Economic Perspectives on Rare Earth Elements

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EPA Workshop on Rare Earth Elements, Denver, Colorado
May 10, 2012

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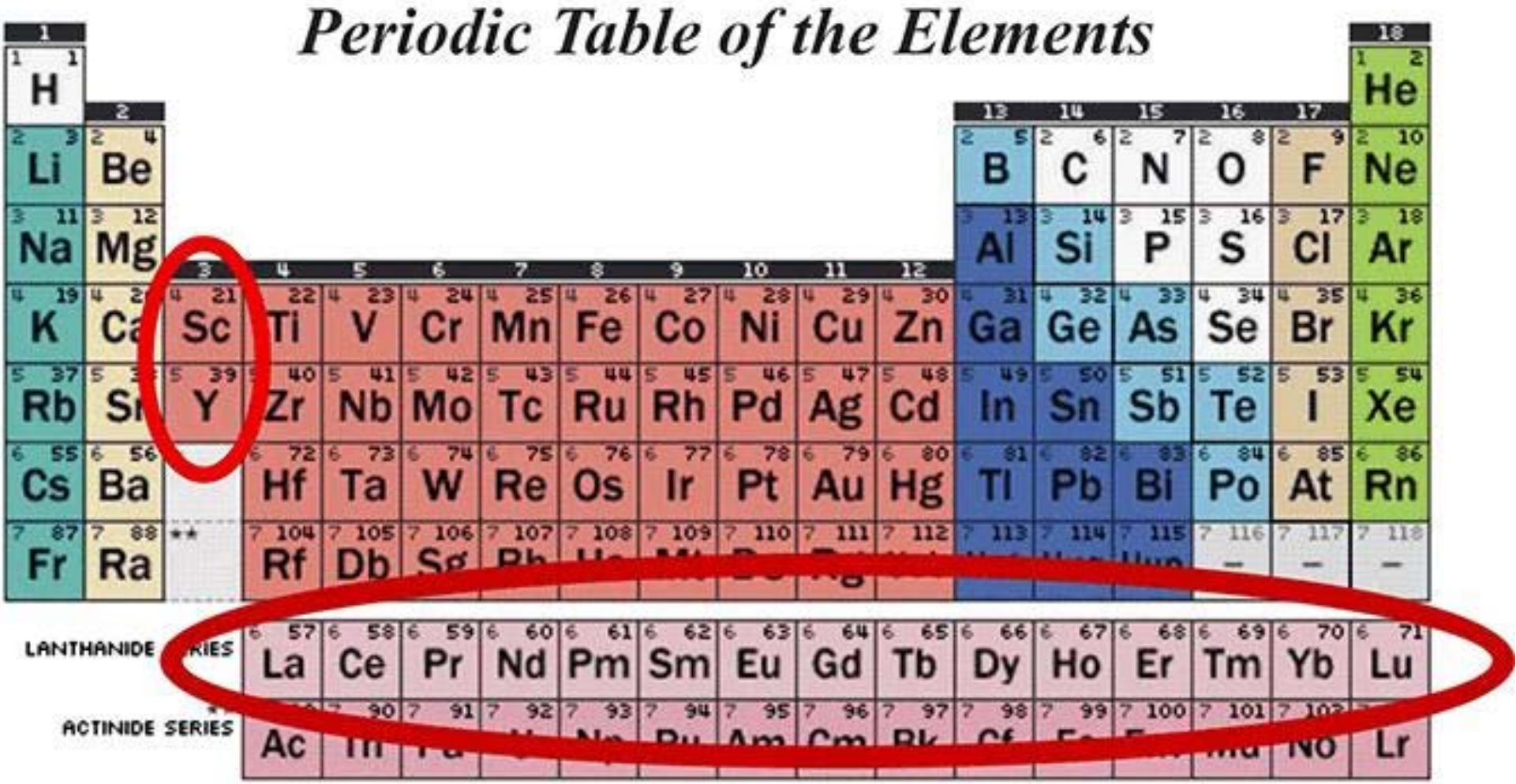
Rare earth elements



Source: www.australianrareearths.com

Outline

- Demand
- Supply
- Markets and prices
- What to do?

1 kg Neodymium, 10-15 kg Lanthanum per Prius—'Vitamins'

Sources: www.molycorp.com (figure), Reuters (usage per vehicle)

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Rare-earth applications by element: 'vitamins' of modern engineered materials

Element	Principal Applications
Lanthanum	Ni-metal-hydride batteries, optics, petroleum cracking catalysts
Cerium	Catalysts, UV light absorption in glasses, polishing media
Praseodymium	Additive to Nd-Fe-B magnets
Neodymium	Nd-Fe-B permanent magnets (motors, hard drives, cell phones, wind turbines, other)
Samarium	Sm-Co permanent magnets
Europium	Phosphors (the color red in TVs and fluorescent lamps)
Gadolinium	Host for phosphors, MRI contrast agents, X-ray screens
Terbium	Phosphors (green color) in fluorescent lamps, monitors and TV screens, LEDs, other
Dysprosium	Additive to Nd-Fe-B permanent magnets to improve high-temperature performance, increase coercivity
Yttrium	Host for phosphors, others

Source: Gschneidner 2011

Rare-earth applications 2008 (%)

	By Weight	By Value
Magnets	21	36
Catalysts	19	5
Metal Alloys	18	14
Polishing	12	5
Glass	10	2
Phosphors	7	31
Ceramics	6	4
Other	7	3

Source: John Kaiser, quoting IMCOA (www.kaiserbottomfish.com)

Use of rare earths by application and country, 2011 (tonnes REO equivalent +/- 15%)

	China	Japan/NE Asia	USA	Other	Total
Magnets	16,500	3,500	500	500	21,000
Metal alloys	15,000	4,000	1,000	1,000	21,000
Catalysts	11,000	2,000	5,000	2,000	20,000
Polishing	10,500	2,000	750	750	14,000
Glass	5,500	1,000	750	750	8,000
Phosphors	5,000	2,000	500	500	8,000
Ceramics	3,000	2,000	1,500	500	7,000
Other	3,500	1,500	500	500	6,000
Total	70,000	18,000	10,500	6,500	105,000

Source: Kingsnorth 2012

Potential demand growth (± 20%)

	2011 (tonnes REO)	2016 (tonnes REO)	% Growth
Magnets	21,000	36,000	71
Metal alloys	21,000	30,000	43
Catalysts	20,000	25,000	25
Polishing	14,000	18,000	29
Glass	8,000	10,000	25
Phosphors	8,000	12,000	50
Ceramics	7,000	10,000	43
Other	6,000	19,000	217
Total	105,000	160,000	52

Source: Kingsnorth 2012

270 Years of Progress in Magnet Technology

Each magnet produces half a Joule of magnetic energy, yet the size has decreased by a thousand fold.

- Lodestone
- Ferrite
- Nd-Fe-B

Source: Alex King (Ames Laboratory)

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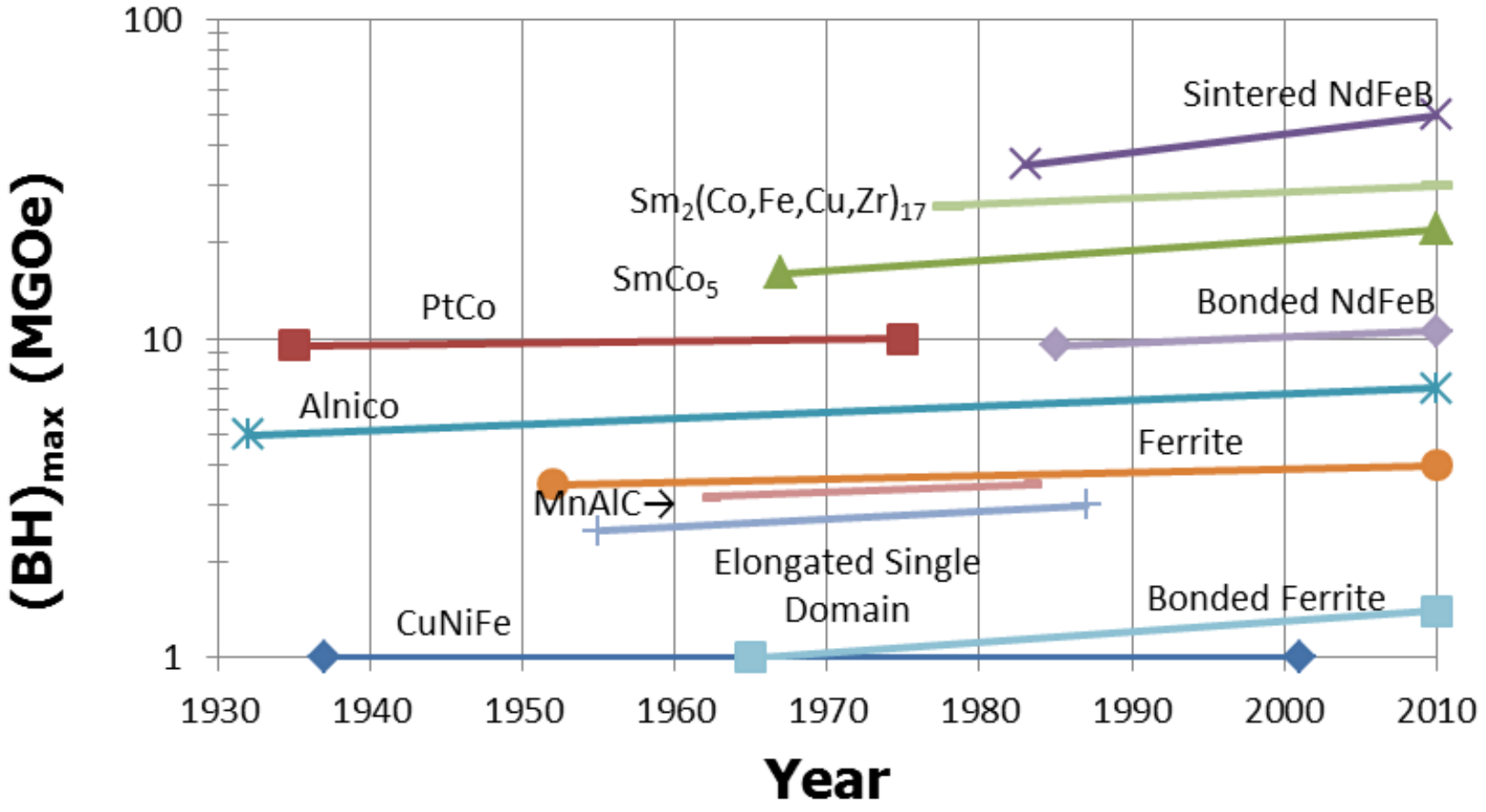
Permanent Magnets 1930 to 2010



Spontaneous Materials

Source: Stan Trout (Molycorp)

Phosphors in Advanced Lighting

- **Red (Eu, Y) + green (Ce, La, Tb) + blue (Eu) phosphors yield white light**

Sources: sylvania.com; en.wikipedia.com; home.howstuffworks.com; shattershield.wordpress.com

Outline

- Demand: the 'vitamins' of many modern materials
- *Supply*
- Markets and prices
- What to do?

Supply—dominated by China, but this is changing slowly

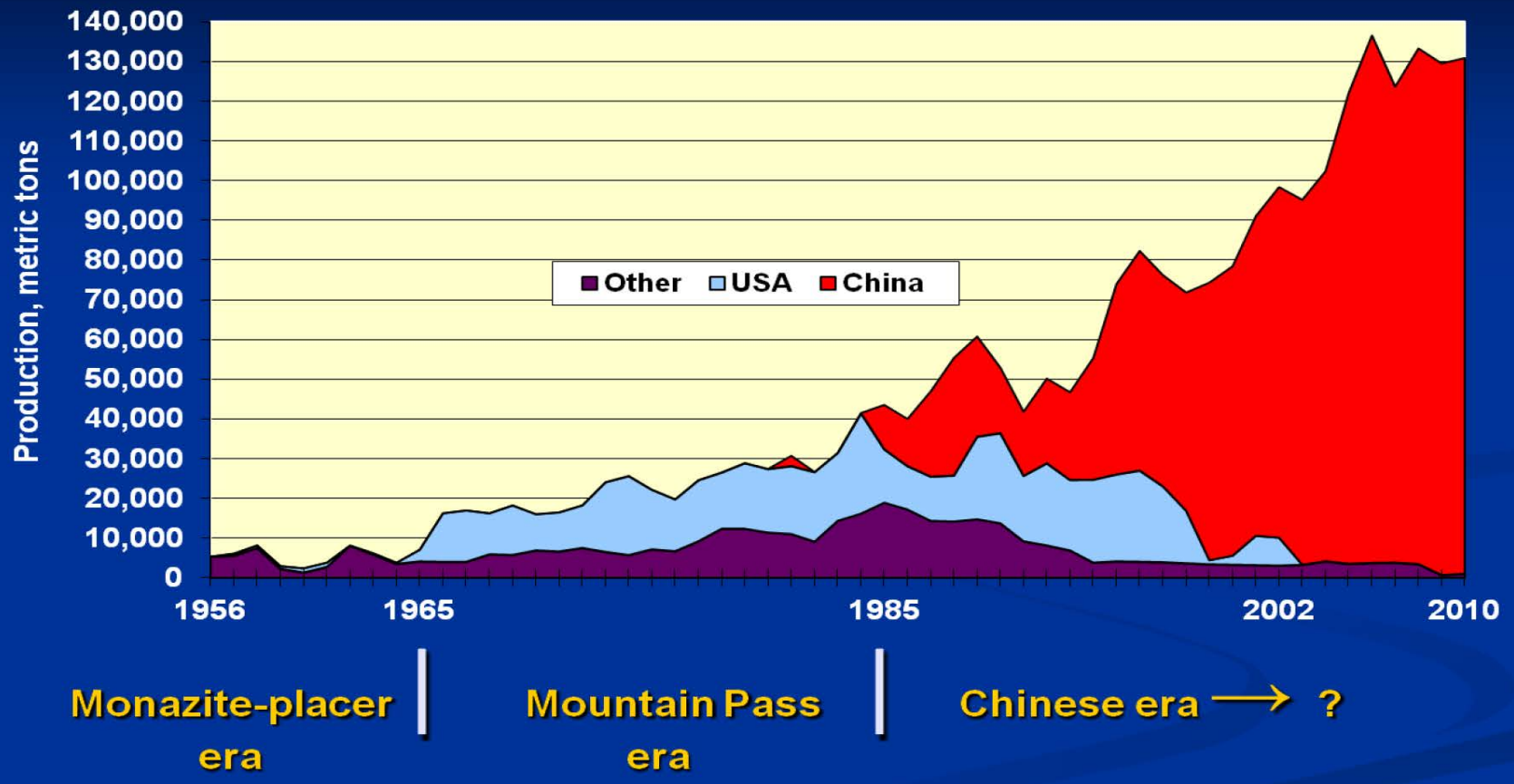
- > 95% of current mine production in China, along with production of most alloys, metals, and other intermediate products; Chinese export restrictions
- ~500 exploration projects worldwide, perhaps 5-10 will become mines
- Not all rare-earth deposits are the same (mix of elements, availability of processing technology)
- Will production of downstream (intermediate) products also grow outside of China?

The supply chain and its geography

Stage	Location of Production
Mining & concentration	>95% China
Separated oxides	>95% China
Reduction to metal	~100 China
Production of alloys and magnet powders	75-80% China 20-25% Japan
Manufacture of NdFeB magnets	75-80% China 17-25% Japan 3-5% Europe

Source: Buchert (2011)

Global Rare Earth Oxide (REO) Production Trends



USGS

Source: minerals.usgs.gov

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Production and reserves 2011
(metric tons REO)

	Mine Production	Reserves (Resources?)
Australia	0	1,600,000
Brazil	550	48,000
China	130,000	55,000,000
CIS	na	19,000,000
India	3,000	3,100,000
Malaysia	30	30,000
United States	0	13,000,000
Other	na	22,000,000
TOTAL	133,580	110,000,000

Source: US Geological Survey, *Mineral Commodity Summaries*, January 2012 (minerals.usgs.gov)

Distribution of world mine production, 2010

	% World REO	Mineral Produced
Inner Mongolia, China (Bayan Obo mine)	53	Bastnesite, monazite
Southern China[1]	16	Ionic clays
Sichuan	26	Bastnesite
USA (Mountain Pass mine)	3	Bastnesite
Russia	2	Loparite
India & SE Asia	<1	Monazite

Note: [1]For Southern China, this is the official number. Roskill (2011) believes actual production there was higher due to unreported, smuggled output.

Source: Roskill 2011

Varying Distribution of Rare Earths (%)

	Mountain Pass, California	Bayan Obo, China	Longnan, China	Xunwu, China	Bear Lodge, Wyoming	Strange Lake, Canada
La	33.8	23.0	1.8	43.4	30.4	4.6
Ce	49.6	50.0	0.4	2.4	45.5	12.0
Pr	4.1	6.2	0.7	9.0	4.7	1.4
Nd	11.2	18.5	3.0	31.7	15.8	4.3
Sm	0.9	0.8	2.8	3.9	1.8	2.1
Eu	0.1	0.2	0.1	0.5	0.4	0.2
Gd	0.2	0.7	6.9	3.0	0.7	2.5
Tb	0.0	0.1	1.3	trace	0.1	0.3
Dy	0.0	0.1	6.7	trace	0.2	8.2
Y	0.1	trace	65.0	8.0	<0.01	52.8

Source: US Geological Survey, *The Principal Rare Earth Deposits of the United States—A Summary Of Domestic Deposits and a Global Perspective*, 2010,minerals.usgs.gov

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- Supply: dominated by China, but slowly changing
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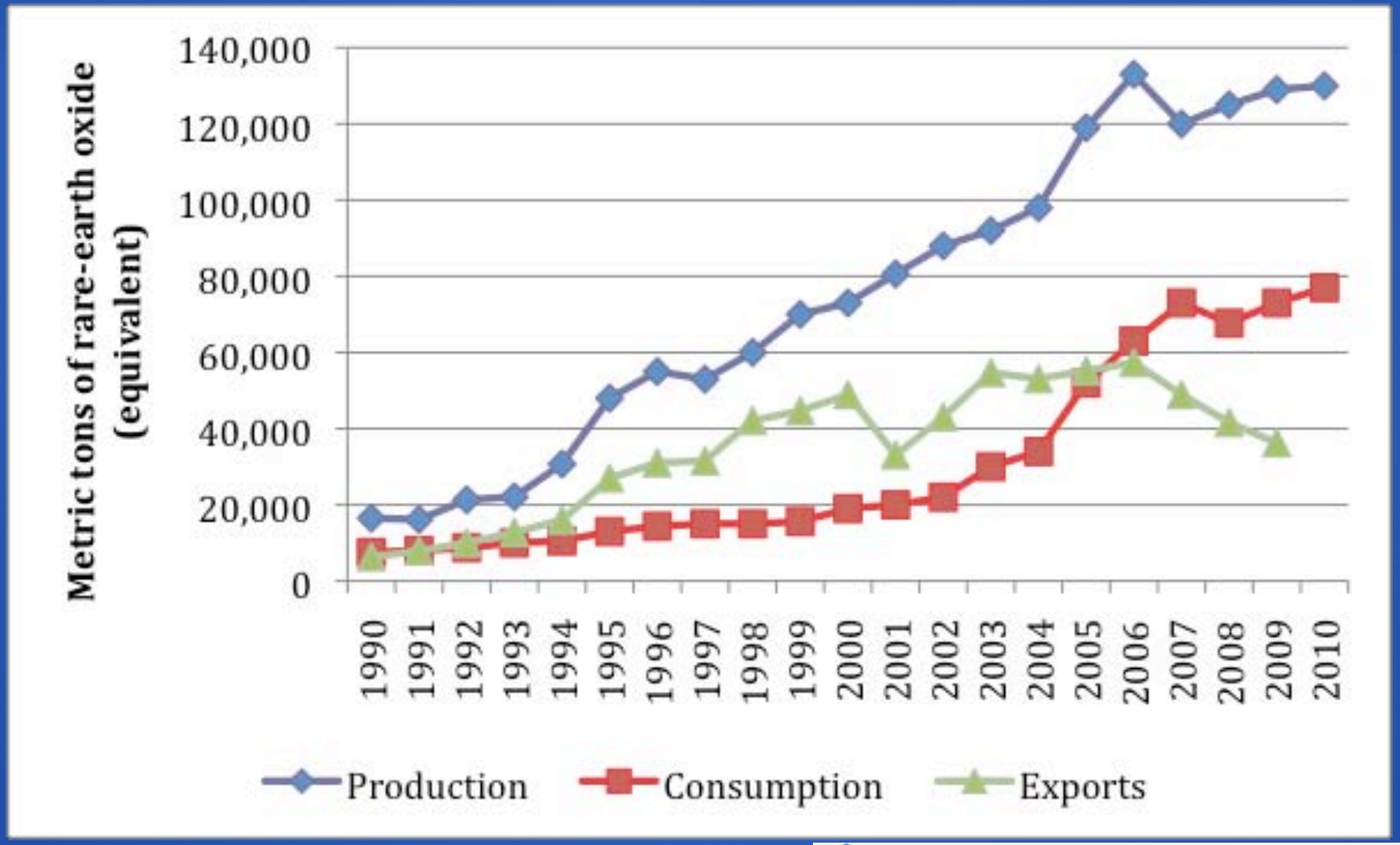
- What to do?

Chinese production, consumption, and exports, 1990-2010 (tonnes REO)

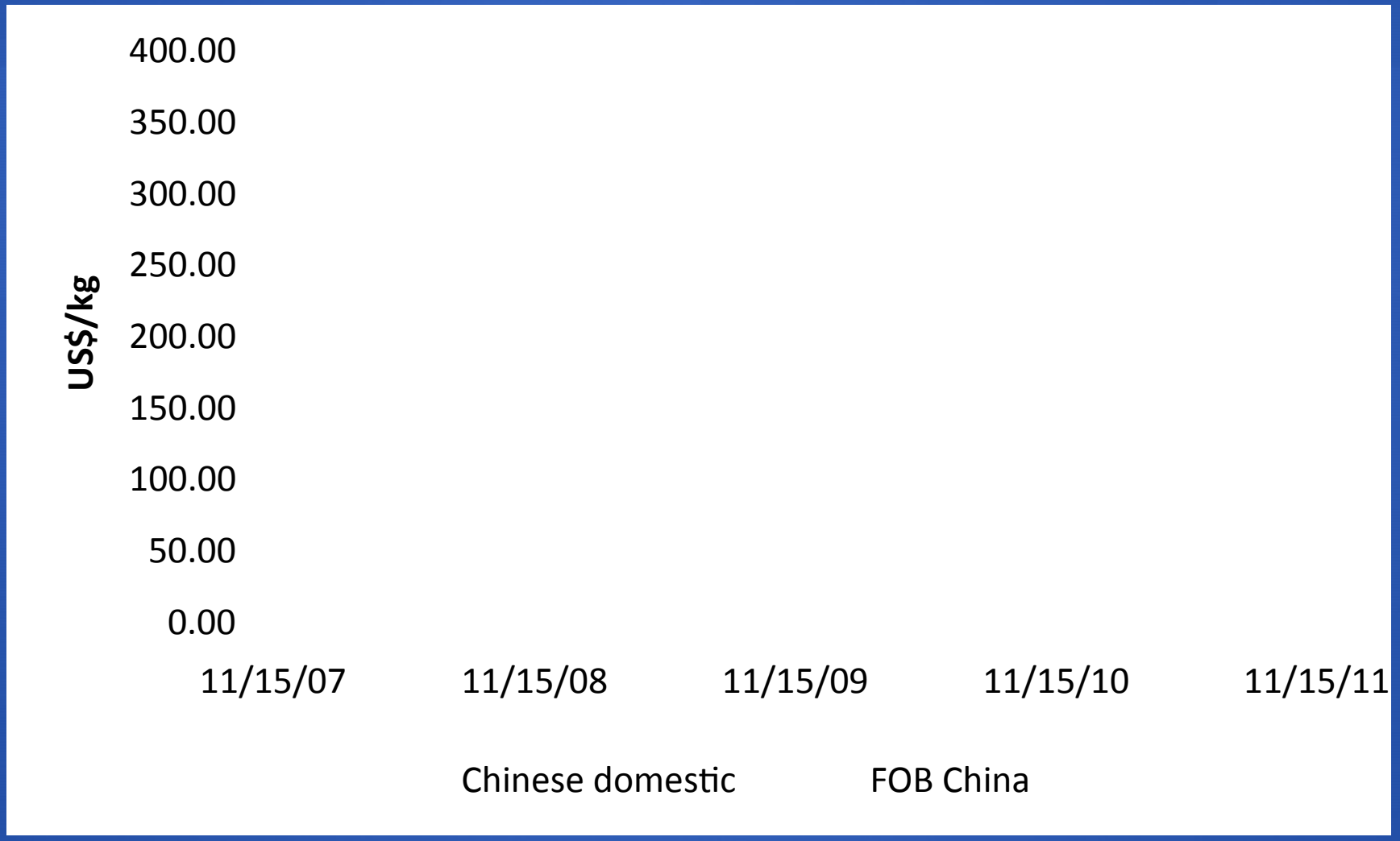


Source: U.S. Geological Survey; Chen 2011

Current Chinese Policy

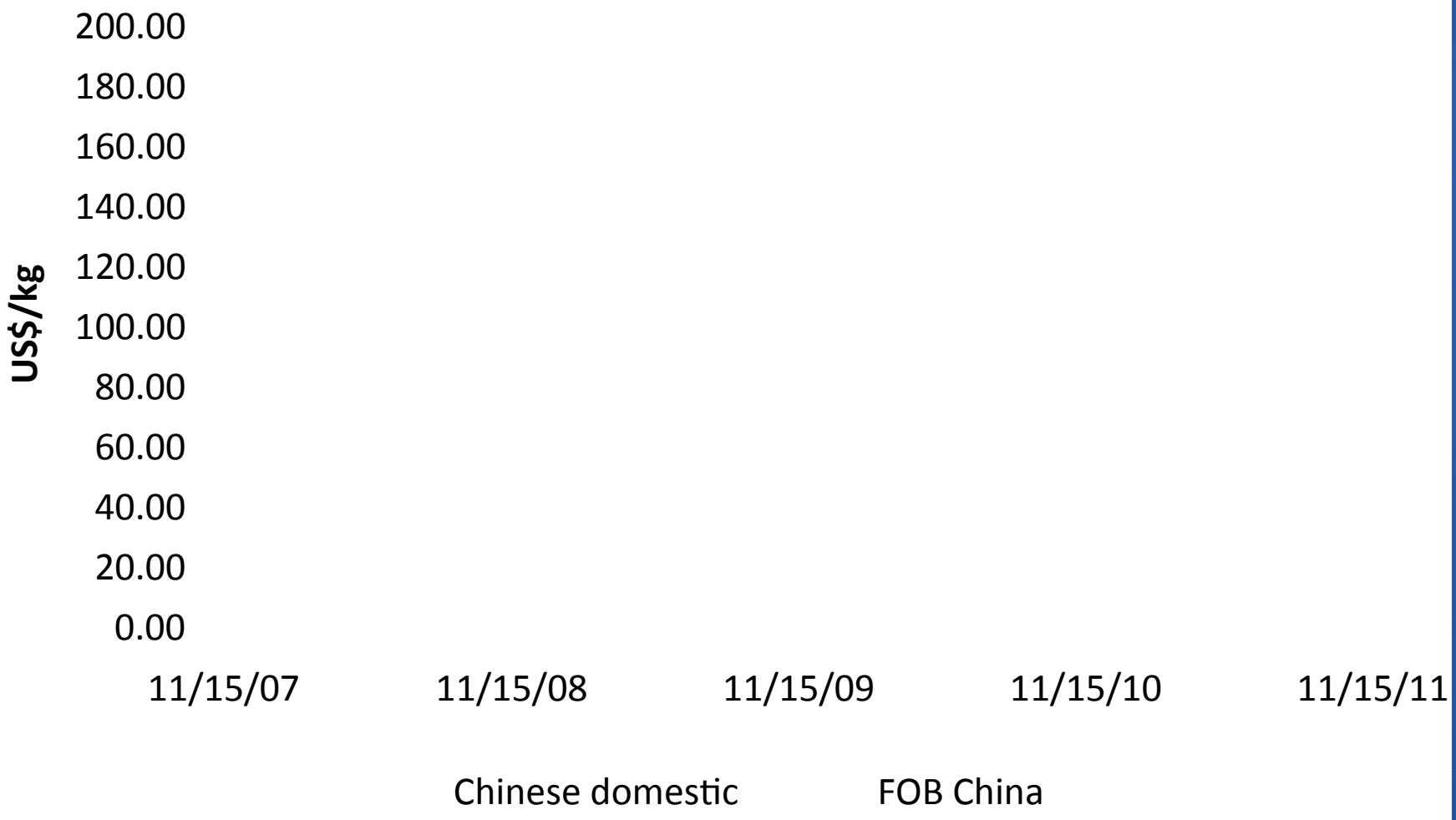
- Production targets (Baotou, Sichuan, Ionic clays)
- Consolidation, environmental permits
- Export quotas (domestic companies, sino-foreign joint ventures)
- Export taxes

Neodymium-oxide prices, 2007-2011



Source: metal-pages.com

Yttrium-oxide prices, 2007-2011



Source: metal-pages.com

Chinese domestic and world prices for rare-earth oxides, December 29, 2011 (US$/kg)

Oxide 99% min purity	Chinese domestic	FOB China
Lanthanum	16.02	51.00
Cerium	18.36	42.50
Praseodymium	85.94	165.00
Neodymium	100.00	195.00
Samarium	11.72	78.50
Europium	1,765.63	3,790.00
Gadolinium	25.78	102.50
Terbium	1,484.38	2,810.00
Dysprosium	453.13	1,410.00
Yttrium	34.38	90.50

Source: metal-pages.com. Note: Exchange rate of 6.4 RMB/US$ used to convert Chinese domestic prices into US$ prices.

RE-oxide prices, FOB China (US$/kg)

Oxide 99% min purity	2007	2008	2009	2010	31 March 2011	30 June 2011	29 Dec 2011
Cerium	3.65	4.25	4.15	61.00	121.00	149.00	42.50
Dysprosium	93.00	94.50	116.50	295.00	640.00	1510.00	1410.00
Europium	350.00	480.00	480.00	630.00	940.00	3190.00	3790.00
Gadolinium	10.45	7.75	6.75	44.50	147.50	202.50	102.50
Lanthanum	4.70	7.75	5.55	60.00	120.50	148.00	51.00
Neodymium	29.25	14.24	22.75	87.00	201.50	317.50	195.00
Praseodymium	29.75	14.25	22.25	86.50	196.00	238.50	165.00
Samarium	4.05	4.50	4.50	34.50	106.50	128.50	78.50
Terbium	610.00	410.00	350.00	605.00	990.00	2910.00	2810.00
Yttrium	11.40	15.25	10.25	72.50	142.50	169.50	90.50

Source: metal-pages.com

Note: For 2007-2010, prices in last week of the year

2014 projected market balance, Hatch (tonnes REO)

	Supply	Demand	Balance
Lanthanum	50,794	40,119	10,675
Cerium	76,115	56,887	19,228
Neodymium	29,181	27,994	1,187
Europium	451	569	(118)
Terbium	306	346	(40)
Dysprosium	1,158	1,846	(688)
Yttrium	7,131	10,710	(3,579)

Source: Hatch (2011)

2016 projected market balance, Kingsnorth (tonnes REO)

	Supply	Demand	Balance
Cerium	75,000-85,000	60,000-70,000	5,000-25,000
Neodymium	30,000-35,000	25,000-30,000	0-10,000
Europium	450-550	625-725	(75-275)
Terbium	300-400	450-550	(50-250)
Dysprosium	1,300-1,600	1,500-1,800	100-(500)
Yttrium	9,000-11,000	12,000-14,000	(1,000-5,000)

Source: Kingsnorth (2012)

Outline

- Demand: the 'vitamins' of many modern materials
- Supply: dominated by China, but slowly changing
- Markets and prices:
  - Rare earths are not created equal
  - 2-tier pricing
- *What to do?*

Allow markets to work, recognize there are time lags

- Markets provide powerful incentives
- Supply side
  - Exploration boom for rare earths
  - R&D on extraction technologies, manufacturing efficiency, recycling

Allow markets to work

- Markets provide powerful incentives
- Supply side
- Demand side: insurance
  - Short term: working inventories, diversified supply, sharing arrangements with other users, strategic relationships with suppliers
  - Long term: element-for-element substitution, system substitution

Recognize essential roles for government

- Pushing for undistorted international trade
- Improving the process of regulatory approval for domestic resource development
- Facilitating provision of information and analysis
- Facilitating research and education over the entire supply chain
  - Geoscience → mining, mineral processing, extractive metallurgy → materials → recycling

Summing Up

- Demand: The 'vitamins' of many modern materials
- Supply: Dominated by China, but slowly changing
- Markets and prices:
  - Rare earths are not created equal
  - 2-tier pricing
- What to do? Allow markets to work, recognize essential roles of government

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