Critical Materials Workshop

U.S. Department of Energy

April 3, 2012

Dr. Leo Christodoulou

Program Manager

Advanced Manufacturing Office
Energy Efficiency and Renewable Energy
U.S. Department of Energy

Critical Materials Workshop

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Time (EDT)	Activity	Speaker
8:00 am – 9:00 am	Registration and Continental Breakfast	
9:00 am – 9:05 am	Welcome and Overview of Workshop	Dr. Leo Christodoulou Program Manager EERE Advanced Manufacturing Office
9:05 am – 9:35 am	Welcome and Overview of Energy Innovation Hubs	Dr. Steven Chu Secretary of Energy
9:35 am – 9:45 am	DOE and Critical Materials	David Sandalow Assistant Secretary DOE Office of Policy and International Affairs
9:45 am – 9:55 am	National Academies Criticality Methodology and Assessment	Dr. Elizabeth Eide Senior Program Officer The National Academies
9:55 am – 10:10 am	Department of Energy Critical Materials Strategy	Dr. Diana Bauer DOE Office of Policy and International Affairs
10:10 am – 10:40 am	Critical Materials Research in DOE	Dr. Mark Johnson Program Manager ARPA-E
10:40 am – 10:45 am	Top Questions to Consider	Dr. Leo Christodoulou
10:45 am – 12:15 pm	Breakout #1	
	Elimination/Substitution Dr. Mark Johnson	Recovery and Separation Dr. Eric Rohlfing
12:15 pm – 1:15 pm	Lunch	
1:15 pm – 1:45 pm	Working lunch & open discussion on policy and markets led by Leo Christodoulou	
1:45 pm – 3:15 pm	Breakout #2	
	Reduction Dr. Linda Horton	Sustainable and Adaptive use Dr. Colin McCormick
3:15 pm – 3:45 pm	Break	
3:45 pm – 4:50 pm	Report out by Rapporteurs and open comments from audience	
4:50 pm – 5:00 pm	Closing Remarks	Dr. Leo Christodoulou
5:00 pm	No-host networking session	18 Eads Lounge, Crystal City Sheraton

Dr. Steven Chu

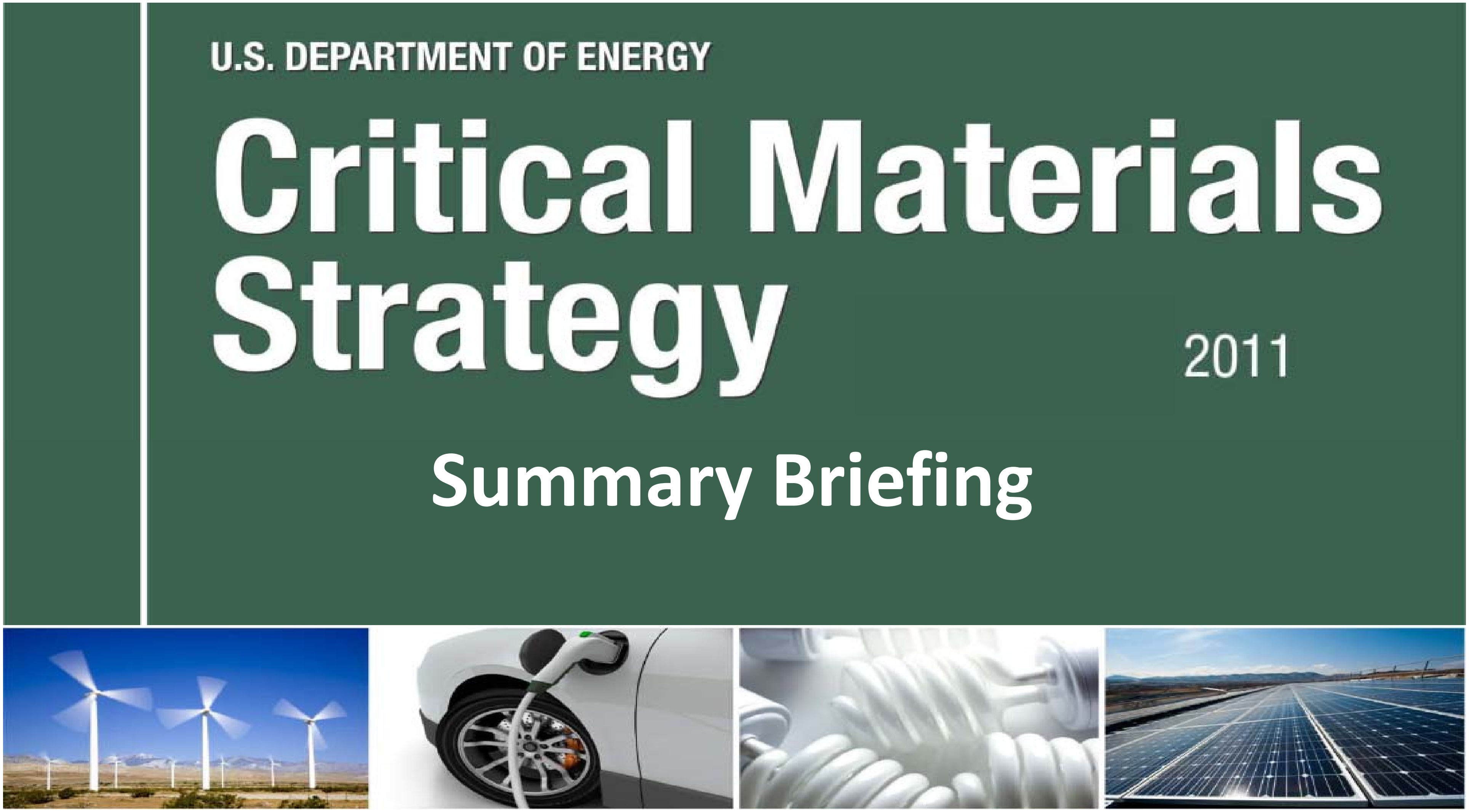
Secretary of Energy

U.S. Department of Energy

David Sandalow

Assistant Secretary

Office of Policy and International Affairs
U.S. Department of Energy



U.S. DEPARTMENT OF ENERGY

Critical Materials Strategy

2011

Summary Briefing

David Sandalow

Office of Policy & International Affairs

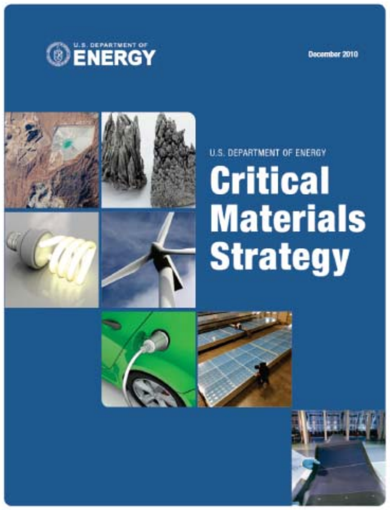
Critical Materials Workshop

April 3, 2012

Timeline

- March 2010 – DOE begins work on first strategy
- December 2010 – 2010 Critical Materials Strategy released

- Spring 2011 – Public Request for Information
- December 2011 – 2011 Critical Materials Strategy released

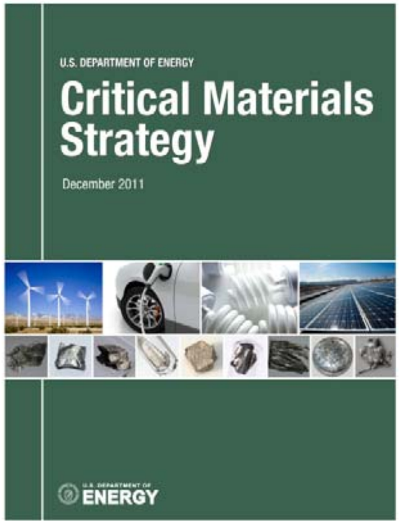


U.S. DEPARTMENT OF ENERGY

December 2010

U.S. DEPARTMENT OF ENERGY

Critical Materials Strategy



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Critical Materials Strategy

December 2011

U.S. DEPARTMENT OF ENERGY

Project Scope

New for 2011

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
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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
			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**

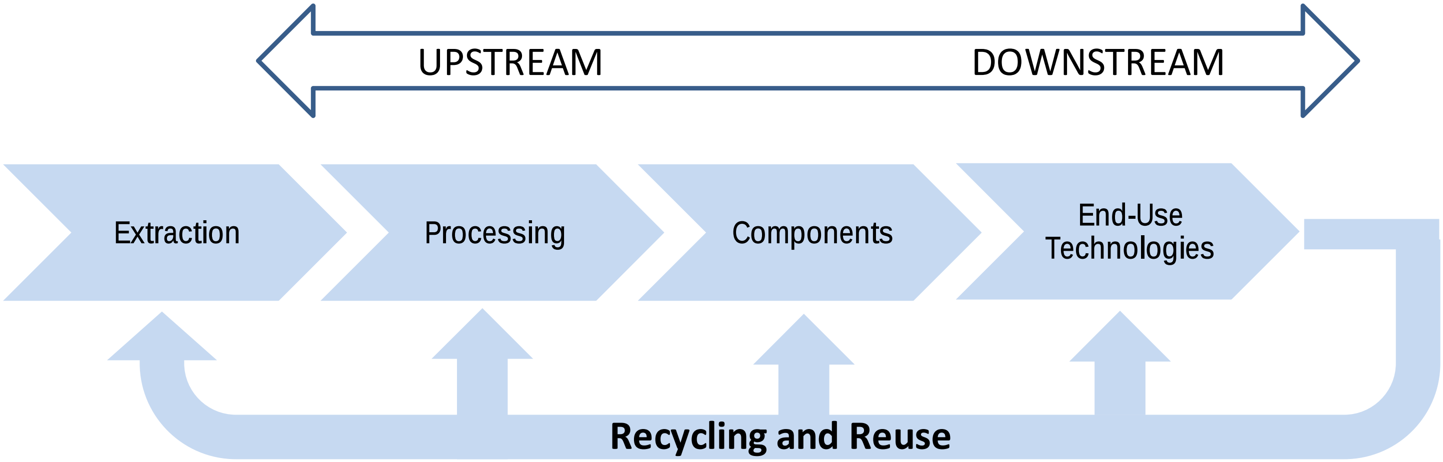
🟥 **Lighting**

🟩 **Solar PV**

🟦 **Wind**

Strategic Pillars

- *Diversify global supply chains*
- *Develop substitutes*
- *Reduce, reuse and recycle*



UPSTREAM

DOWNSTREAM

Extraction

Processing

Components

End-Use Technologies

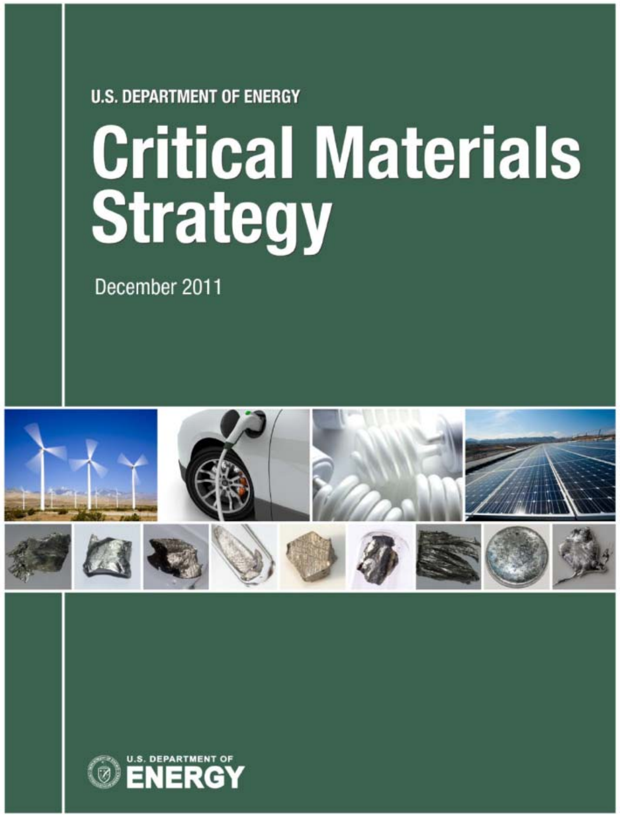
Recycling and Reuse

Material supply chain with environmentally-sound processes

2011 Critical Materials Strategy

2011 Critical Materials Strategy:

- Provides an updated criticality analysis
- Sets forth several case studies, including oil refining catalysts
- Discusses critical materials market dynamics
- Presents DOE's Critical Materials R&D Plan



U.S. DEPARTMENT OF ENERGY

Critical Materials Strategy

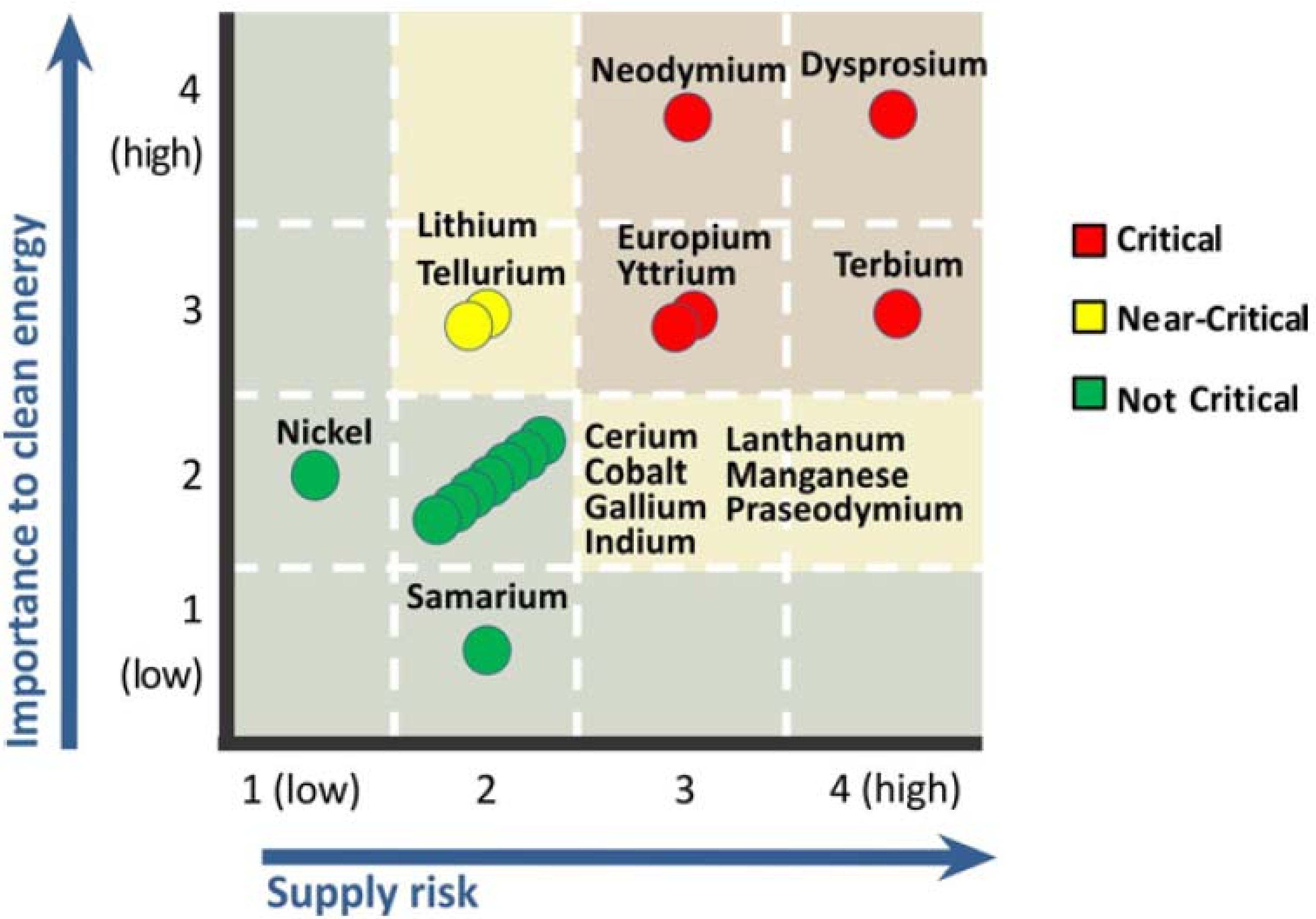
December 2011

U.S. DEPARTMENT OF ENERGY

DOE's 2011 Critical Materials Strategy - Main Messages

1. Critical supply challenges for five rare earths (dysprosium, neodymium, terbium, europium, yttrium) may affect energy technologies in years ahead
2. In past year, DOE and other stakeholders have scaled up work to address these challenges
3. Building workforce capabilities through education and training will help realize opportunities
4. Much more work required in years ahead

2011 CMS Medium-Term Criticality (2015-2025)



Interagency Coordination

Office of Science and Technology Policy (OSTP) convened four work groups:

- Critical Material Criteria and Prioritization
- Federal R&D Prioritization
- Globalization of Supply Chains
- Depth and Transparency of Information

Government Policies

Critical materials are receiving attention from governments around the world.

2011 *Critical Materials Strategy* summarizes policy goals and strategies of:

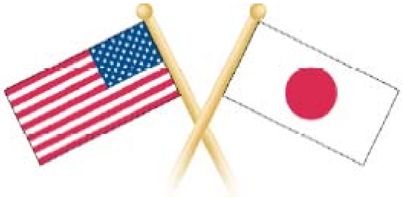
- **Japan**
- **European Union**
- **Australia**
- **Canada**
- **China**

Cooperation among countries can:

- Accelerate global innovation on key topics
- Improve transparency in critical materials markets
- Advance environmentally sound mining and processing

R&D Workshops & International Meetings

- Japan-US Workshop (Lawrence Livermore National Lab – Nov 18-19, 2010)



- Transatlantic Workshop (MIT – Dec 3, 2010)

US-EU ENERGY COUNCIL

- ARPA-E Workshop (Ballston, VA – Dec 6, 2010)

arpa·e

- US- Australia Joint Commission Meeting (DC – Feb 14, 2011)

- Trilateral R&D Workshops with Japan and EU (DC – Oct 4-5, 2011, Tokyo – March 28-29, 2012)

EU-JAPAN-US TRILATERAL CRITICAL MATERIALS INITIATIVE

Education and Training:
Skills Required Across the Rare Earth Supply Chain

Disciplines

Bioengineering
Chemical Engineering
Chemistry
Civil Engineering
Electrical Engineering
Economics
Environmental Engineering
Environmental Science
Geosciences
Hydrology
Industrial Ecology
Materials Science
Mechanical Engineering
Physics

Concentrations

Process Operations
Separations
Lanthanide chemistry
Solid-state chemistry
Ecology
Economic Geology
Geology
Mineralogy
Mining sciences
Ceramics
Magnetic materials
Metallurgy
Optical sciences
Solid-state physics

Trans-disciplinary Skills

Characterization/Instrumentation
Green Chemistry/Engineering
Manufacturing Engineering
Materials recycling technology
Modeling
Product design
Rational design

R&D Plan

- DOE R&D aligns with the 3 strategic pillars
  - Diversification of Supply: Separation and processing
  - Substitutes
    - Magnets, motors, generators
    - PV
    - Batteries
    - Phosphors
  - Recycling

Next Steps

- Implement DOE's integrated research plan
- 3rd Trilateral EU-Japan-US Conference in Brussels in fall 2012
- Strengthen information-gathering capacity
- Continue to work closely with:
  - Interagency colleagues
  - International partners
  - Congress
  - Public
- Update the Strategy periodically

U.S. DEPARTMENT OF ENERGY

Critical Materials Strategy

2011

Summary Briefing

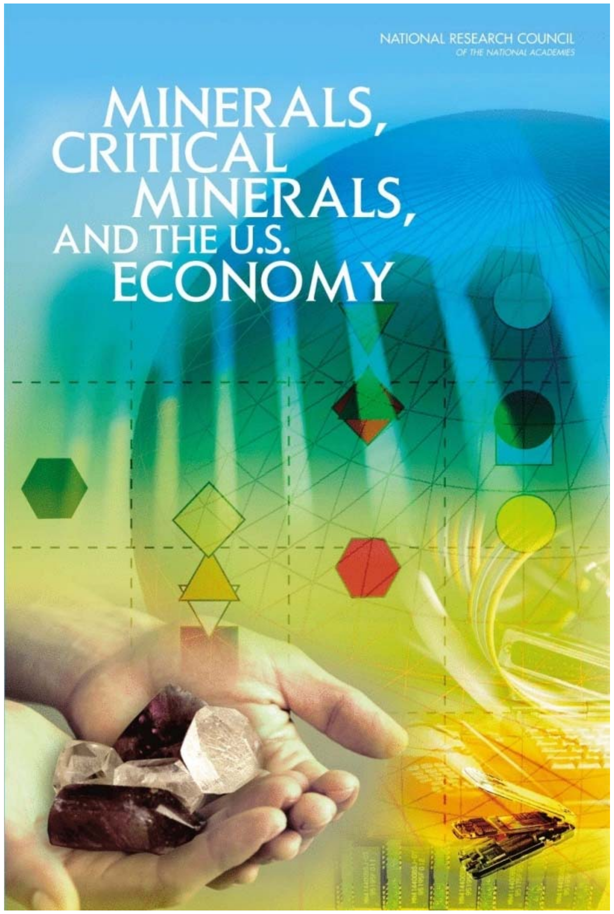
DOE Welcomes Comments

MaterialStrategy@hq.doe.gov

Dr. Elizabeth Eide

Senior Program Officer

The National Academies



REVIEW: DEVELOPMENT OF THE CRITICALITY MATRIX METHODOLOGY

U.S. Department of Energy
Critical Materials Workshop
April 3, 2012

Committee on Critical Mineral Impacts on the U.S. Economy

Dr. Elizabeth A. Eide
Director, Board on Earth Science and Resources

Background

- Minerals are essential for U.S. economic activity and quality of life: e.g., cellular telephones, automobiles, energy technology.

- Mineral demands and supply chains are complex.

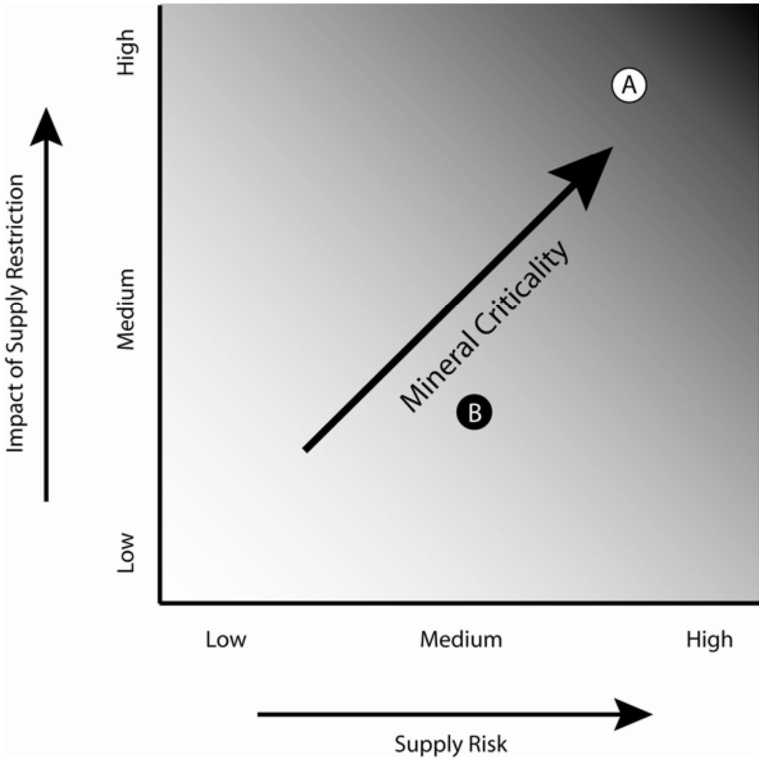
- Many technologies require minerals not available in the United States.

- The report:
  - developed a methodology to analyze the degree to which a mineral is both essential in use and subject to supply risk—a ‘criticality matrix’;
  - analyzed the information and research needs to implement the method.

Overview

- Criticality matrix components—the methodology
- Example application: Copper
- Example application: Platinum Group Metals

Criticality Matrix



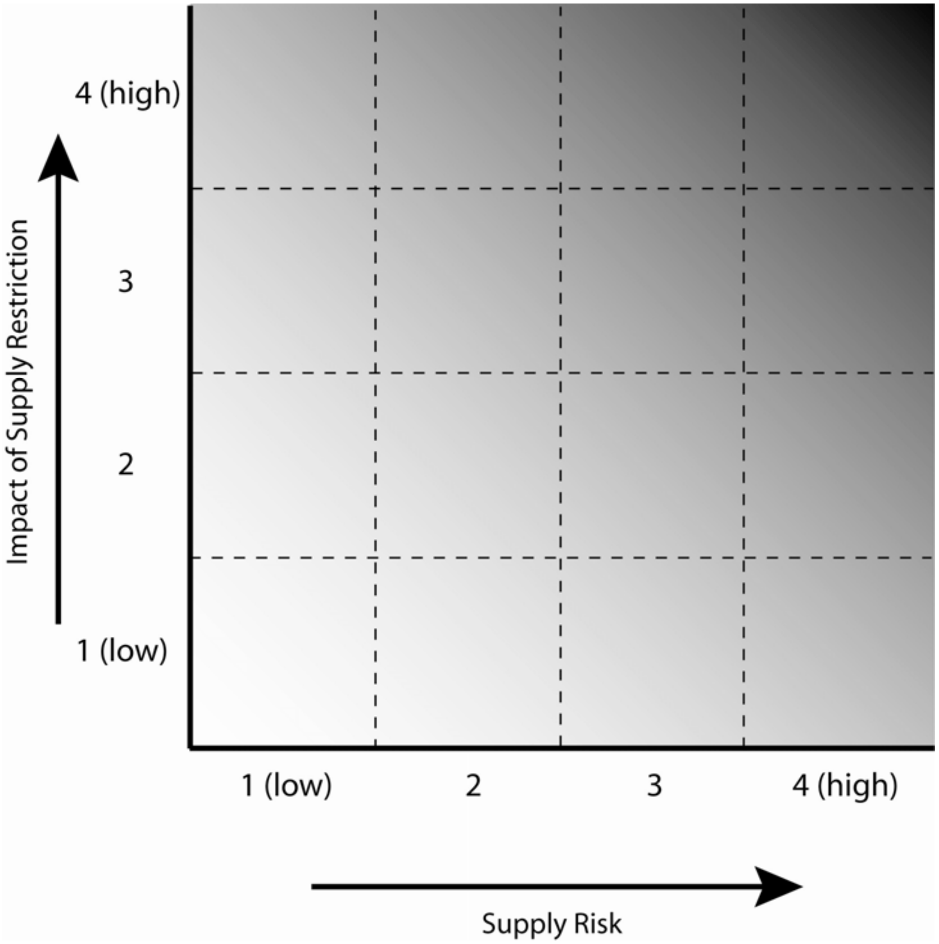
- ☐ Criticality is dynamic.

- ☐ Criticality is 'more or less', not 'either/or'
  --a matter of degrees.

- ☐ Degree of criticality determined by: importance in use (vertical axis) & supply risk (horizontal axis).

- ☐ Report evaluated 11 minerals to demonstrate application of the matrix methodology.

Methodology : Applying the Matrix



Methodology : Applying the Matrix

1. **IMPORTANCE IN USE / IMPACT OF SUPPLY RESTRICTION (Vertical Axis)**:

- Which products or applications use a mineral of interest
- Some minerals are more important to the function of specific products
- Functionality = related to mineral's physical and chemical properties
- Leads to concept of substitutability

Methodology : Applying the Matrix

2. AVAILABILITY & RELIABILITY OF SUPPLY / SUPPLY RISK (Horizontal Axis):

- Time frame: short-, medium-, & long-term factors.

  Short- to medium-term restrictions due, for example, to:
  - significant increase in demand;
  - concentration of production or production mainly as a byproduct;
  - constraints on recycling.

  Long-term restrictions due to:
  - geology;
  - technology;
  - environmental and social concerns;
  - politics; and/or
  - economics.

- Greater the difficulty to find a substitute for a mineral, the greater the impact of a restriction in that mineral's supply.

- Import dependence by itself is not a complete indicator of supply risk.

Example—Copper

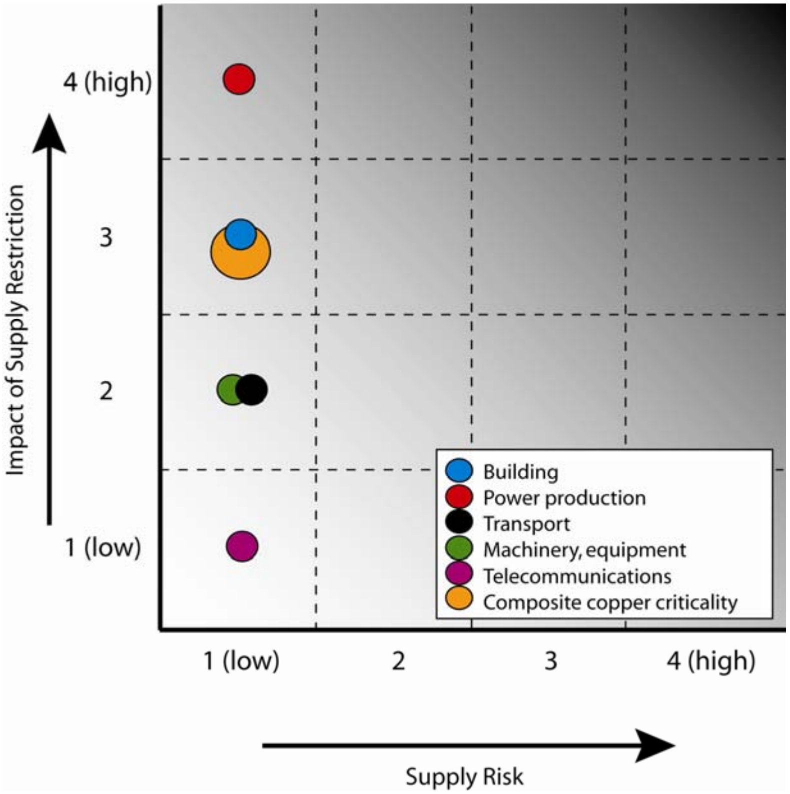
- Applications/Uses: building and construction, energy provision, transport, electronics and appliances, telecommunications.

- Important Applications: incorporate 70% of total copper used annually in U.S.

- Physical/Chemical Properties: make substitution difficult for wiring; substitution in plumbing applications becoming common.

- Short-, Medium-, and Long-term Issues: diverse availability (internationally); some domestic supply; technical aspects of extraction and processing well developed; low geopolitical or environmental concern for availability; recycling becoming more prevalent.

Example—Copper



- ❑ Vertical axis: Composite, weighted impact of supply restriction = **relatively high** (*orange*) because of building and power production applications**.**

- ❑ Horizontal axis: Low risk to supply at present time.

Example—Platinum Group Metals (PGMs)

- Applications: catalytic converters, industrial chemicals (e.g., fertilizers, explosives, caustic soda), crude oil refining, fuel cells, fine jewelry, dental and electronics.

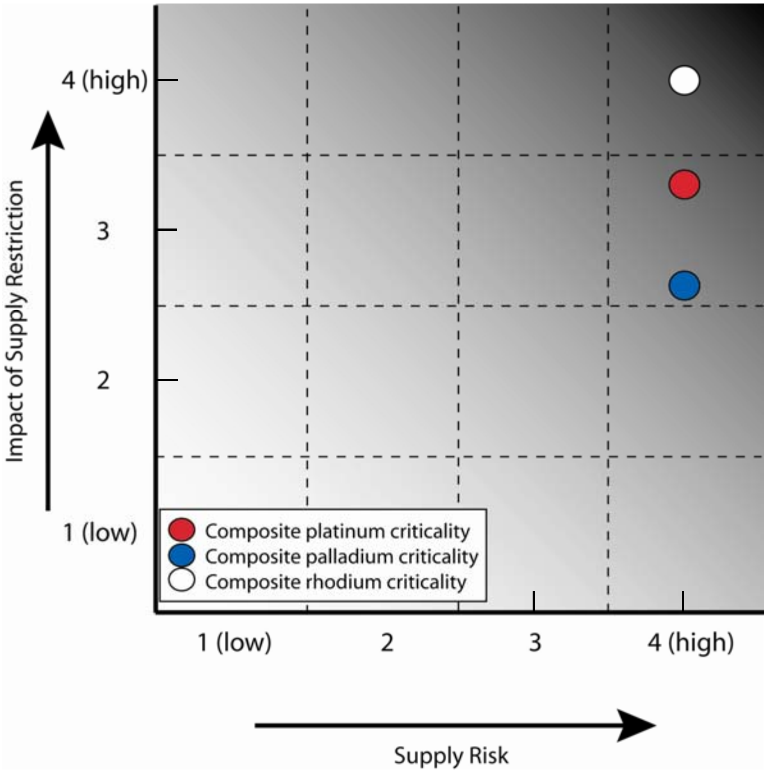
- Most Important Application: auto catalysts for emission controls use 50-85% of PGMs annually in the United States.

- Chemical and Physical Properties: make substitution with other minerals difficult or impossible; e.g., ‘*no-build*’ situation for automobiles.

- Import Dependence:
    - -just two countries (South Africa and Russian Federation) are main suppliers
    - -small number of mining, smelting, refining companies in those countries

- Recycling: significant production from scrap in U.S. Supply risk would be greater in absence of recycling.

Example—Platinum Group Metals (PGMs)



- ☐ Vertical axis: Impact of supply restriction for auto catalysts and chemicals is high.

- ☐ Horizontal axis: Reliance on imports with supply controlled by a small number of companies in two countries yields a high supply risk.

National Research Council
Study Committee Membership

Roderick G. Eggert, *chair*, *Colorado School of Mines*
Ann S. Carpenter, *U.S. Gold Corporation*
Stephen W. Freiman, *Freiman Consulting, Inc.*
Thomas E. Graedel, *Yale University*
Drew A. Meyer, *Vulcan Materials Company (retired)*
Terence P. McNulty, *T.P. McNulty and Associates, Inc.*
Brij M. Moudgil, *University of Florida*
Mary M. Poulton, *University of Arizona*
Leonard J. Surges, *Natural Resources Canada*

Study overseen by NRC Committee on Earth Resources & Board on Earth Sciences and Resources
Study sponsored by the U.S. Geological Survey and National Mining Association

Dr. Diana Bauer

Office of Policy and International Affairs
U.S. Department of Energy

U.S. DEPARTMENT OF ENERGY

Critical Materials Strategy

2011

Criticality Assessment

Diana Bauer

Office of Policy & International Affairs

Critical Materials Workshop

April 3, 2012

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Vehicles

Lighting

Solar PV

Wind

Current and Projected Rare Earth Projects

(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

Source: Watts 2011

Rare earth metals are not rare –
found in many countries including the United States

Current and Projected Rare Earth Oxide Supply by Element – 2011 Critical Materials Strategy

	2010 Production	Potential Sources of Additional Production between 2010 and 2015									Total 2015 Production Capacity
		United States		Australia			Vietnam	South Africa			
		Mt. Pass Phase I	Mt. Pass Phase II	Mt. Weld	Nolans Bore	Dubbo Zirconia	Dong Pao	Steenkamps-kraal	Russia & Kazakhs-tan	India	
La	**31,000**	5,800	6,800	5,600	2,000	510	970	1,100	140	560	54,000
Ce	**42,000**	8,300	9,800	10,300	4,800	960	1,500	2,300	290	1200	81,000
Pr	**5,900**	710	840	1,200	590	110	120	250	20	140	9,900
Nd	**20,000**	2,000	2,300	4,100	2,200	370	320	830	44	460	33,000
Sm	**2,800**	130	160	510	240	56	27	125	5	68	4,000
Eu	**370**	22	26	88	40	2		4	1		550
Gd	**2,400**	36	42	176	100	56		83	1	30	3,000
Tb	**320**	5	6	22	10	8		4	0.4		370
Dy	**1,600**	9	10	22	30	53		34	1		1,700
Y	**10,500**			66		410	21	250			11,300
Others	**2,000**	73	86			75	25	12	3	25	2,300
Total	**120,000**	17,000	20,000	22,000	10,000	2,600	3,000	5,000	500	2,500	200,000

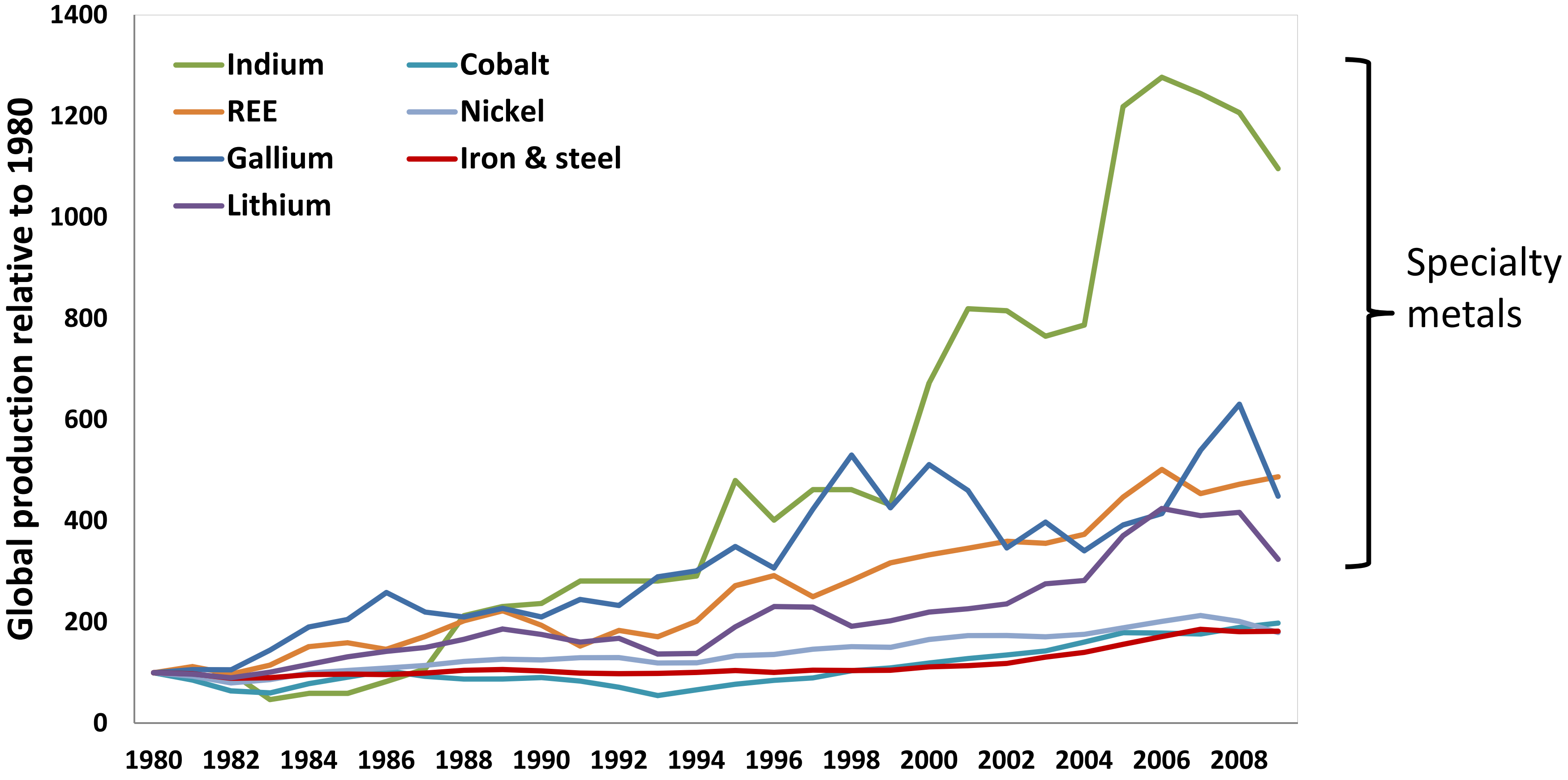
Sources: Kingsnorth, Lynas, Molycorp, Roskill(2011)

Current and Projected Material Supply
2011 Critical Materials Strategy

	Potential Sources of Additional Production between 2010 and 2015			
	2010 Production	Additional Amount	Sources	2015 Production Capacity
Indium	1,300	270	Recovery as byproduct from maximum utilization of current production and refining capacity plus additional zinc production, as well as recycling	1,600
Gallium	270	90	Recovery as byproduct from maximum utilization of current production and refining capacity plus additional alumina and bauxite production	360
Tellurium	630	210	Recovery as byproduct from copper anode slimes	840
Cobalt	90,000	91,000	Mines	180,000
Lithium Carbonate Equivalent	150,000	100,000	Brines and mines	250,000
Nickel	1,600,000	840,000	Mines	2,400,000
Manganese Dioxide	790,000	47,000	Synthetic (electrolytic and chemical) manganese dioxide	840,000

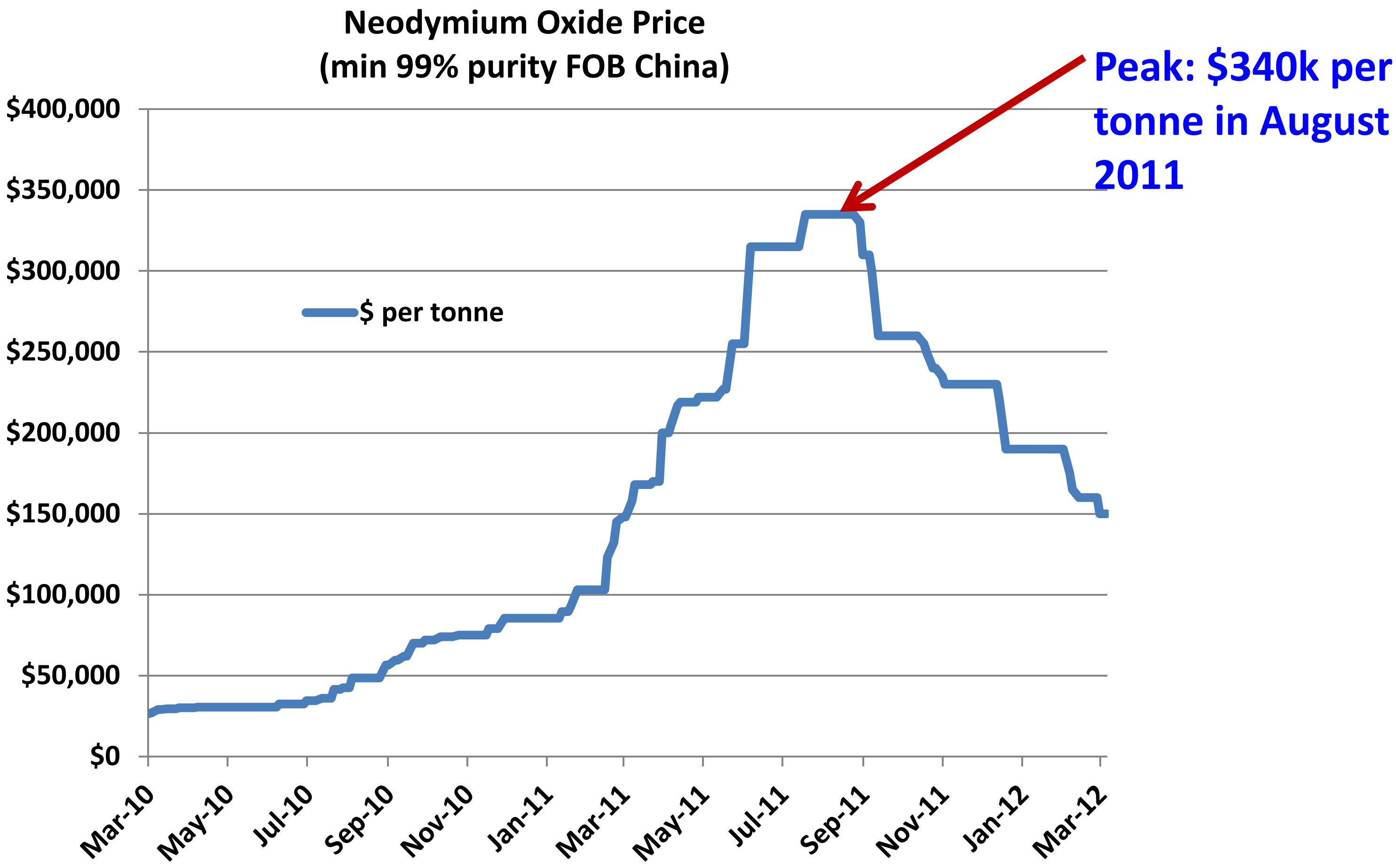
(Sources: USGS; Indium Corp. 2010)

Demand for Materials



- *Global Demand for rare earths and other specialty materials has outpaced that of base metals (e.g., iron and steel)*

Rare Earth Price Volatility



Peak: $340k per tonne in August 2011

Demand Projections: Four Trajectories

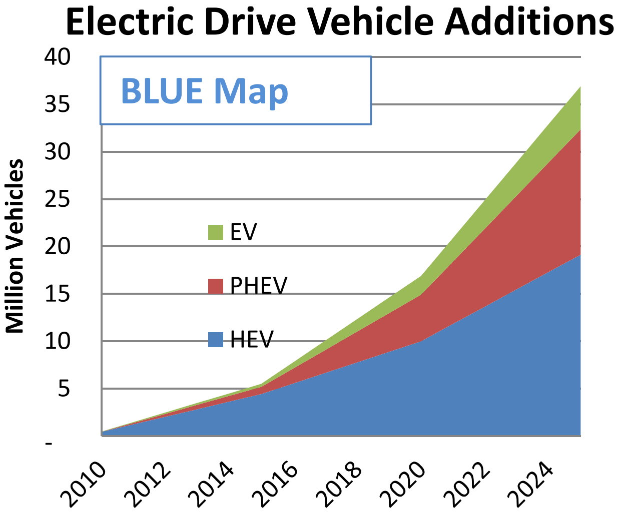
Material Demand Factors

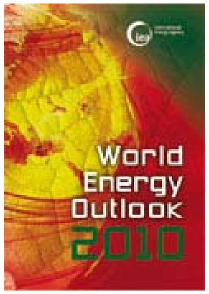
	Market Penetration	Material Intensity
Trajectory D	High	High
Trajectory C	High	Low
Trajectory B	Low	High
Trajectory A	Low	Low

- ***Market Penetration = Deployment*** (total annual units of a clean energy technology) ***X Market Share*** (% of units using materials analyzed)
- ***Material Intensity =*** Material demand per unit of the clean energy technology

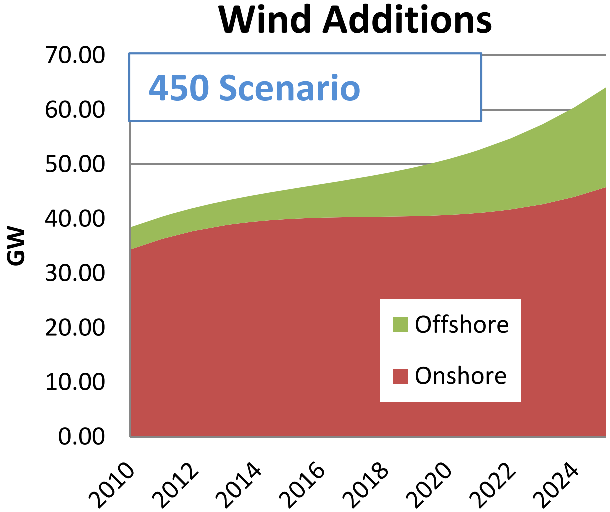
High Technology Deployment Scenarios – 2011 Critical Materials Strategy

IEA Energy Technology Perspectives

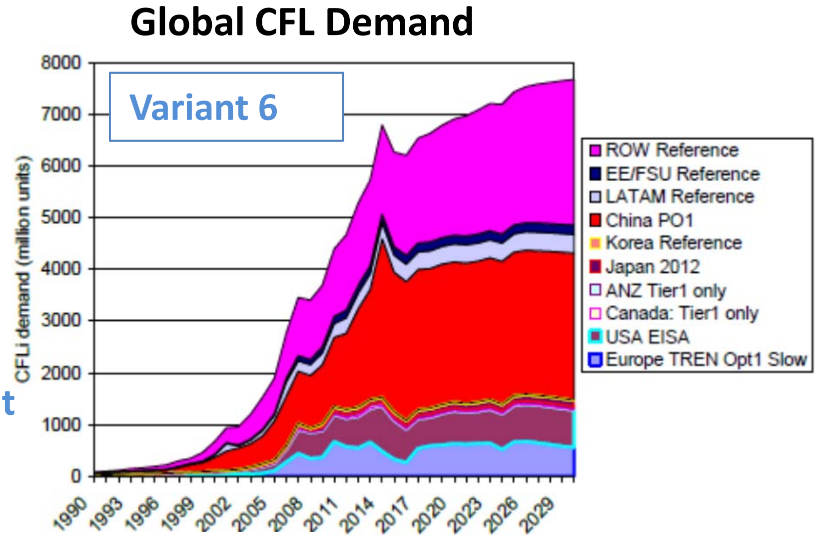




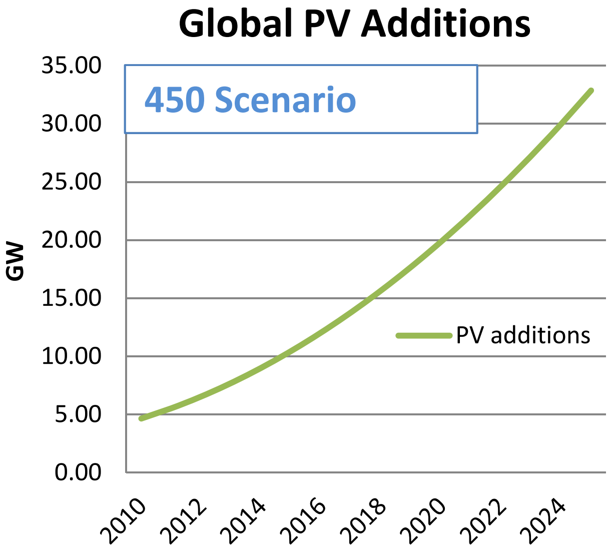
IEA World Energy Outlook



IEA: Phase Out of Incandescent Lights



Plus High LFL Demand Estimate



Material Intensity – 2011 Critical Materials Strategy

Technology	Component	Material	High Intensity*	Low Intensity*
Wind	**Generators**	Neodymium	186 kg/MW	62 kg/MW
		Dysprosium	24 kg/MW	4 kg/MW
Vehicles	**Motors**	Neodymium	0.62 kg/vehicle	0.31 kg/vehicle
		Dysprosium	0.12 kg/vehicle	0.045 kg/vehicle
	Li-ion Batteries (HEVs, PHEVs and AEVs)	Lithium	0.6-12.7 kg/vehicle	0.2-3.4 kg/vehicle
		Cobalt	0.43-9.4 kg/vehicle	0 kg/vehicle
		Nickel	2.3-46.5 kg/vehicle	0 kg/vehicle
		Manganese	4.6-91.5 kg/vehicle	0 kg/vehicle
	NiMH Batteries (HEVs)	Rare Earths (Ce, La, Nd, Pr)	2.2 kg/vehicle	1.4 kg/vehicle
		Cobalt	0.66 kg/vehicle	0.44 kg/vehicle
		Nickel	3.2 kg/vehicle	2.1 kg/vehicle
		Managese	0.34 kg/vehicle	0.23 kg/vehicle

*elemental content

- *Calculation methods differed by component based on available data*
- *High Intensity = material intensity with current generation technology*
- *Low Intensity = intensity with feasible improvements in material efficiency*

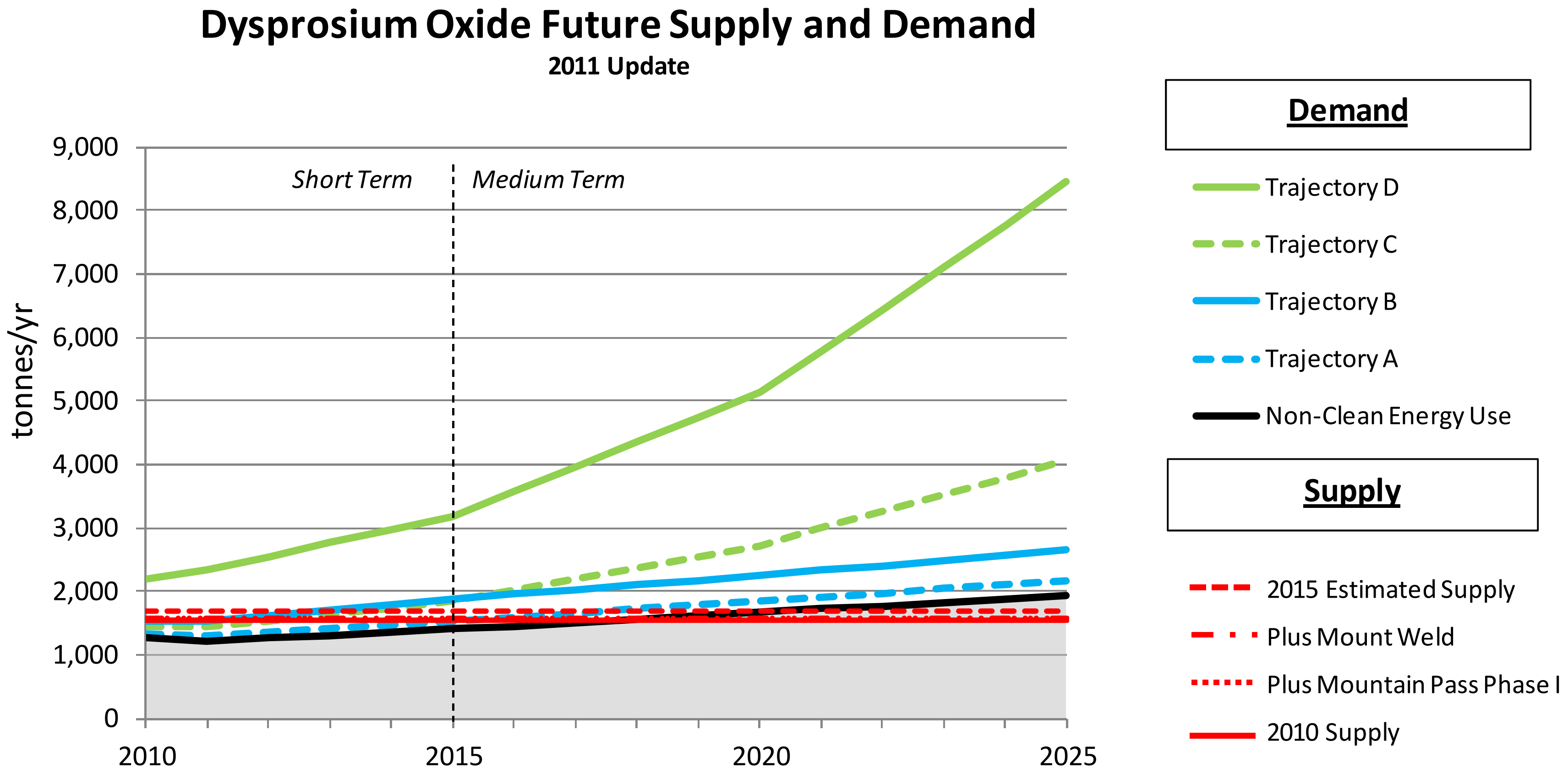
Material Intensity – 2011 Critical Materials Strategy

Technology	Component	Material	High Intensity*	Low Intensity*
PV Cells	**CIGS Thin Films**	Indium	23 kg/MW	15 kg/MW
		Gallium	19 kg/MW	12 kg/MW
	CdTe Thin Films	Tellurium	74 kg/MW	17 kg/MW
Lighting	**LFLs (Medium Efficiency)**	Rare Earth (Ce, La, Y, Tb, Eu) in phosphor coating	0.72 mg/cm2	0.54 mg/cm2
	LFLs (High Efficiency)	Rare Earth (Ce, La, Y, Tb, Eu) in phosphor coating	2.4 mg/cm2	1.8 mg/cm2
Lighting	**CFLs**	Rare Earth (Ce, La, Y, Tb, Eu)	0.9 g per bulb	0.68 g per bulb

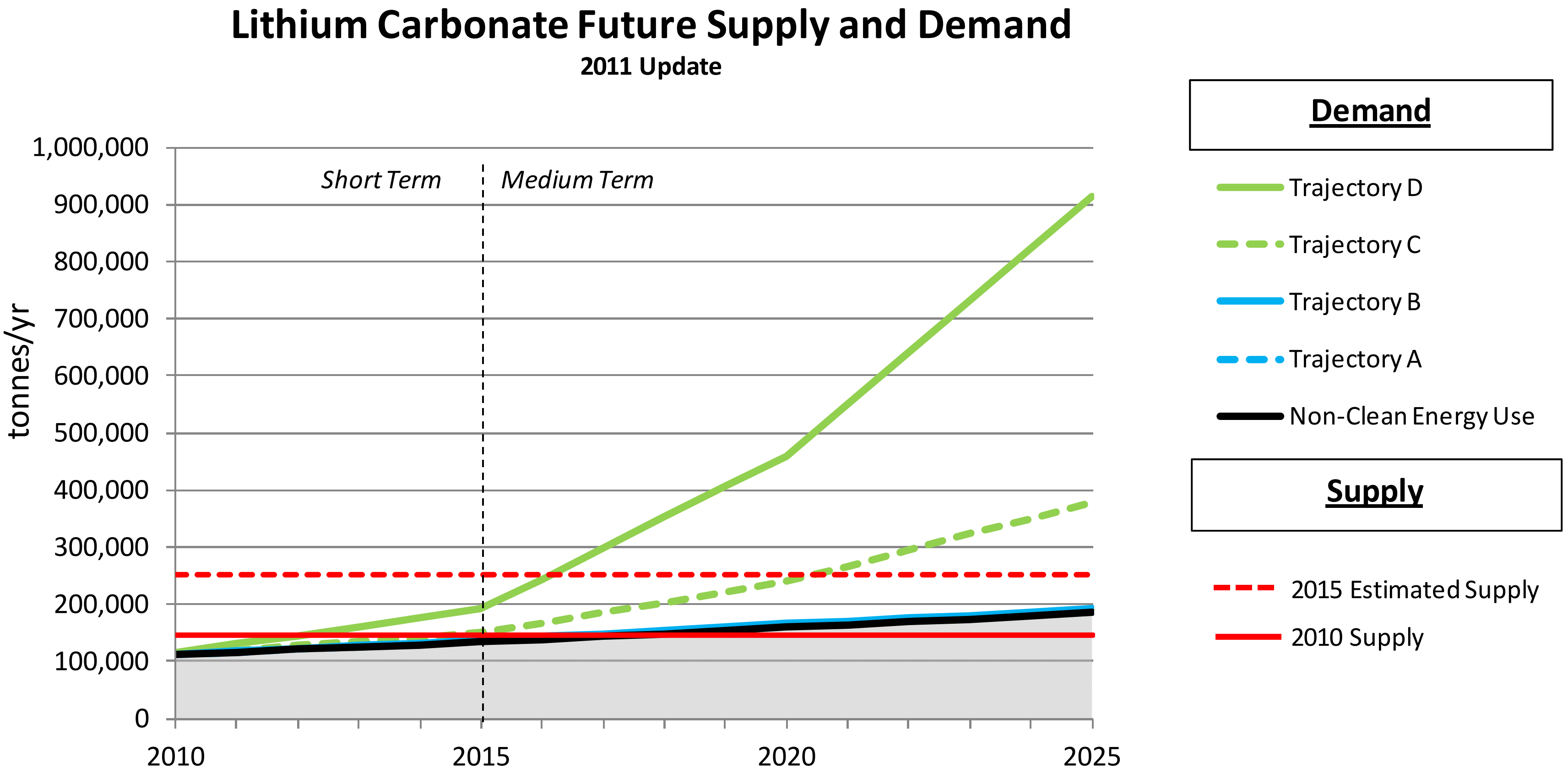
*elemental content

- ***Calculation methods differed by component based on available data***
- ***High Intensity = material intensity with current generation technology***
- ***Low Intensity = intensity with feasible improvements in material efficiency***

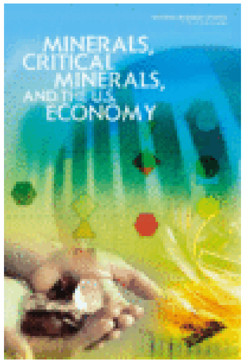
Dysprosium Oxide- Supply and Demand Projections
2011 Critical Materials Strategy



Lithium – Supply and Demand Projections
2011 Critical Materials Strategy

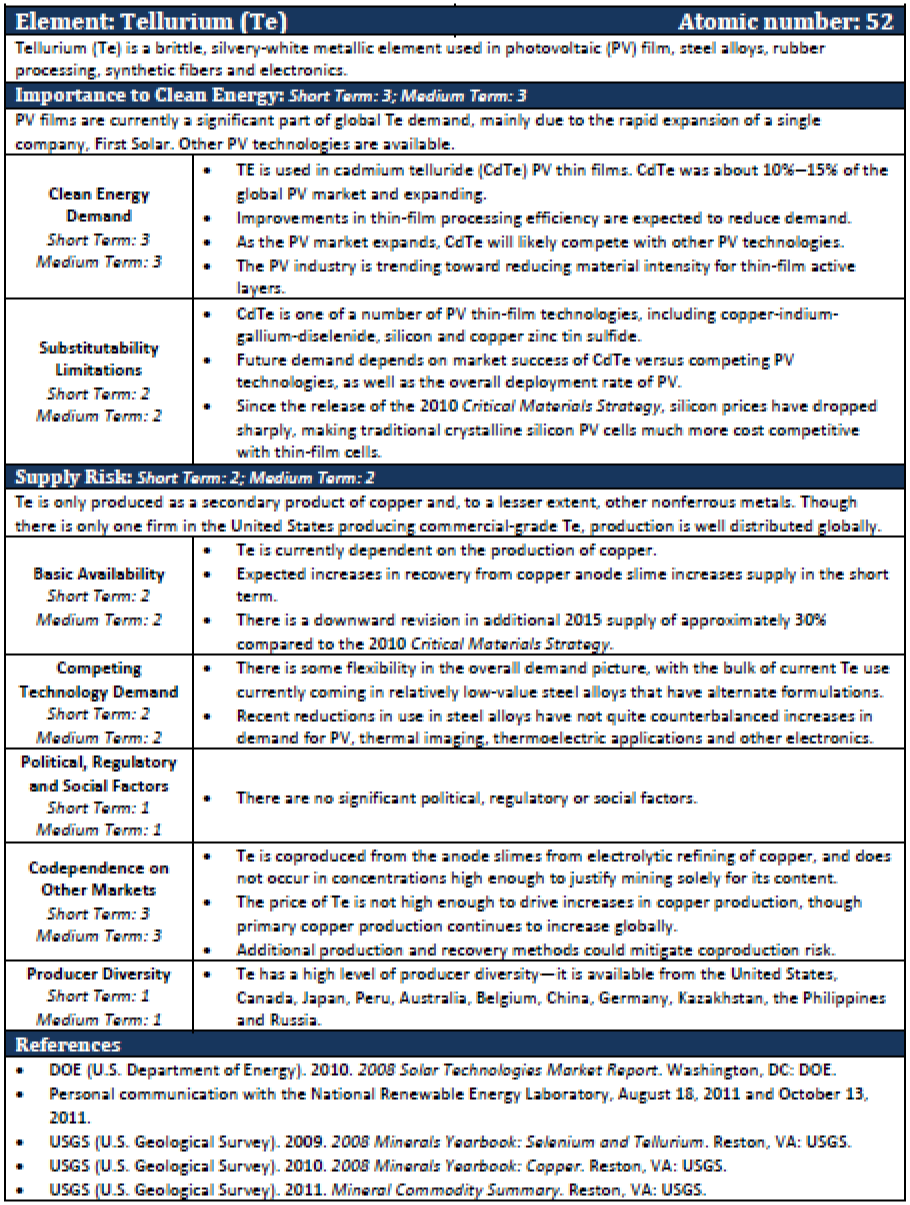


Criticality Assessments


MINERALS, CRITICAL MINERALS, AND THE U.S. ECONOMY

- Methodology adapted from National Academy of Sciences
- *Criticality* is a measure that combines
    - Importance to clean energy technologies
        - Clean Energy Demand (75%); Substitutability Limitations (25%)
    - Risk of supply disruption
        - Basic Availability (40%); Competing Technology Demand (10%); Political, Regulatory and Social Factors (20%); Co-Dependence on Other Markets (10%); Producer Diversity (20%)
- Time frames:
    - Short-term (Present - 2015)
    - Medium-term (2015 - 2025)

Example Criticality Assessment



Element: Tellurium (Te) **Atomic number: 52**

Tellurium (Te) is a brittle, silvery-white metallic element used in photovoltaic (PV) film, steel alloys, rubber processing, synthetic fibers and electronics.

Importance to Clean Energy: ***Short Term: 3; Medium Term: 3***

PV films are currently a significant part of global Te demand, mainly due to the rapid expansion of a single company, First Solar. Other PV technologies are available.

Clean Energy Demand *Short Term: 3* *Medium Term: 3*	• TE is used in cadmium telluride (CdTe) PV thin films. CdTe was about 10%–15% of the global PV market and expanding. • Improvements in thin-film processing efficiency are expected to reduce demand. • As the PV market expands, CdTe will likely compete with other PV technologies. • The PV industry is trending toward reducing material intensity for thin-film active layers.
Substitutability Limitations *Short Term: 2* *Medium Term: 2*	• CdTe is one of a number of PV thin-film technologies, including copper-indium-gallium-diselenide, silicon and copper zinc tin sulfide. • Future demand depends on market success of CdTe versus competing PV technologies, as well as the overall deployment rate of PV. • Since the release of the 2010 *Critical Materials Strategy*, silicon prices have dropped sharply, making traditional crystalline silicon PV cells much more cost competitive with thin-film cells.

Supply Risk: ***Short Term: 2; Medium Term: 2***

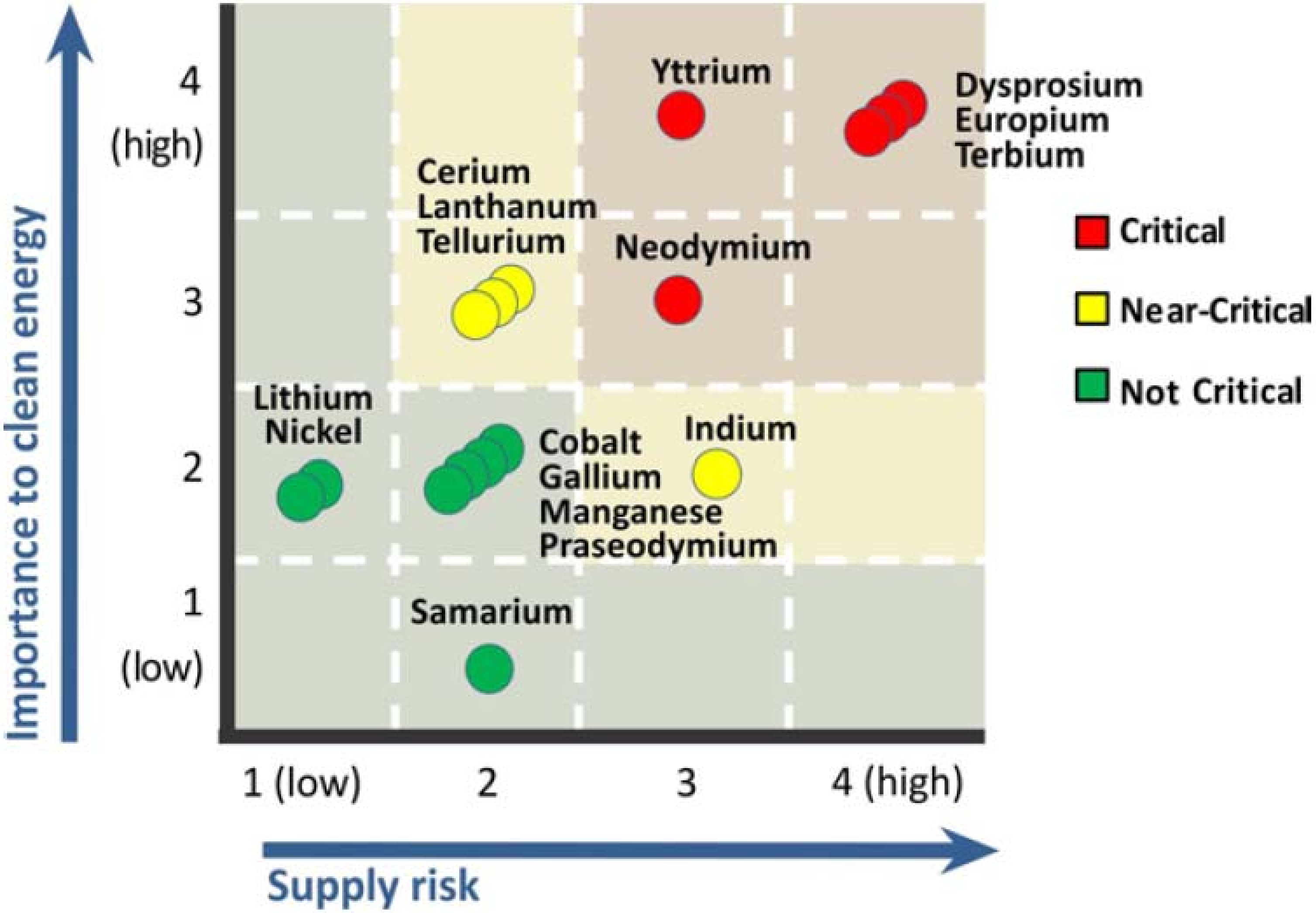
Te is only produced as a secondary product of copper and, to a lesser extent, other nonferrous metals. Though there is only one firm in the United States producing commercial-grade Te, production is well distributed globally.

Basic Availability *Short Term: 2* *Medium Term: 2*	• Te is currently dependent on the production of copper. • Expected increases in recovery from copper anode slime increases supply in the short term. • There is a downward revision in additional 2015 supply of approximately 30% compared to the 2010 *Critical Materials Strategy*.
Competing Technology Demand *Short Term: 2* *Medium Term: 2*	• There is some flexibility in the overall demand picture, with the bulk of current Te use currently coming in relatively low-value steel alloys that have alternate formulations. • Recent reductions in use in steel alloys have not quite counterbalanced increases in demand for PV, thermal imaging, thermoelectric applications and other electronics.
Political, Regulatory and Social Factors *Short Term: 1* *Medium Term: 1*	• There are no significant political, regulatory or social factors.
Codependence on Other Markets *Short Term: 3* *Medium Term: 3*	• Te is coproduced from the anode slimes from electrolytic refining of copper, and does not occur in concentrations high enough to justify mining solely for its content. • The price of Te is not high enough to drive increases in copper production, though primary copper production continues to increase globally. • Additional production and recovery methods could mitigate coproduction risk.
Producer Diversity *Short Term: 1* *Medium Term: 1*	• Te has a high level of producer diversity—it is available from the United States, Canada, Japan, Peru, Australia, Belgium, China, Germany, Kazakhstan, the Philippines and Russia.

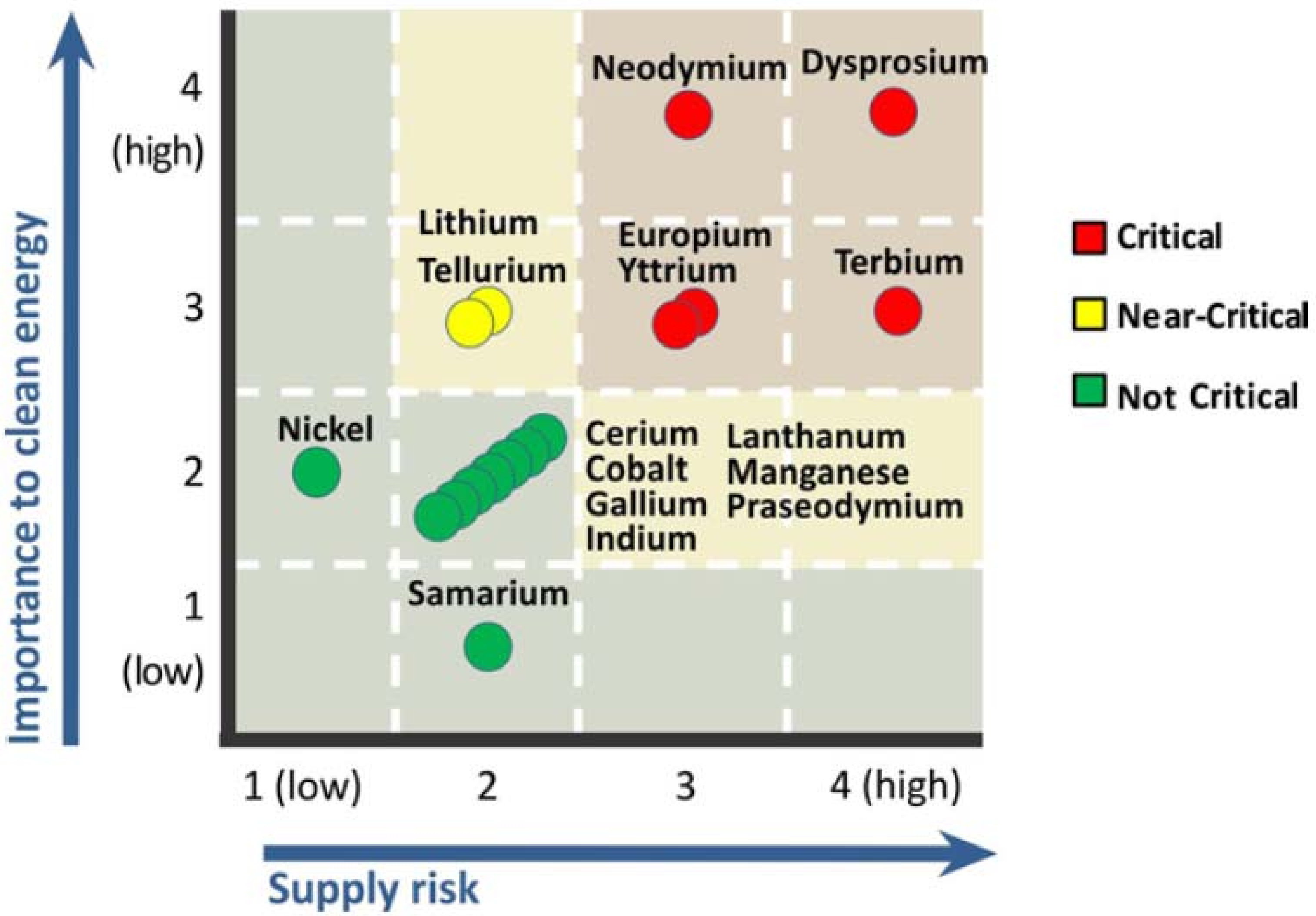
References

- DOE (U.S. Department of Energy). 2010. *2008 Solar Technologies Market Report*. Washington, DC: DOE.
- Personal communication with the National Renewable Energy Laboratory, August 18, 2011 and October 13, 2011.
- USGS (U.S. Geological Survey). 2009. *2008 Minerals Yearbook: Selenium and Tellurium*. Reston, VA: USGS.
- USGS (U.S. Geological Survey). 2010. *2008 Minerals Yearbook: Copper*. Reston, VA: USGS.
- USGS (U.S. Geological Survey). 2011. *Mineral Commodity Summary*. Reston, VA: USGS.

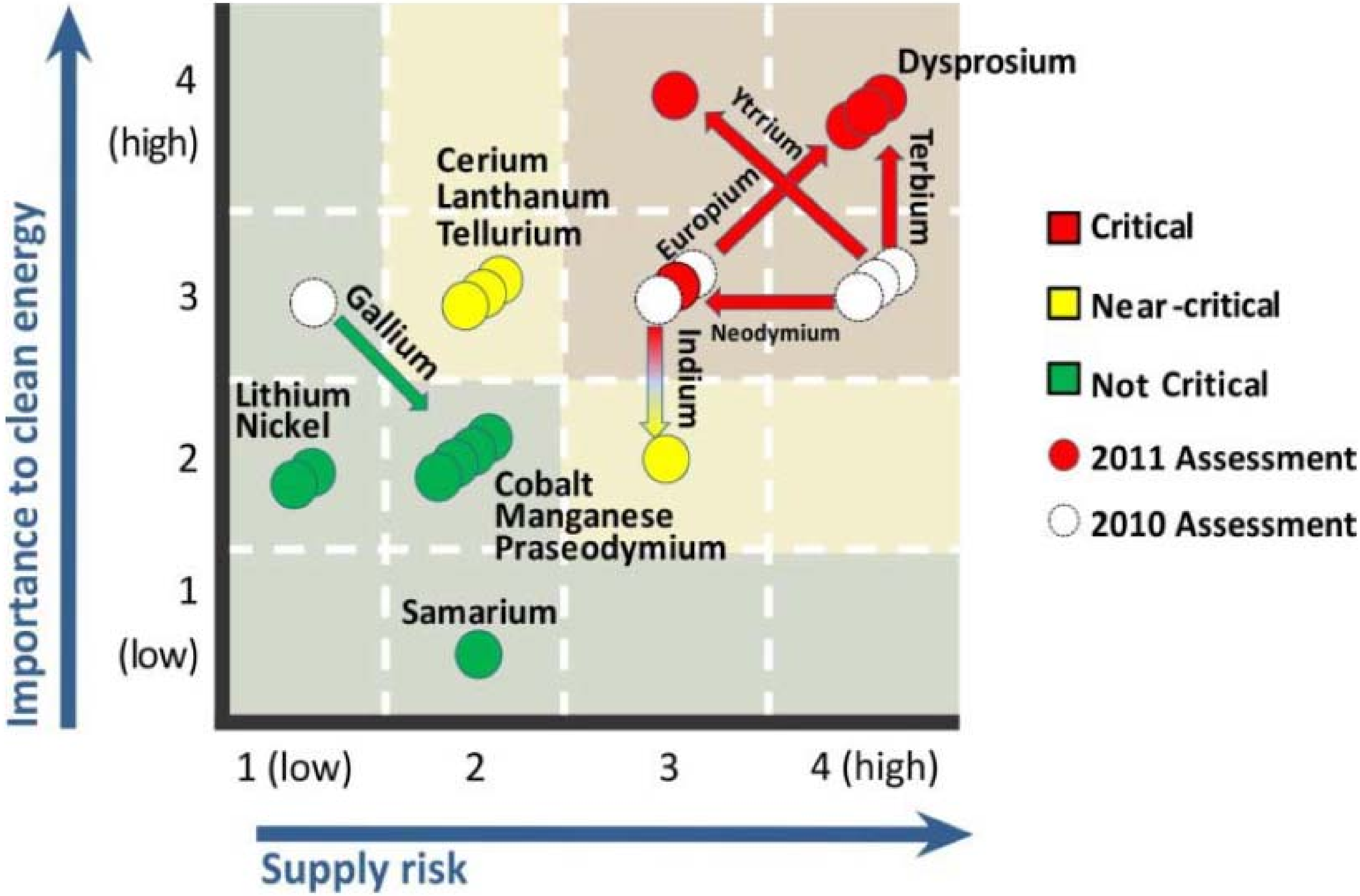
2011 CMS Short-Term Criticality (Present - 2015)



2011 CMS Medium-Term Criticality (2015-2025)



Short-Term Comparison between 2010 CMS and 2011 CMS



Technology Case Studies

1. Fluid Catalytic Cracking (FCC) Catalysts

   Lanthanum and Cerium

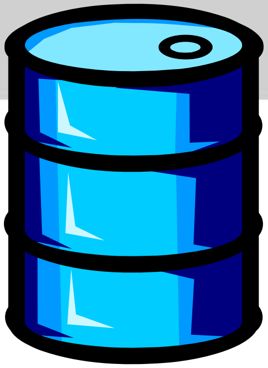
2. Permanent Magnets

   Neodymium and Dysprosium

3. Lighting

   Cerium, Lanthanum, Yttrium, Europium and Terbium

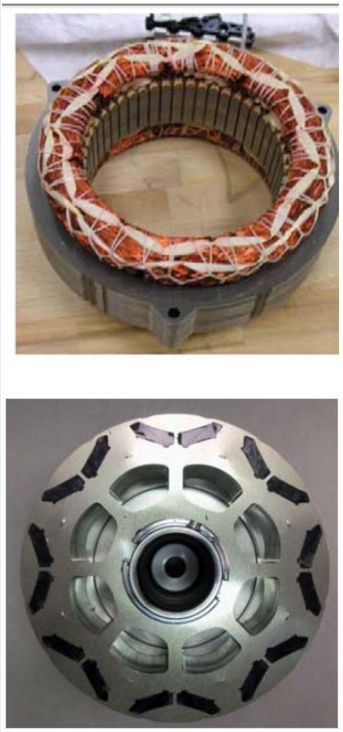
Case Study: Petroleum Refining



- Lanthanum in fluid catalytic cracking (FCC) increases gasoline yield from a barrel of oil
- Reduced rare earth content lowers gasoline yields, resulting in lower revenues
- Lanthanum price increases in 2010-2011 likely added less than 1 penny to the price of gasoline
  - Lanthanum supplies are less tight than some other rare earths
  - FCC manufacturers are developing zero and low rare earth catalysts with improved performance

Rare earths play an important role in petroleum refining, but the sector's vulnerability to rare earth supply disruptions is limited

Case Study: Magnets



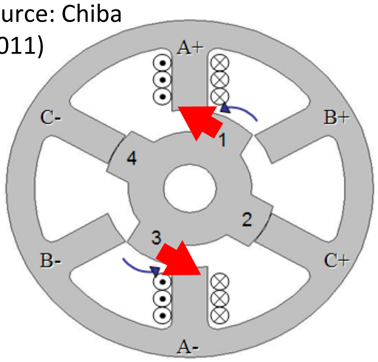
Source: Miller (2011)

Toyota Prius Hybrid Drive Motor

Source: Shiohara (2011)

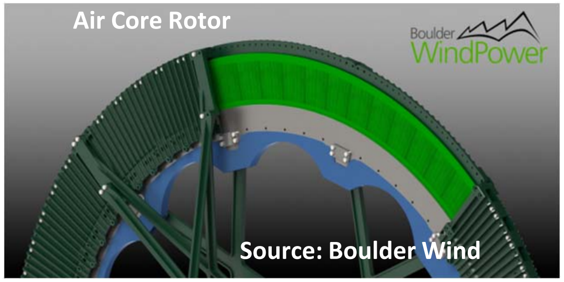
Induction Motors

Source: Chiba (2011)



Switched Reluctance Motors

Alternatives to Rare Earth Motors in Electric Vehicles

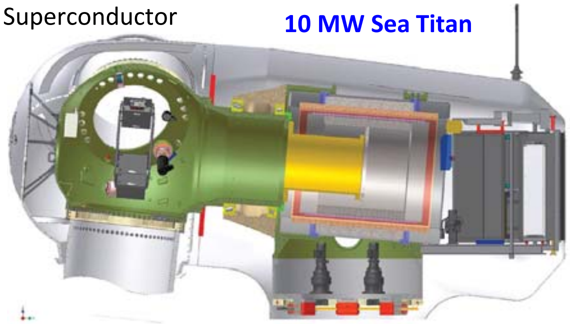


Source: Boulder Wind

Dysprosium-free permanent magnet wind turbines

Source: American Superconductor

10 MW Sea Titan



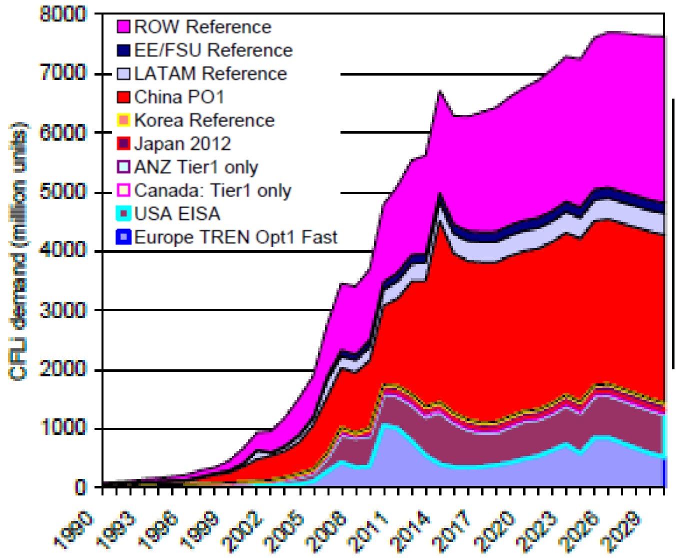
Superconducting wind turbines with no Rare Earth

New Wind Turbine Designs

- *The rare earth situation is affecting technology deployment decisions in the wind and EV sectors.*

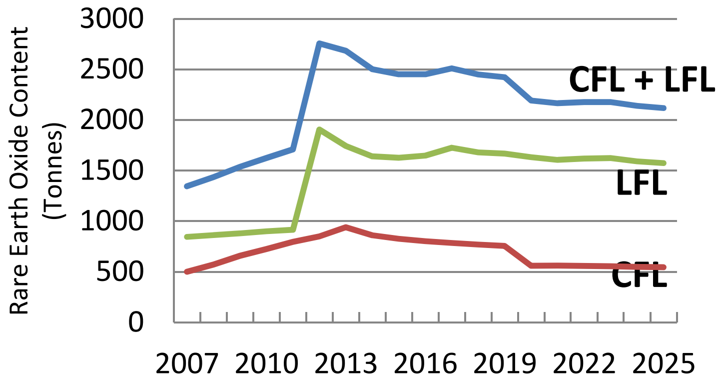
Case Study: Lighting Phosphors

Global CFL Demand ***High Deployment Projection***



Source: IEA

REO Content in Domestic Lighting Phosphors



Many countries are moving to energy efficient lighting, increasing demand for fluorescent lighting with phosphors containing heavy rare earths (europium, terbium and yttrium).

Supply of these elements is tight and additional supply is limited in the short term.

U.S. lighting standards will likely increase demand for rare earth phosphors in the short term.

In the medium to long term, LED market share expected to grow, reducing pressure on rare earth supplies.

U.S. DEPARTMENT OF ENERGY

Critical Materials Strategy

2011

Summary Briefing

DOE Welcomes Comments

MaterialStrategy@hq.doe.gov

Dr. Mark Johnson

Program Manager

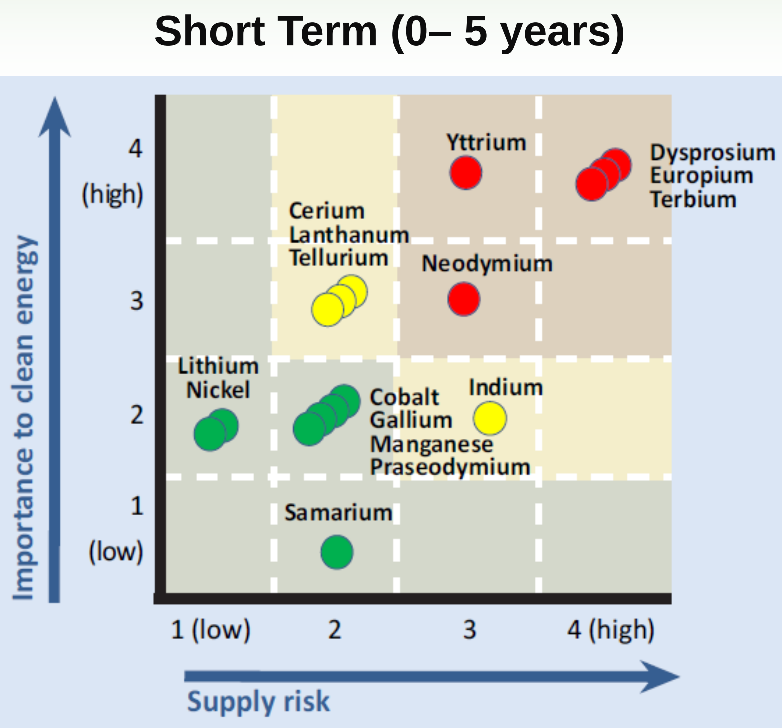
Advanced Research Projects Agency - Energy
Energy Efficiency and Renewable Energy
U.S. Department of Energy

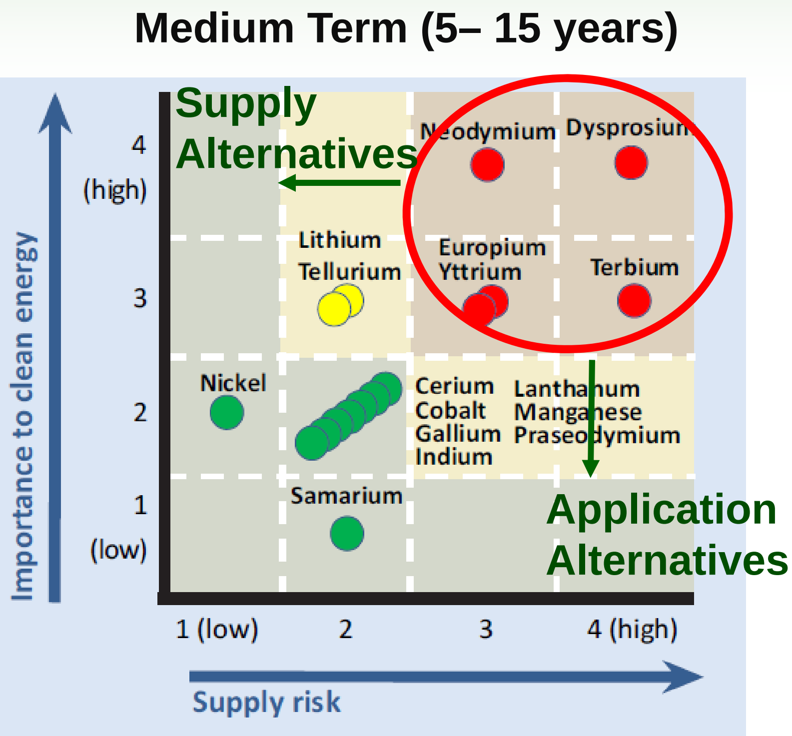
Rare-Earth and Critical Materials Research at DOE

Mark Johnson, Program Director

Arlington, VA
April 2, 2012

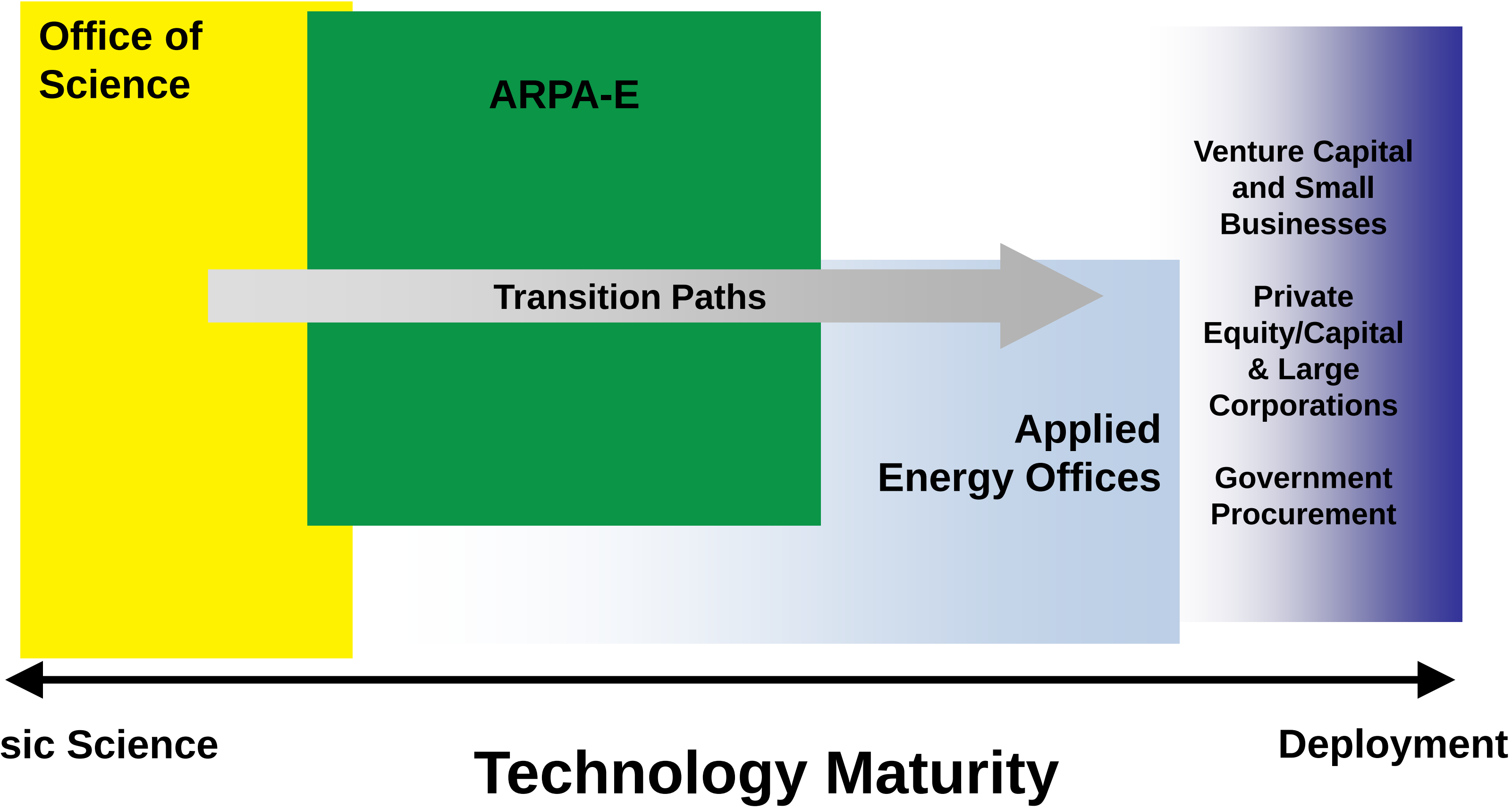
Rare Earth Criticality by Element





US DOE: Critical Materials Strategy (Dec 2010, 2011)

Energy Innovation Pipeline



Office of Science

ARPA-E

Transition Paths

Applied Energy Offices

Venture Capital and Small Businesses

Private Equity/Capital & Large Corporations

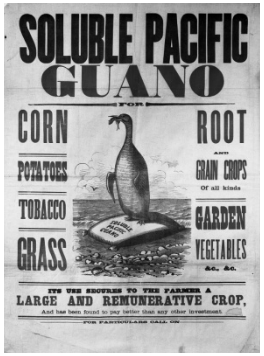
Government Procurement

Basic Science

Technology Maturity

Deployment

Ammonia: Critical Material of 1898



Gunpowder

Fertilizer

Food Global Population, on Track to Exceed 2,000,000,000

Food Production (Wheat) in Concentrated Locations (US)

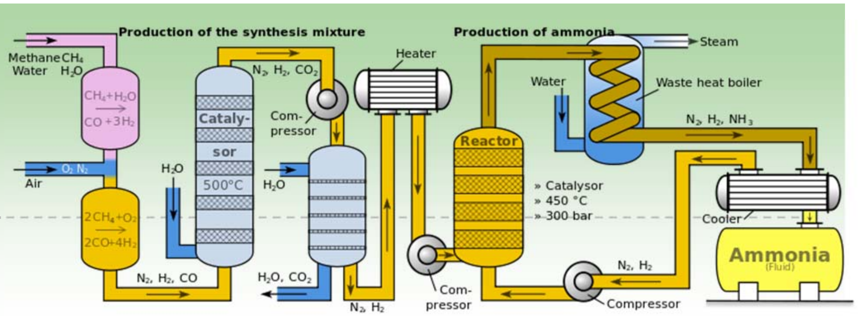
$$N_2 + 3H_2 \rightarrow 2NH_3$$

$$\Delta G^\circ(J) = -87{,}030 + 5.8T\ln T + 31.7T$$

"…the fixation of Nitrogen is vital to the progress of civilized humanity"

William Crookes (1898)

Ammonia R&D



Royal Academy “Wheat Problem”

Understanding Properties Of Ammonia

Academic Fight

Contract

Lab Demo

Pilot Scale

Production

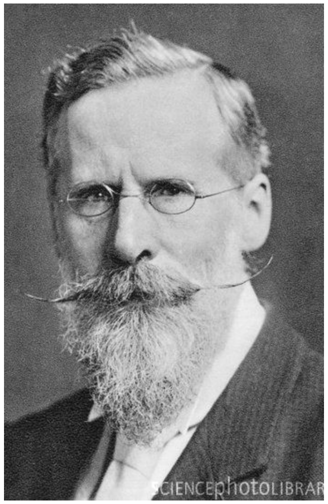
“Grand Challenge”

Basic Research

Break-Through

“Catalyst Genomics”

1898	1900	1902	1904	1906	1908	1910	1912	1914



Crookes

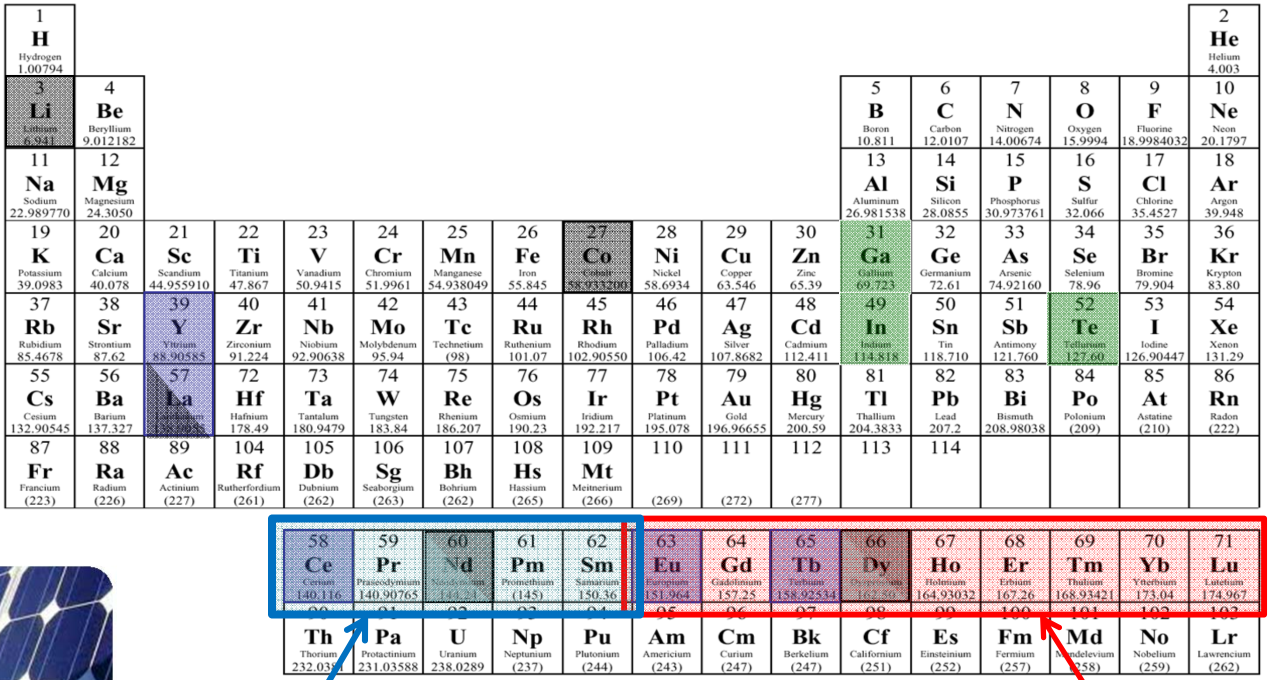
Ostwald & Nernst

Haber

Bosch

Mittasch

Critical Materials in Clean Energy



Light Rare Earths

Heavy Rare Earths

▨ Vehicles

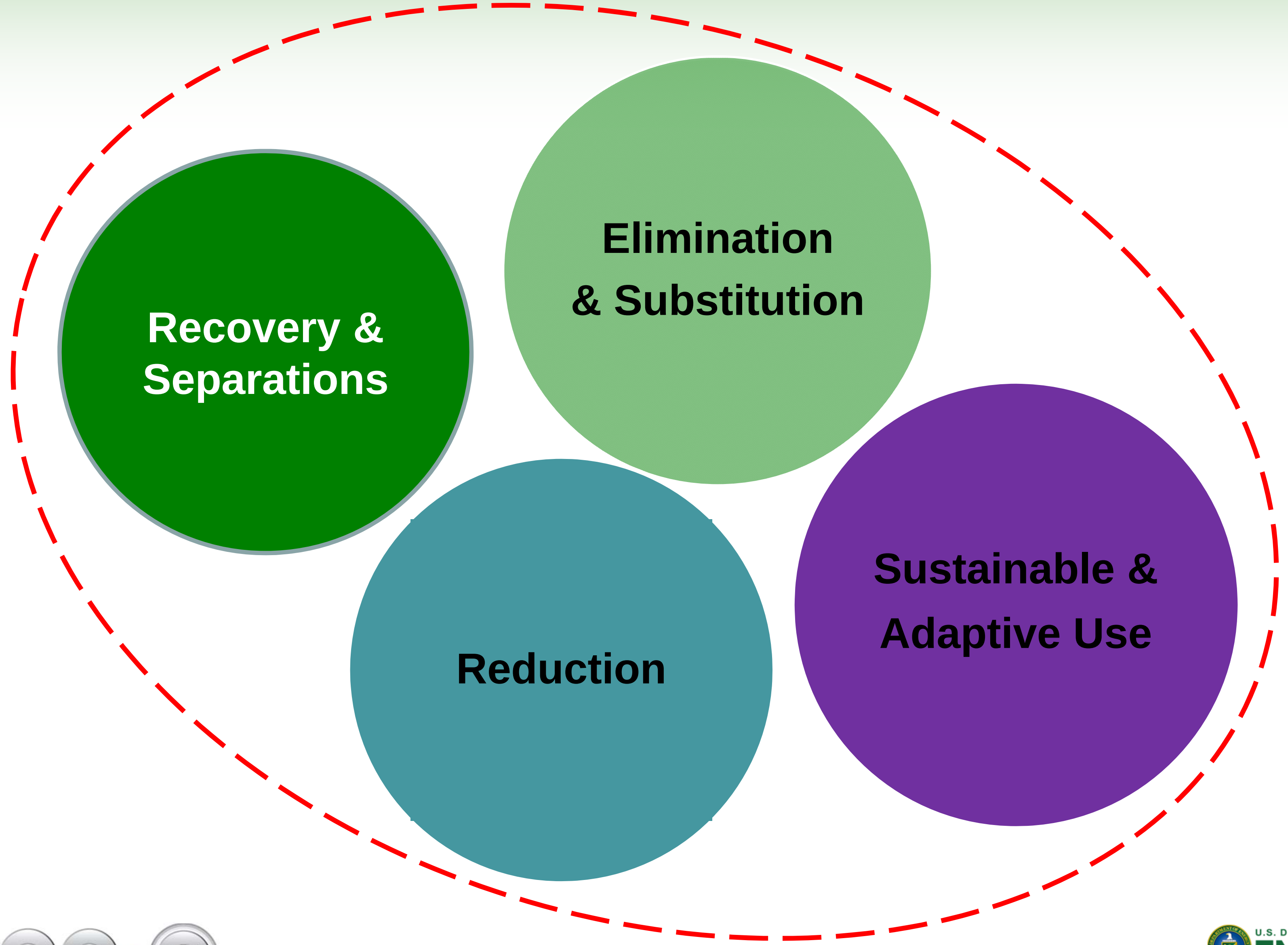
▨ Lighting

▨ Solar PV

▨ Wind

US DOE: Critical Materials Strategies (Dec 2010, 2011)

Critical Materials Technology

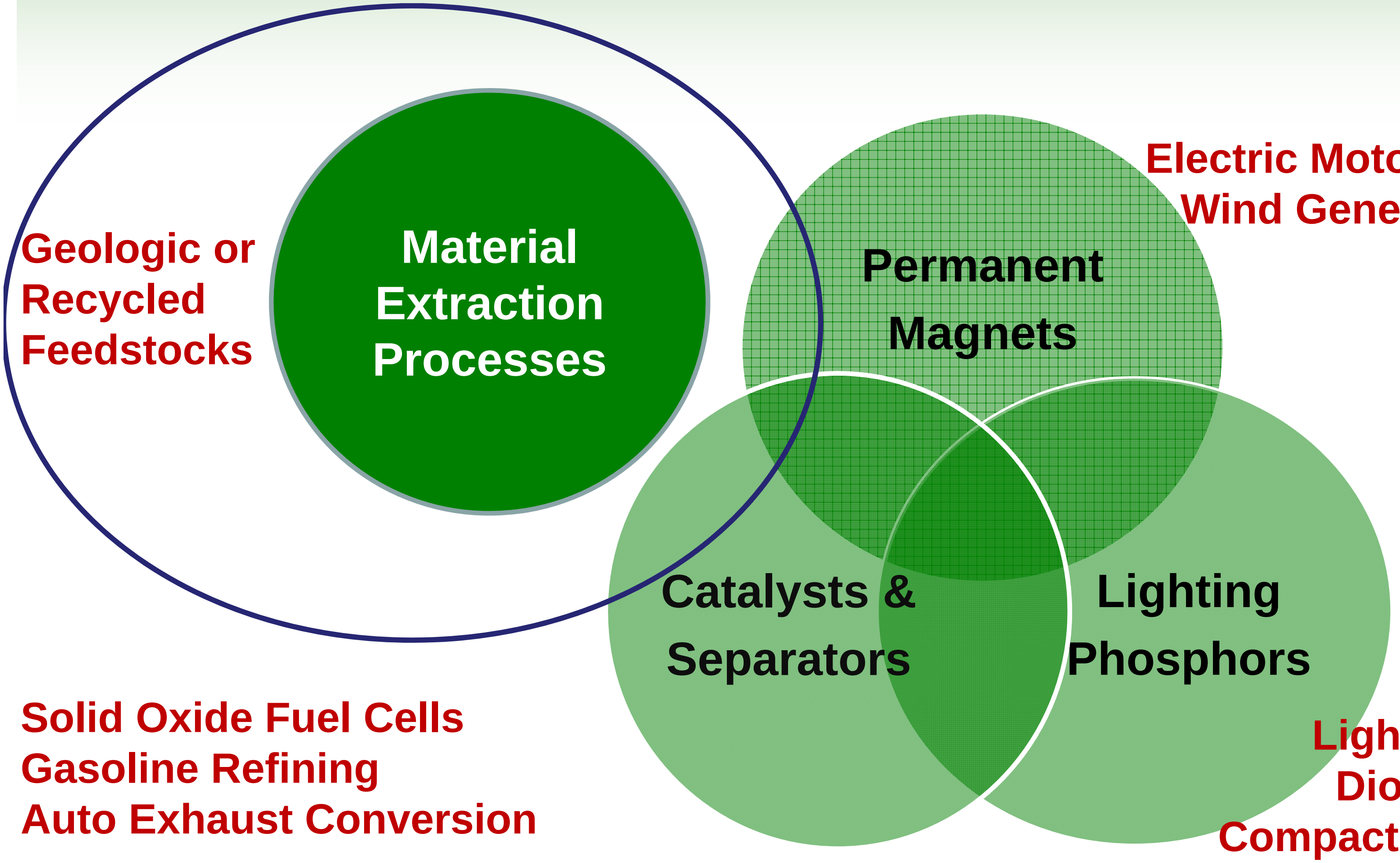

Elimination & Substitution

Recovery & Separations

Sustainable & Adaptive Use

Reduction

Critical Materials – ARPA-E Study Areas



Geologic or
Recycled
Feedstocks

Material
Extraction
Processes

Permanent
Magnets

Electric Motors
Wind Generators

Catalysts &
Separators

Lighting
Phosphors

Solid Oxide Fuel Cells
Gasoline Refining
Auto Exhaust Conversion

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

Supply Technologies ⟷ Application Technologies

REACT PROGRAM GOALS: DISRUPTIVE ALTERNATIVES TO RARE EARTH ELEMENTS IN PERMANENT MAGNETS

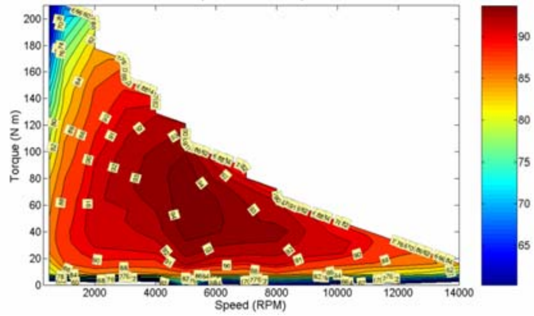
Permanent Magnet Electric Motors for High Efficiency across Torque / Velocity Range

Electric Motors

Wind Generators

Permanent Magnet Content in Direct Drive Generators as Power Capacity Goes to 10MW

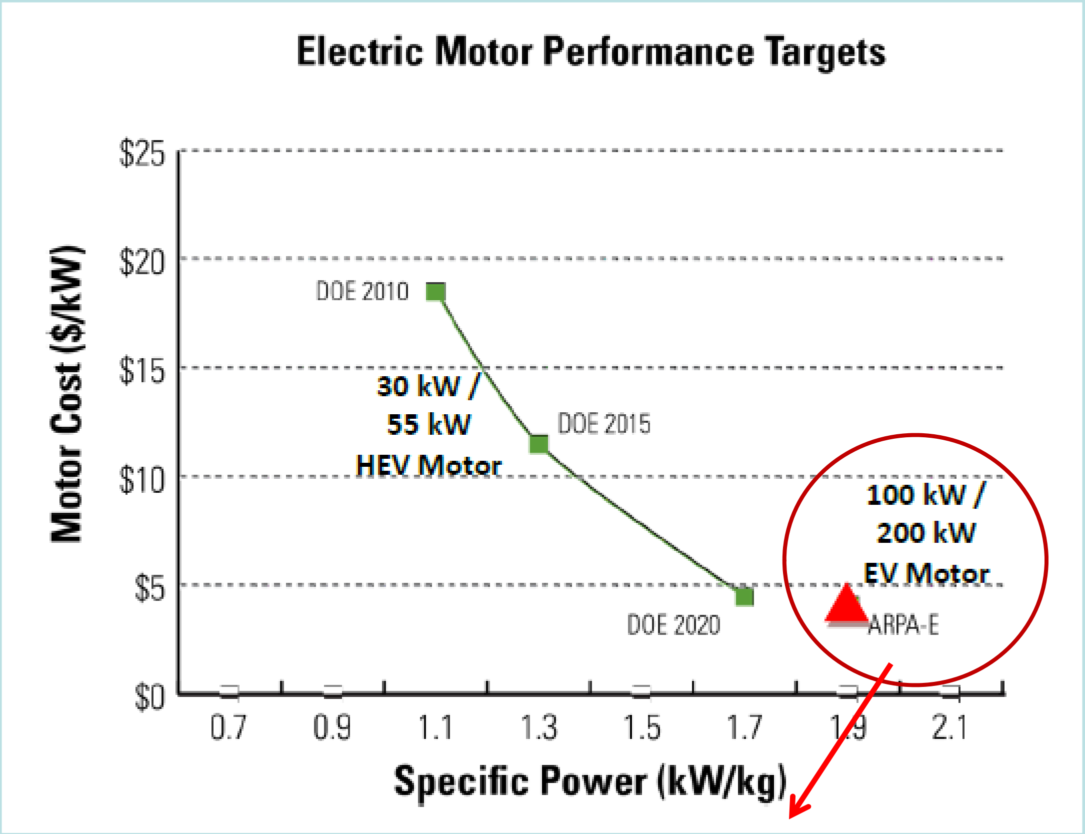
SmCo or
$Nd(Dy)_2Fe_{14}B$
Permanent
Magnets



Function: Magnetic Coupling of Torque and Electricity

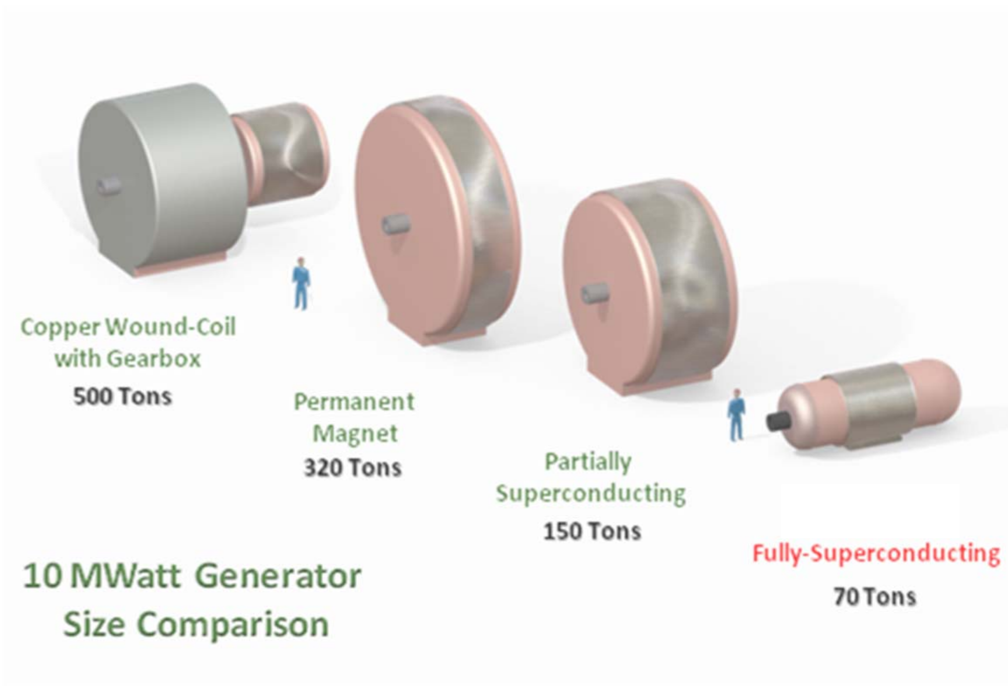
ADVANCED ELECTRIC MACHINES FOR ELECTRIC VEHICLES

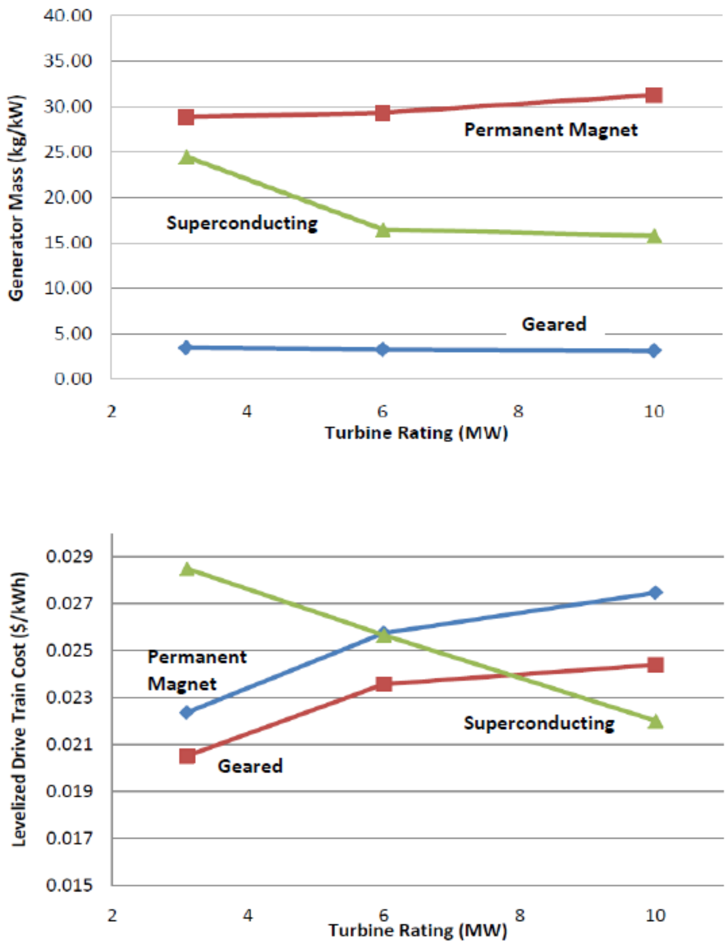
Enabling Larger, More Powerful Electric Vehicles



and Order of Magnitude Reduction in Rare Earth Content: less than 0.33kg/kW

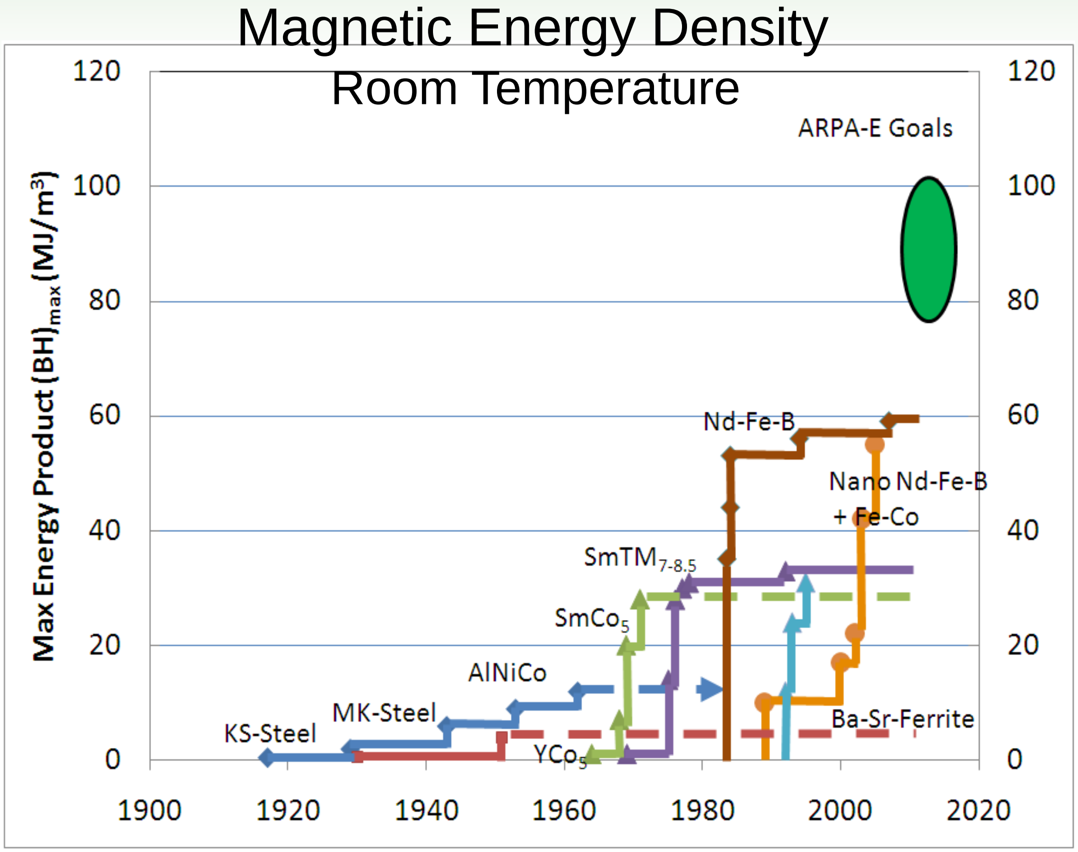
LARGE SCALE WIND GENERATOR (>10MW) SYSTEMS





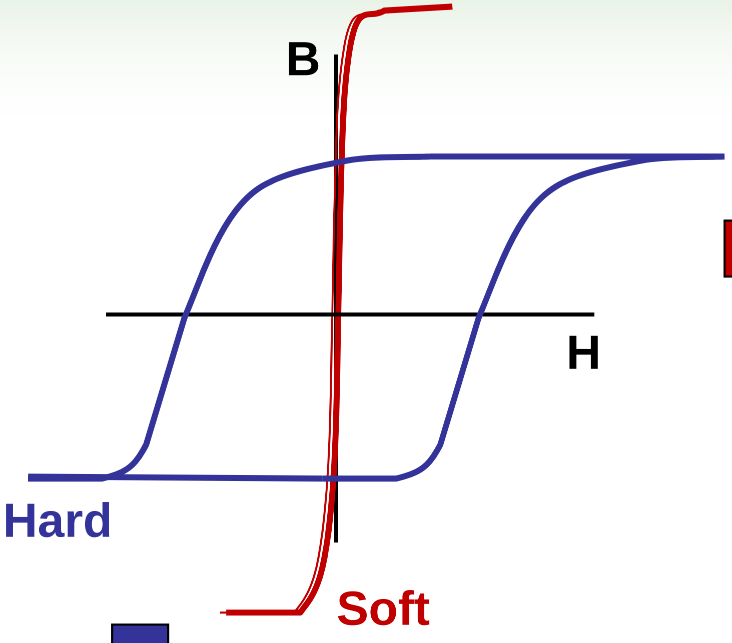
Analysis: National Wind Technology Center

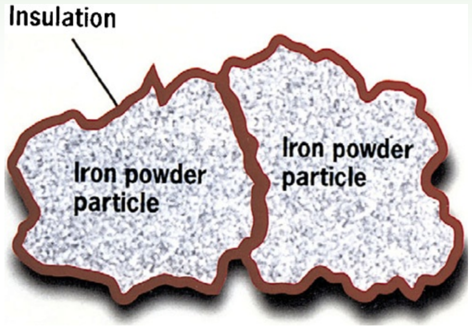
Historical Trajectory for Permanent Magnets



Higher Performing Permanent Magnet Materials Historically Increase Opportunities, not Displace Incumbents from from Market

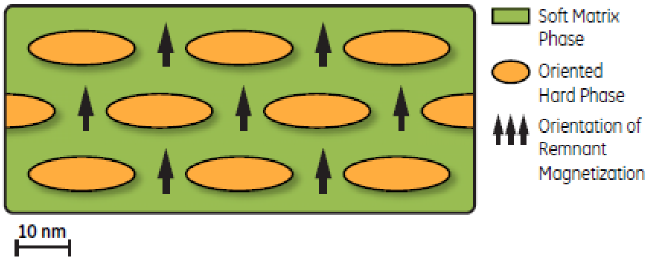
NANOSTRUCTURES ENABLING MAGNETIC MATERIALS





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

Rare Earth Alternatives in Critical Technologies (REACT)

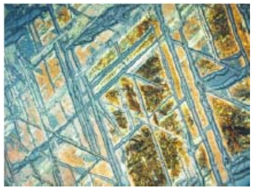
RE-Free Magnetic Materials

Low- RE, high Jc Super-conductors

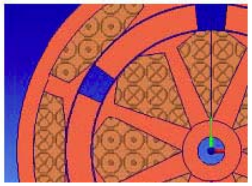
Low RE- Electric Machines

Electric Vehicle Motors (>200 kW)
Wind Generators (>10MW)

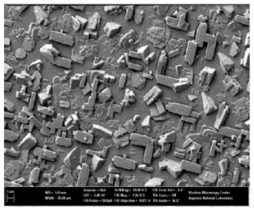
Example Projects



Magnetic FeNi $L1_0$
Phase in meteorites

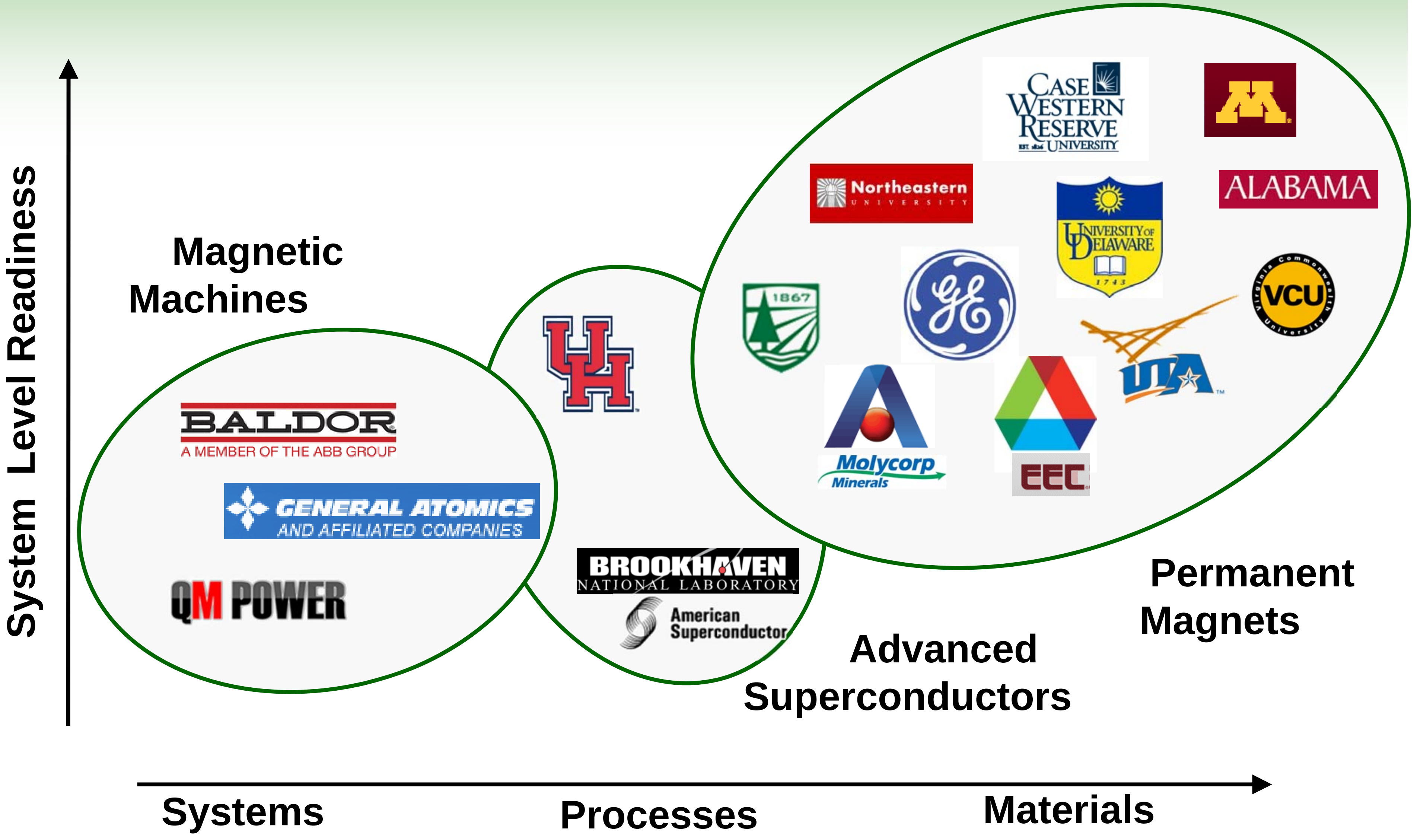


Double-stator switched
reluctance motor

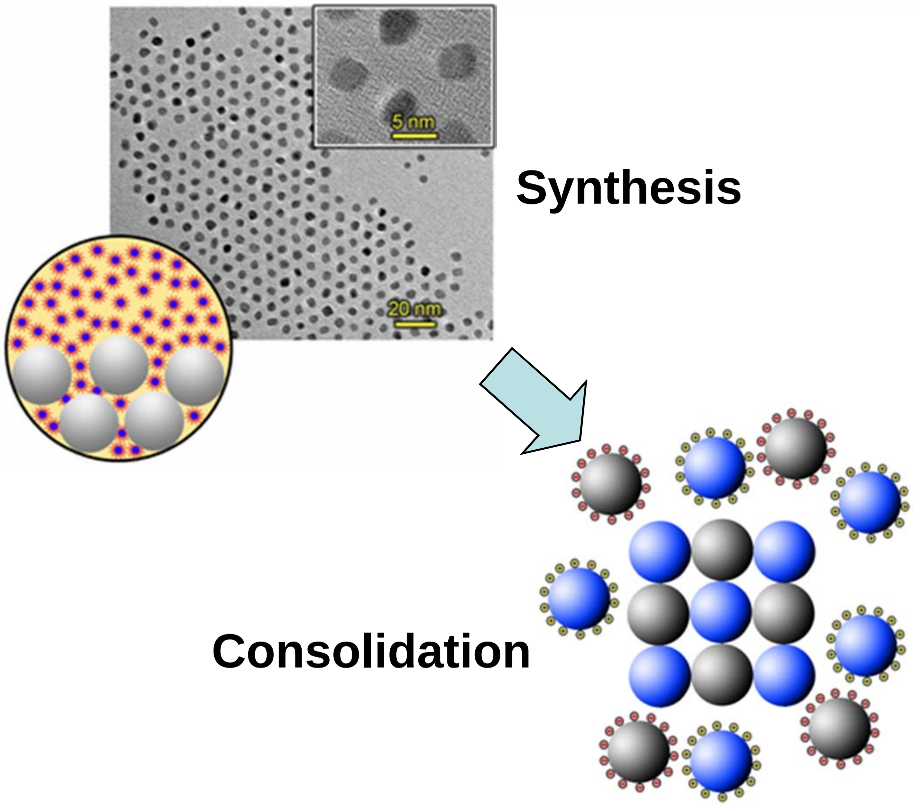


Enhanced 2G HTS wire
with 4X J_c Increase

Rare Earth Alternatives for Critical Technologies



High Energy Permanent Magnets for Hybrid Vehicles and Alternative Energy (FOA1)

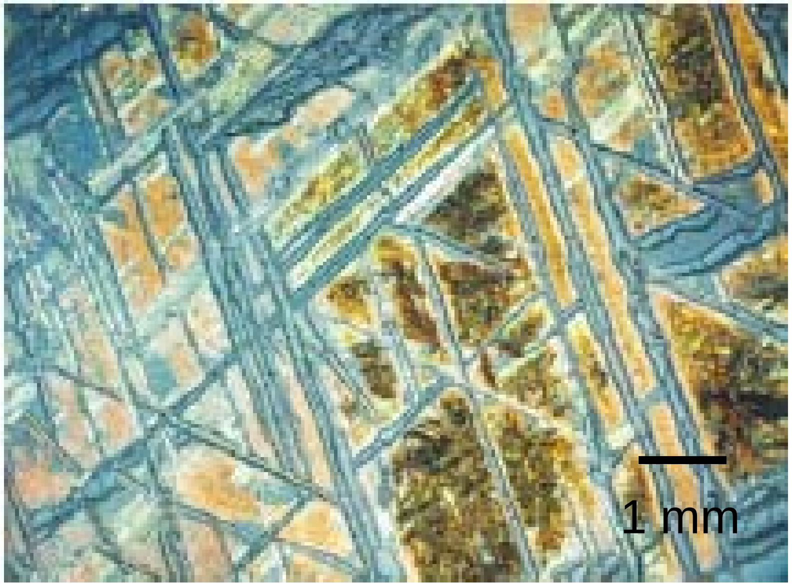


Synthesis

Consolidation

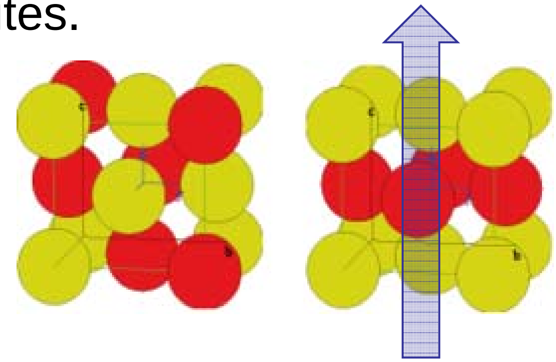
- Target: $(BH)_{max}$> 100 MGOe, no rare earth restriction (RT)
- Permanent magnets based on newly-discovered compounds
- New doped Fe-Co intermetallics
- Anisotropic nanocomposite magnets via a bottom-up fabrication routes
- Modeling for validation

Northeastern University: Multiscale Development of $L1_0$ Materials for Rare-Earth-Free Permanent Magnets



Polished and etched slices of the Carlton IIICD iron meteorite showing Widmanstätten patterns. Kamacite plates (blue) formed on the close-packed planes of the parent taenite phase. (J. I. Goldstein *et al*., *Microsc. Microanal*. **14** (Suppl 2), 520 (2008)).

- $|BH|_{max}$ > 12 MGOe at 180 °C
- The Widmanstätten pattern of meteorites that contains $L1_0$-type FeNi;
- Phase naturally occurs only in meteorites.



Disordered FCC

$L1_0$-type, AuCu I structure with magnetic anisotropy.

Team:

ARNOLD MAGNETIC TECHNOLOGIES Precision Magnetics - Lupfig

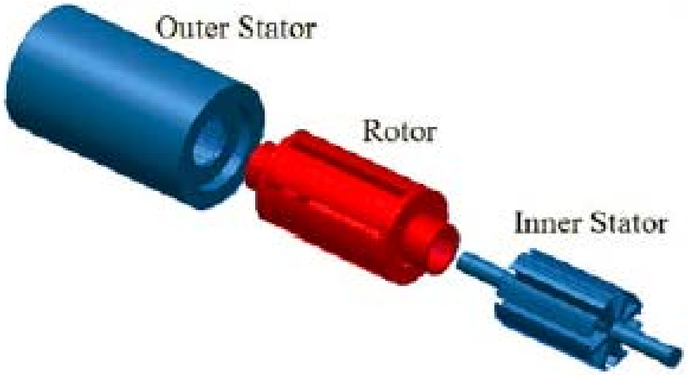
Columbia University

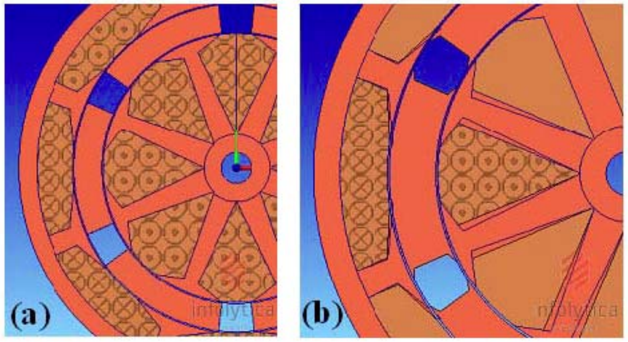
GM

Northeastern University

UMassAmherst

Alternative Motor / Generator Topologies and Processes





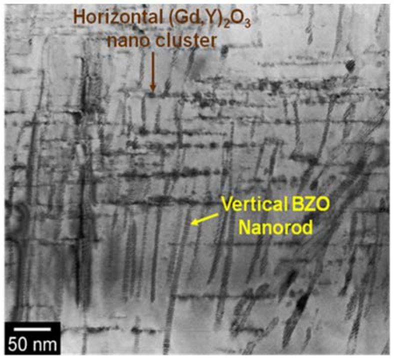
Double Stator Switched Reluctance Machine

GENERAL ATOMICS

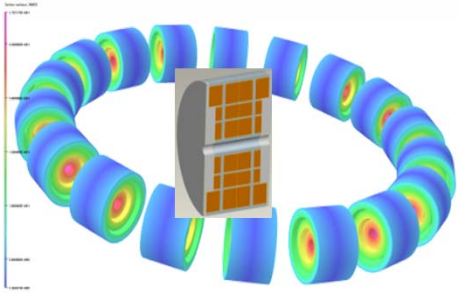
UT DALLAS
The University of Texas at Dallas

Nanomaterial R&D Enabling Application Driven 3rd Generation of High-Temperature Superconductors

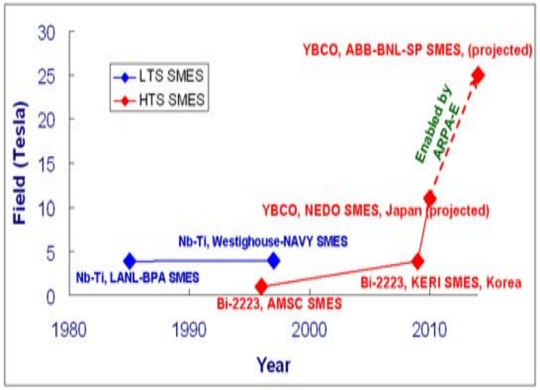
Grid Stability and Storage



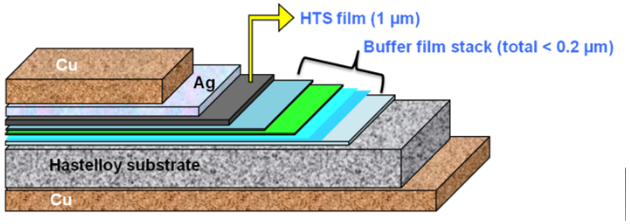
Engineered nanoscale defects



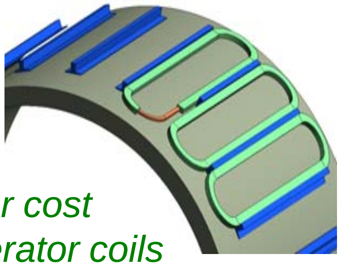
High Field SMES coils



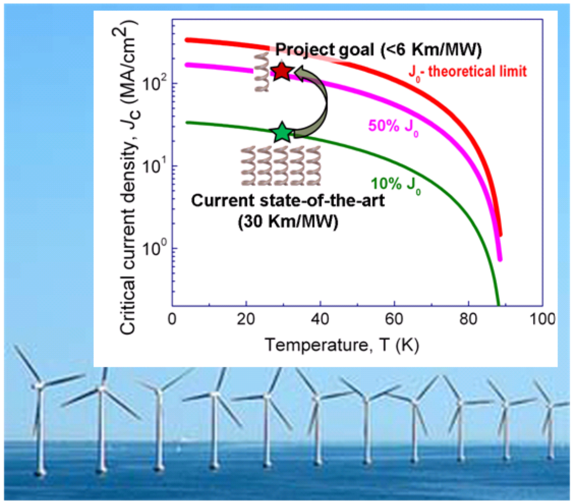
Offshore Wind Generation (>10MW)



Bi-axial Strain Engineered 3G Superconducting Tape

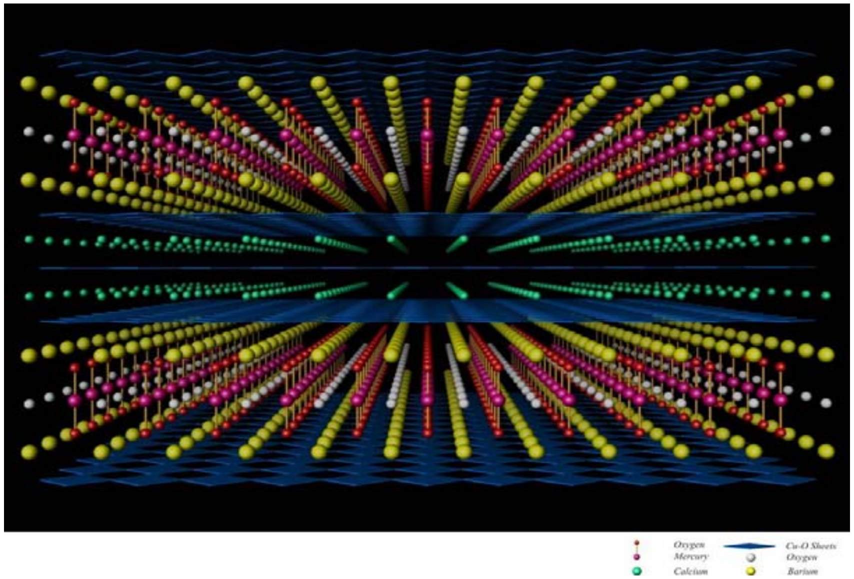


Lower cost Generator coils



Center for Emergent Superconductivity
(J.C. Séamus Davis, Brookhaven National Lab)

The objectives of CES are to explore and develop higher temperature and higher critical current superconductivity with the potential for application to a superconducting power grid.



CES RESEARCH PLAN AND DIRECTIONS

CES research will be directed towards three key areas: finding new strongly correlated superconducting materials, understanding the mechanisms leading to higher temperature superconductivity, and controlling vortex matter so as to raise the loss-less current carrying performance of these superconductors.

U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

Argonne NATIONAL LABORATORY

BES Supports a Core of Rare-Earth Focused Research at the Ames Laboratory

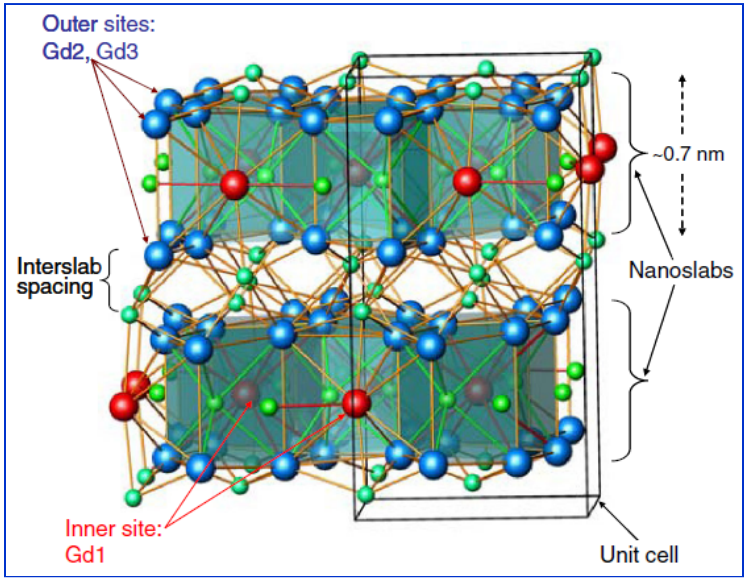
- Extraordinary Responsive Rare Earth Magnetic Materials
- Novel Materials Preparation & Processing Methodologies
- Correlations & Competition Between the Lattice, Electrons, & Magnetism
- Nanoscale & Ultrafast Correlations & Excitations in Magnetic Materials

U.S. DEPARTMENT OF ENERGY | Office of Science

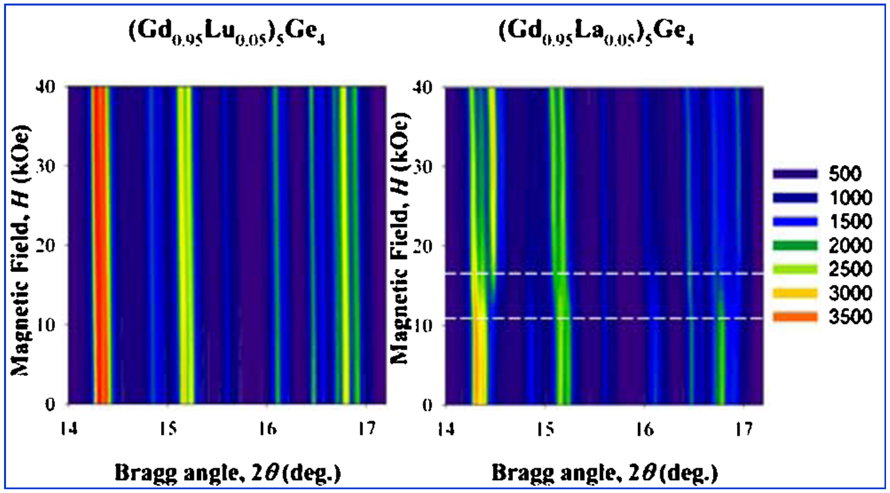
THE Ames Laboratory
Creating Materials & Energy Solutions

Controlling Magnetism of a Complex Rare Earth Metallic System Using Atomic Substitution

In complex metallic compounds, a specific structural location may be critically responsible for a given fundamental material property. For the highly magnetoresponsive intermetallic compound Gd_5Ge_4 a controlled alteration of the magnetism using precise chemical tools has been achieved based on first-principles theory. Magnetically active Gd atoms are substituted by non-magnetic rare earth elements.



Crystal structure of the nonferromagnetic Gd_5Ge_4 phase. The germanium atoms are shown as small green (light gray – inner sites) spheres.

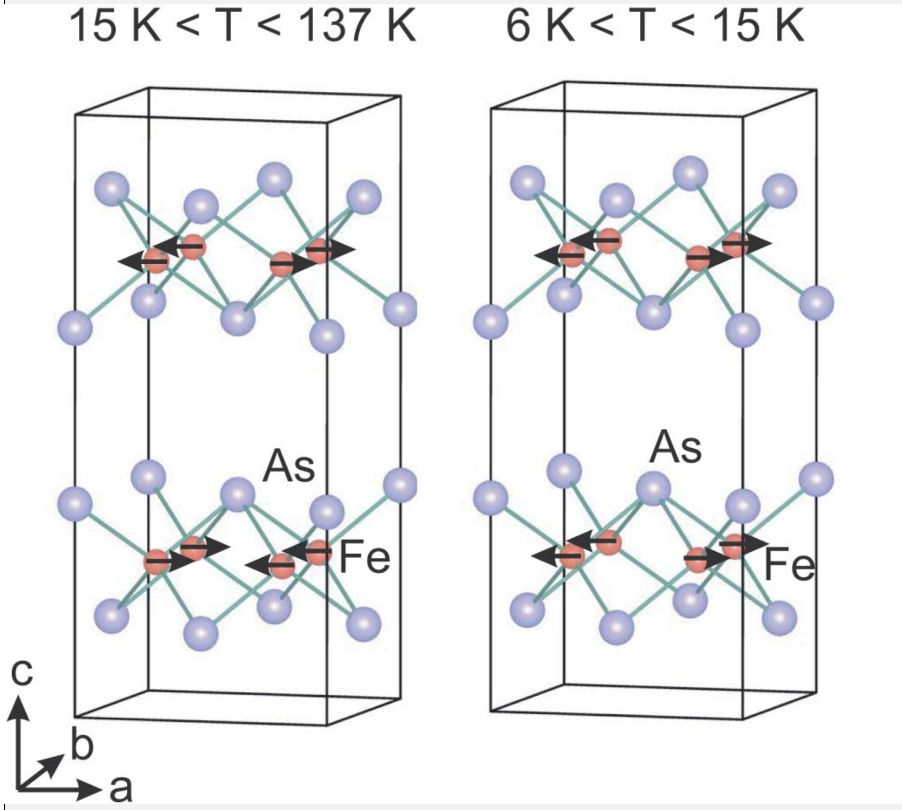


The x-ray powder diffraction patterns of $(Gd_{0.95}Lu_{0.05})_5Ge_4$ (left) and $(Gd_{0.95}La_{0.05})_5Ge_4$ (right) are used to verify the site substitutions

Only Gd atoms in the inner sites are determined to be responsible for the observed extraordinary responsive magnetic properties. Replacing even a few of the magnetic Gd atoms within these sites with nonmagnetic atoms leads to a catastrophic loss of ferromagnetism

Physical Review Letters 105, 066401 (2010)

Interplay of Rare-Earth and Iron Magnetism in a High-Temperature Superconductor



For the first-time, the interplay between rare-earth and iron magnetism in a rare-earth iron arsenide superconductor (NdFeAsO) has been observed, furthering our understanding of the mechanisms and potential applications of high temperature superconductors

Large single crystals coupled with x-ray and neutron diffraction enabled the discovery that iron magnetic moments in this compound are anti-parallel with respect to the adjacent iron moments along two crystallographic directions, but parallel in the third dimension

Below a transition temperature the neodymium magnetic moments also align in an anti-parallel fashion, causing the iron moments that were anti-parallel in one of the directions to switch to a parallel direction

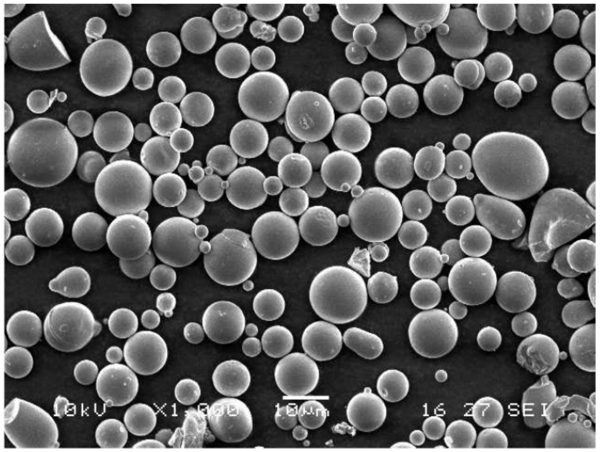
This change in the iron magnetic order is unique compared to other rare-earth materials studied to date

Physical Reviews B, Aug 2010 (Editor's Suggestion)
Ames and NIST Collaboration

Addressing Rare Earth Issues

Ames National Laboratory (BREM – Beyond Rare Earth Magnets)

- Research to optimize the use of RE materials in PMs
  - Magnet compositions that could use less RE materials
  - Focus on magnet processing, composition, and high-temperature magnetic performance
- FY12 research to develop high performance non-RE magnet materials for use in PM motors for vehicle applications
  - Long-term, high-risk/high-reward research
  - Builds on Office of Science fundamental research with a prospectus of monolithic and composite material systems



Magnet powders produced from gas atomization

Oak Ridge National Laboratory

- R&D focus on alternative motor designs to reduce and/or eliminate the use of rare earth permanent magnets
  - Emphasis on meeting cost, weight, volume, and performance targets

Industry Lead R&D Activity

- **UQM** - Pursue design that enables the use of low coercivity magnets:
  - Unique magnet and supporting rotor geometry
  - Stator and rotor design features that reduce demagnetization fields
- **GE** – Comprehensive approach to exploring motor topologies including no magnets and non-rare earth magnets Advanced materials including magnetic as well as electrical insulating materials will be developed to enable the motors to meet the required set of specifications

U.S. DEPARTMENT OF ENERGY | Office of Science

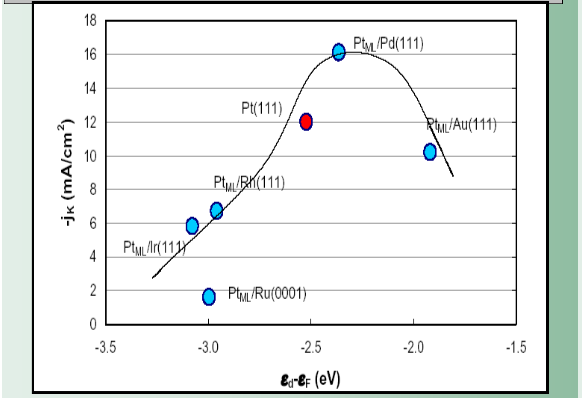
Platinum Monolayer Electro-Catalysts:
Stationary and Automotive Fuel Cells

Basic Science

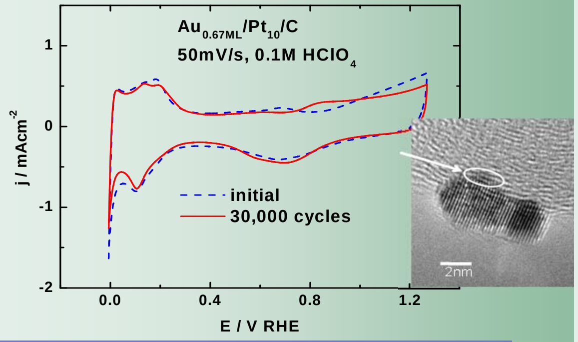
BES

Two research advances

Pt Monolayer catalysis – high activity with ultralow Pt mass



Pt stabilized against corrosion in voltage cycling by Au clusters



Science **315**, 220 (2007)

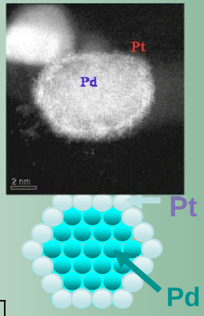
Applied R&D

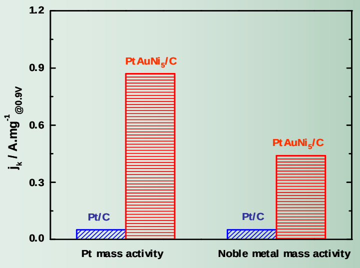
BES → EERE

Core-Shell Nanocatalysts

Active Pt ML shell – Metal/alloy core
Core tunes activity & durability of shell

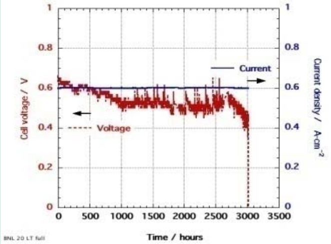
Model and HAADF image of a Pt Monolayer on Pd nanoparticle





Pt-mass weighted activity enhanced 20x

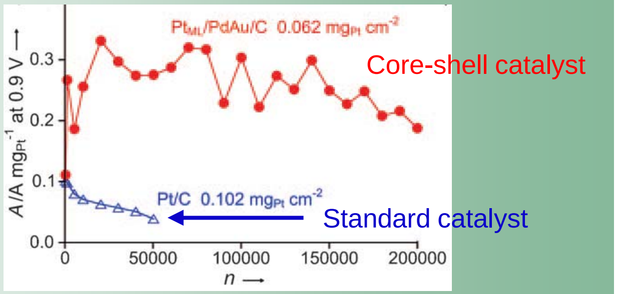
3000 hr Fuel Cell Durability Performance



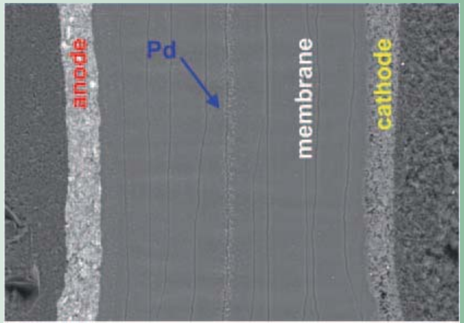
Manufacturing/ Commercialization

BNL-Toyota CRADA

Scale-up synthesis: **Pt-ML/Pd$_9$Au$_1$/C**
Excellent fuel Cell durability 200,000 cycles



Membrane Electrode Assembly >200K cycles
Very small Pt diffusion & small Pd diffusion



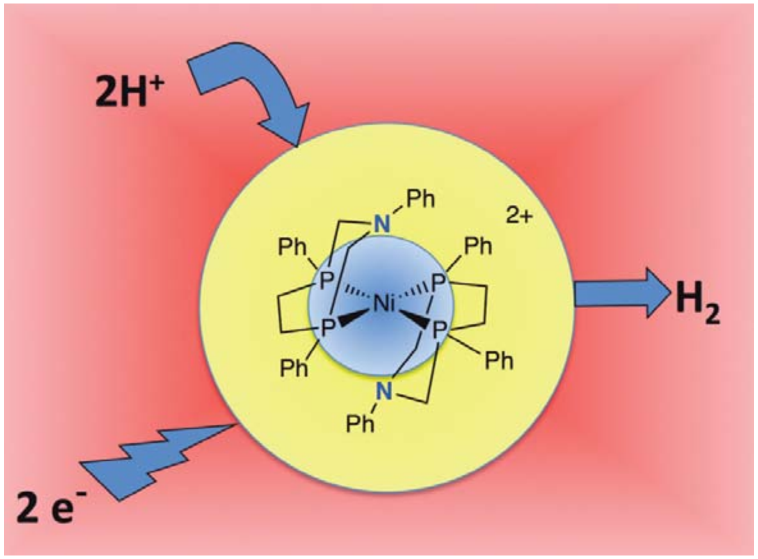
Angewandte Chemie **49**, 8602 (2010)

Fuel Cell Catalyst readied for automotive application

Hydrogen-Producing Catalyst Mimics and Beats Nature

Electrical energy from sustainable sources (solar, wind) can be effectively stored in chemical bonds in a fuel such as hydrogen.

Catalysts are required to promote this conversion. Platinum-based catalysts are effective but the metal is too scarce and too expensive for large-scale use. Natural enzymes use Earth-abundant metals but are difficult to produce and often unstable under industrial conditions.



A natural enzyme has been used to guide the design of a new, nickel-based catalyst that produces H_2 ten times faster than the original enzyme.

Synthetic catalysts that can be produced in bulk and are able to withstand process conditions are key to low-cost inter-conversion between electrical and chemical energy.

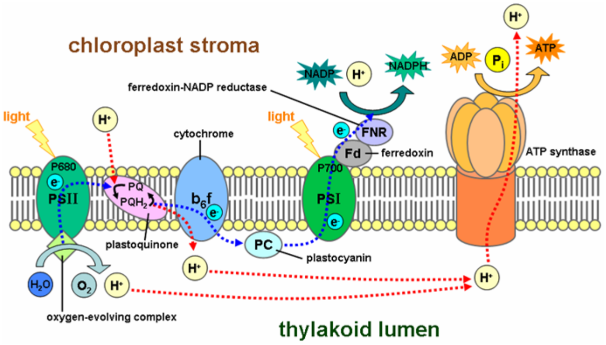
PNNL Center for Molecular Electrocatalysis

U.S. DEPARTMENT OF ENERGY | Office of Science
UNIVERSITY OF WASHINGTON
UNIVERSITY OF WYOMING
PENNSTATE 1855
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965
Center for MOLECULAR ELECTROCATALYSIS

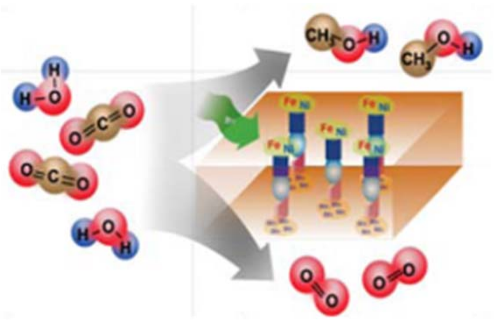
Fuels from Sunlight Energy Innovation Hub:

Joint Center for Artificial Photosynthesis (JCAP)

- The design of highly efficient, non-biological, molecular-level “machines” that generate fuels directly from sunlight, water, and carbon dioxide is the challenge.
- Basic research has provided an understanding of the complex photochemistry of the natural photosynthetic system and the use of inorganic photo-catalytic methods to split water or reduce carbon dioxide – key steps in photosynthesis.
- **JCAP Mission: To demonstrate a scalable, manufacturable solar-fuels generator using Earth-abundant elements, that, with no wires, robustly produces fuel from the sun 10 times more efficiently than (current) crops.**
- JCAP R&D focuses on:
    - Accelerating the rate of catalyst discovery for solar fuel reactions
    - Discovering earth-abundant, robust, inorganic light absorbers with optimal band gap
    - Providing system integration and scale-up
- **Begun in FY 2010, JCAP serves as an integrative focal point for the solar fuels R&D community – formal collaborations have been established with several Energy Frontier Research Centers.**



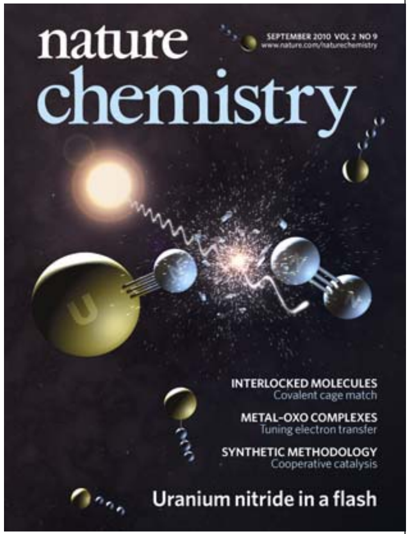
Natural photosynthesis



Artificial photosynthesis

BES Heavy Element Chemistry Program

- Chemical bonding and reactivity of actinides
  - Research to understand the chemical bonding due to 5f electrons, particularly organoactinide, coordination, and supramolecular compounds.
- Synthesis, structure, and properties of actinide materials and technetium
  - Research in chemistry of radionuclides that may occur in or are designed to function in environments such as nuclear reactors and waste repositories
- Separation science for actinides – molecular level principles and new materials
  - Coordination chemistry, ligand design, and synthesis
  - Nanopores and membranes for separations
  - Science of interfaces and solvation



nature chemistry

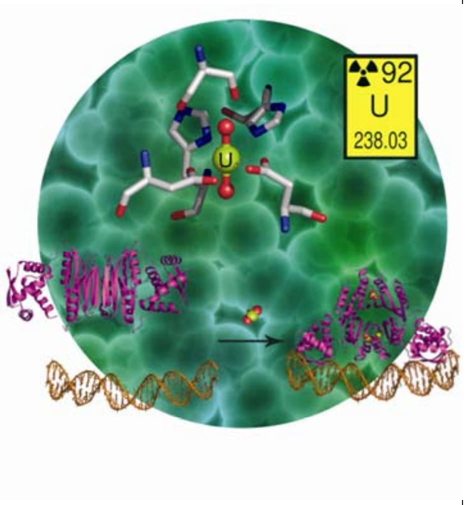
SEPTEMBER 2010 VOL 2 NO 9
www.nature.com/naturechemistry

INTERLOCKED MOLECULES
Covalent cage match

METAL-OXO COMPLEXES
Tuning electron transfer

SYNTHETIC METHODOLOGY
Cooperative catalysis

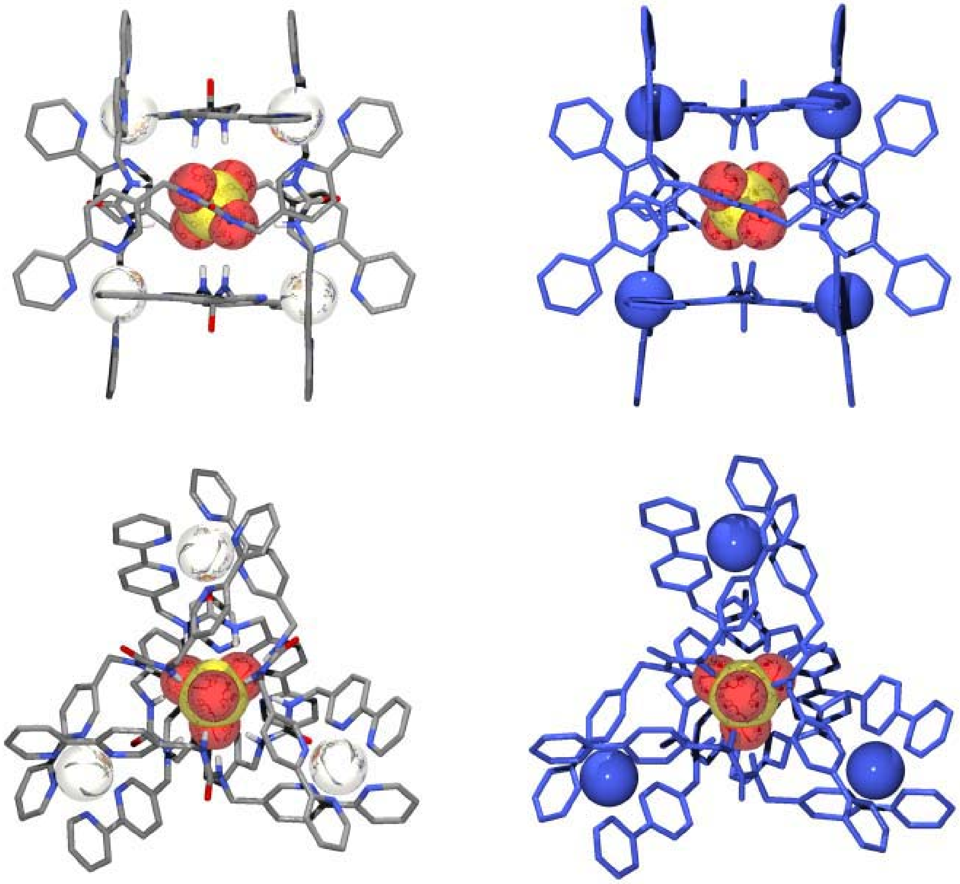
Uranium nitride in a flash



Design and synthesis of complexes for separations

An early example of “materials by design” to create novel molecular complexes for separations.

Computational design of M_4L_6 ligands to encapsulate sulfate anion.



Predicted

X-ray structure

Custelcean, R.; Bosano, J.; Bonnesen, P. V.; Kertesz, V.; Hay, B. P. “Computer-aided design of a sulfate encapsulating receptor,” *Angew. Chem.* ***2009 48, 4025-4029.***

Summary

- Existing Critical Materials Research at DOE Spans Multiple Dimensions

- Spanning Departments - Basic Science, to ARPA-E, to EERE

- Spanning Approaches – Permanent Magnets, Superconductors, Catalysts, Separations

Dr. Leo Christodoulou

Program Manager

Advanced Manufacturing Office
Energy Efficiency and Renewable Energy
U.S. Department of Energy

1. What are the fundamental technical issues that require long term, sustained investment to resolve?

2. What is the right mix of basic vs. applied research?

3. What mix of skill sets is necessary to achieve breakthroughs?
   - Are these skill sets available?
   - Are there opportunities to acquire those skill sets? What are the educational/training opportunities for these skill sets?

4. What are the new opportunities given current technologies (prospective look)?
   - What is the role of large scale modeling and simulation?
   - How do we exploit developments in microelectronics/wireless technology/solid state lasers/ etc.?
   - What opportunities does biotechnology (genomic engineering etc.) afford us?

5. What are the elements of sustainable and robust process for predicting and addressing present and emergent critical materials? Is there an approach that is broadly applicable across different application domains?

6. How do we balance the need for near, mid and long term solutions?

7. What are the technical and/or industry relevant measures of success?

8. Is there a benefit to “shared infrastructure” facilities?

Breakout Sessions will begin at 10:45am

Critical Materials Workshop

1. What are the fundamental technical issues that require long term, sustained investment to resolve?
2. What is the right mix of basic vs. applied research?
3. What mix of skill sets is necessary to achieve breakthroughs?
4. What are the new opportunities given current technologies (prospective look)?
5. What are the elements of sustainable and robust process for predicting and addressing present and emergent critical materials? Is there an approach that is broadly applicable across different application domains?
6. How do we balance the need for near, mid and long term solutions?
7. What are the technical and/or industry relevant measures of success?
8. Is there a benefit to “shared infrastructure” facilities?

Thank You!

CriticalMaterialsHub@ee.doe.gov