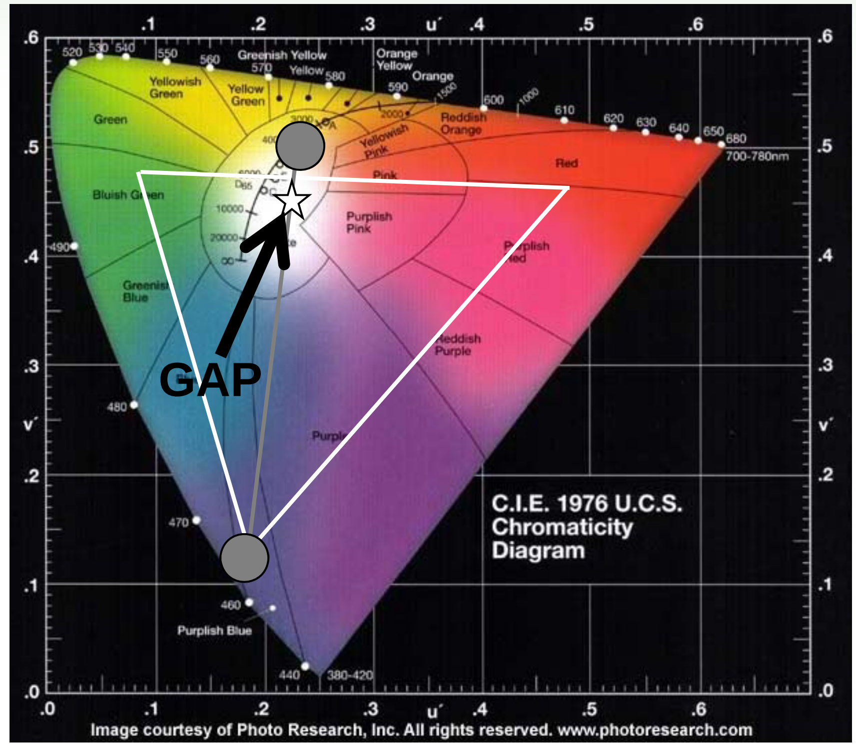
Recover Rare-earth content from spent FCC catalyst could potentially have Impact.

ARPA-E Workshop: Critical Materials Technology



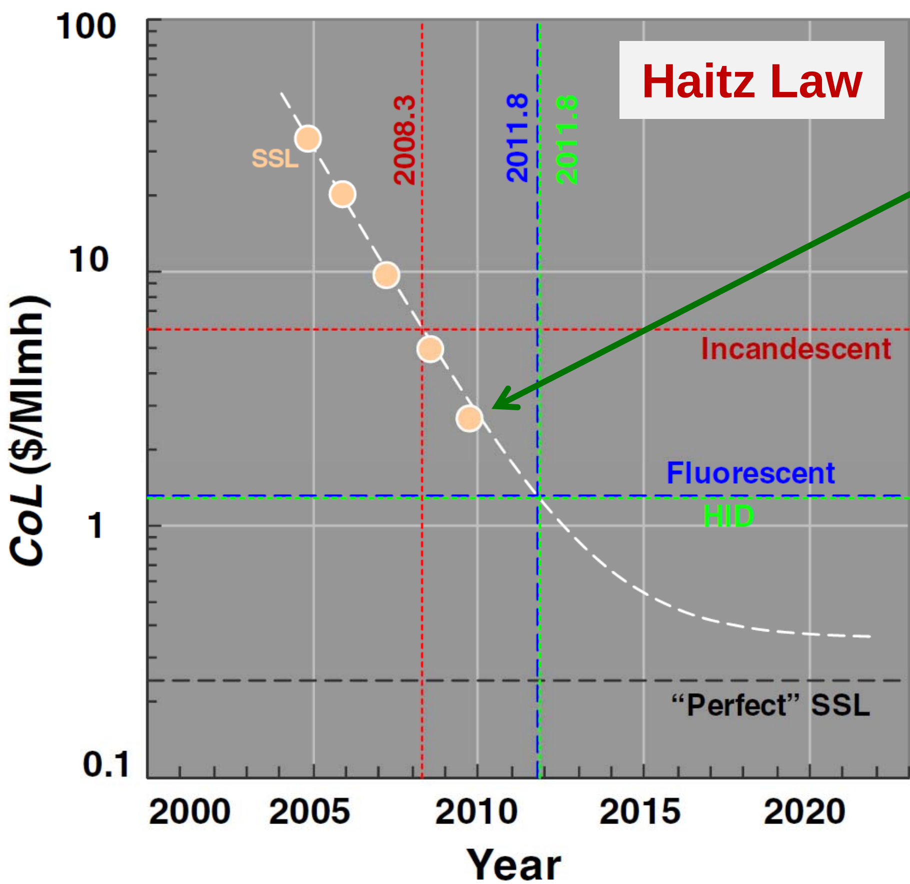
Application: Rare Earth Phosphors for CFLs





Phosphor	Code	Color	Emission Wavelength	Nature	Rare Earth(s)
$BaMgAl_{10}O_{19}:Eu^{2+}$	BAM	Blue	450 nm	Broad band	Eu
$LaPO_4:Ce^{3+}, Tb^{3+}$	LAP	Green	545 nm	Sharp line	La,Ce,Tb
$Y_2O_3:Eu^{3+}$	YEO	Red	610 nm	Sharp line	Y, Eu

Cost of Lighting (CoL) vs. First Lumen Cost (Bulb)



J.Tsao, et.al., *Proc. IEEE* (9/09)

First Purchase Cost (per bulb)

$50-$120	Solid State Bulb
$2.00	Compact Fluorescent
$0.30	Incandescent

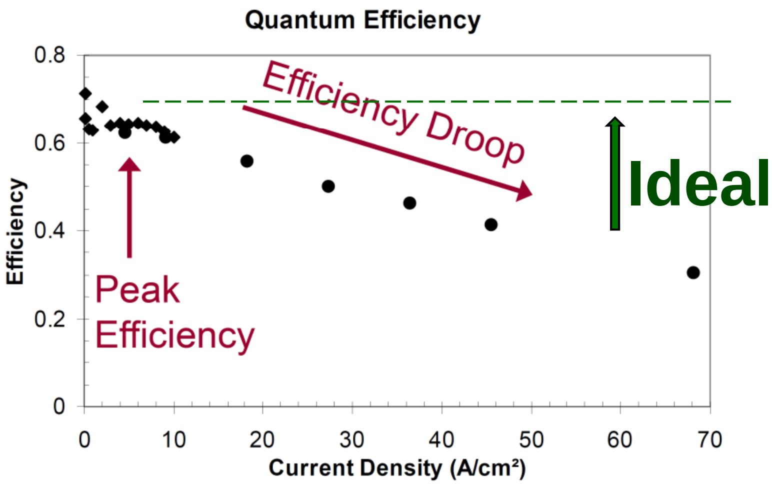
First Cost

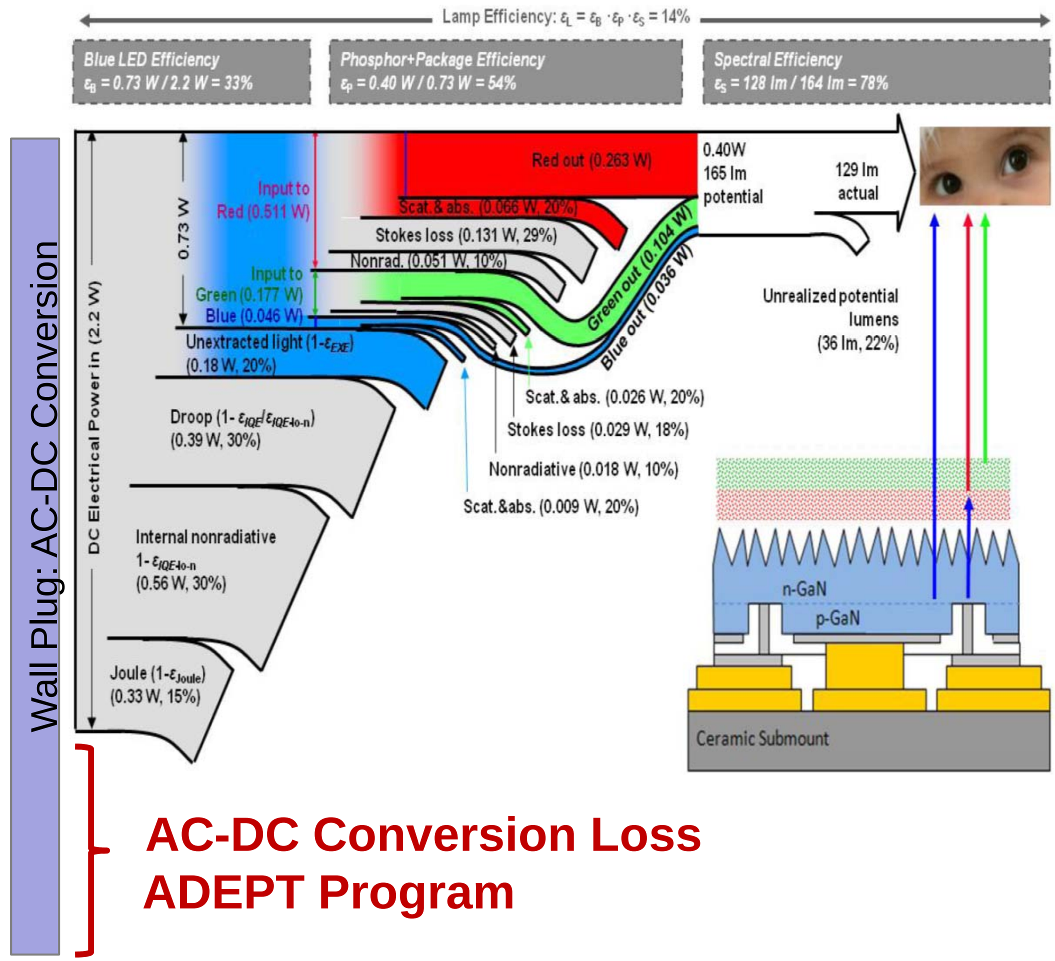
Innovate Faster Than Global Competitors

(cost/klm)

First Purchase Price for Lighting

Technical Pathway to Low First Cost LEDs: Eliminate Droop Losses Through Innovation





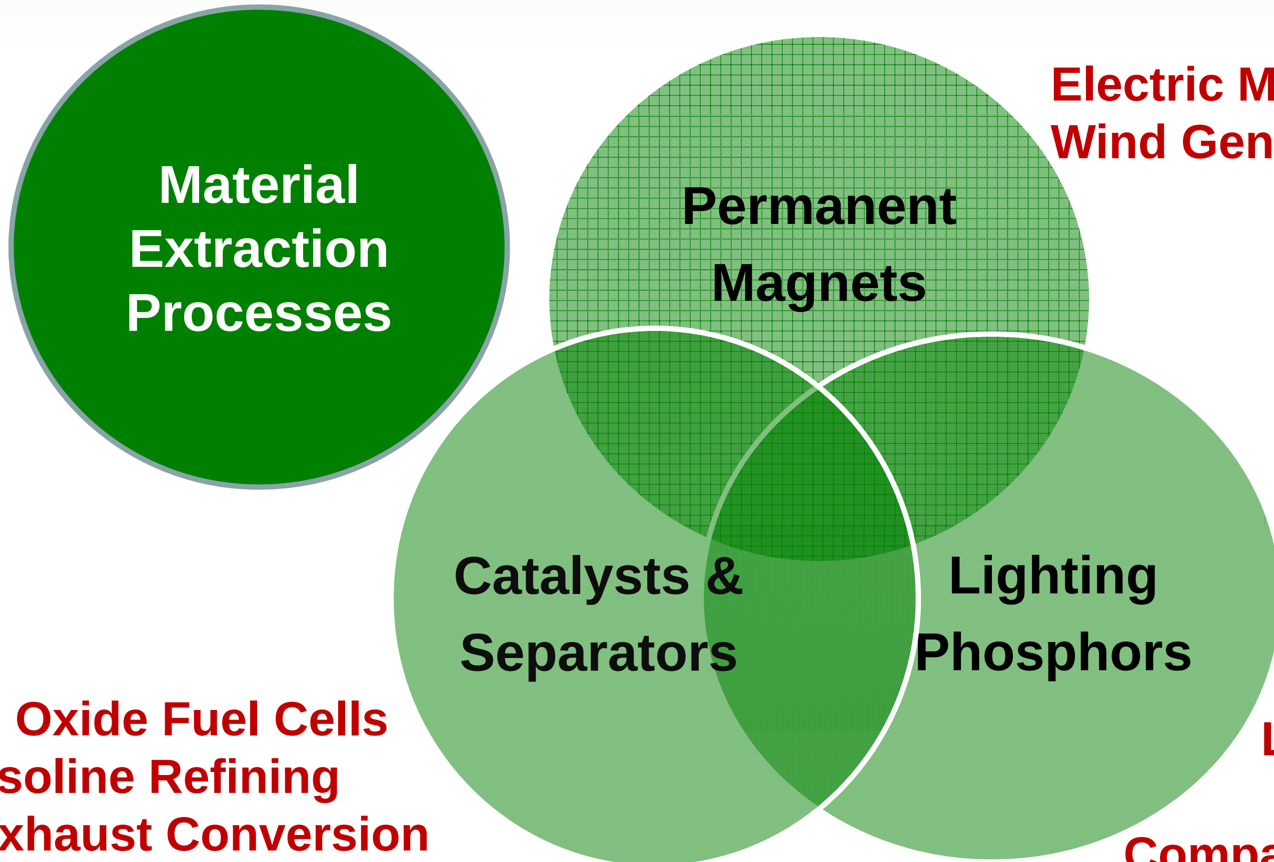
<u>Physical Origins of Droop</u>
Auger Recombination
Non-Radiative Defects
Carrier Overflow from MQWs
Crystal Polarity

<u>Rare Earth Free Phosphors</u>
Luminscent Nanoparticles without Cadmium

J.Tsao, et.al., *Proc. IEEE* (9/09)

Summary: Critical Materials Technology

Geologic or Recycled Feedstocks



Electric Motors
Wind Generators

Solid Oxide Fuel Cells
Gasoline Refining
Auto Exhaust Conversion

Light Emitting Diodes (LED)
Compact Fluorescent Lights (CFL)

Supply Technologies ⟷ Application Technologies

Questions