Rare Earth Elements: Mine to Magnet and Beyond

Module 2. REE Economy

Section 3: Permanent Magnet Markets

Dr. John Ormerod

JOC LLC/Industrial Advisor to CMI

Outline

- Introduction
- Permanent Magnet Markets and Applications
- Critical REE's For Permanent Magnets
- RE Magnet Supply Chain
- The Future

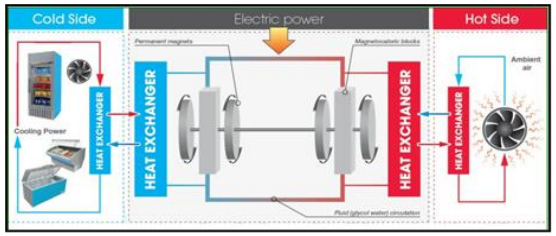
Introduction – John Ormerod

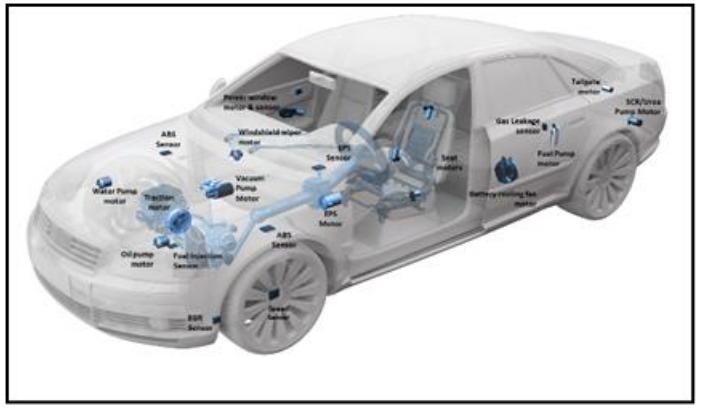
- BSc, MSC and PhD in Metallurgy from the University of Manchester (1972 – 1978).
- Magnetics career began for Philips (UK and Holland) – 1979 – 1990.
  - –Developed and commercialized SmCo5, 2:17 and NdFeB magnets.
- Joined Arnold Magnetic Technologies (US) responsible for soft and hard magnetic materials development and GM for permanent magnets (1990 – 2002).
- 2002 - 2014 President of Res Manufacturing in Milwaukee.
  - –Metal stamping and value-added assemblies to the automotive market (Toyota, GM, Nissan).
  - –Major supplier to Tesla Motors for Model S and Model X.
- Industrial advisor for Focus Area 2 of CMI
- Co-editor of recently published Modern Permanent Magnets link here
- Principal of JOC LLC a business and technology consultancy for magnetics and metals related industries (www.jocllc.com).

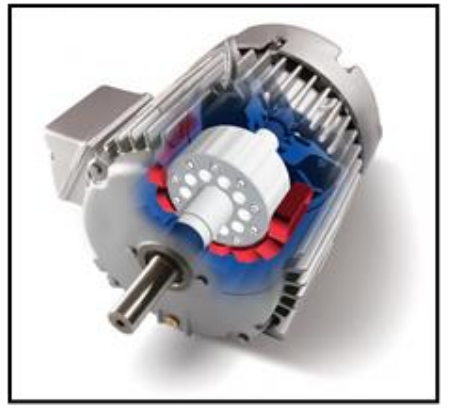
"The Nation That Controls Magnetism Will Control The Universe"

- Dick Tracy cartoon strip, created by Chester Gould.
- Circa early-1960's i.e., before RE magnets and the Chinese dominance of RE supply chain and magnet industry!
- *Or the nation that controls the critical materials supply chain controls their destiny!*

Permanent Magnets – Hidden But Essential!







US Permanent Magnet Industry From 1995 to Today to 2025

Arnold(Ferrite/Alnico/Smco/Bonded)
Crucible(Ferrite/Alnico/NdFeB) Closed
Kane Magnetics(Ferrite/Alnico/Bonded) Closed
Permanent Magnet Co. (Alnico) Closed
General Magnetics (Ferrite) Closed
Ugimag(NdFeB) Acquired/Closed
TDK(Ferrite)
Hitachi Metals(Alnico/Ferrite/NdFeB)
Electron Energy (SmCo)
Dynacast(Bonded Magnets) Acquired
Thomas & Skinner(Alnico/SmCo)
Magnequench(NdFeB) Relocated
Tengam(Bonded)
Magnet Applications (Bonded)
Electrodyne(Bonded)
RJF (Bonded) Acquired
Magnum (Bonded)
Magnetic Specialty (Bonded) Acquired
Flexmag Industries (Bonded) Acquired

1995

Industry consolidation, relocation and closure

Arnold(Alnico/Bonded)
Urban Mining (NdFeB) – Operational?

~~TDK(Ferrite) – Closing 2022~~
Hitachi Metals (Ferrite)
Electron Energy (SmCo)

Thomas & Skinner(Alnico)

Tengam(Bonded)
Magnet Applications/Bunting-DuBois (Bonded)
Electrodyne(Bonded)
Magnum(Bonded)

Today

Massive investment in NdFeB supply chain -$100's million

Arnold(Alnico/Bonded)
Urban Mining/Noveon (NdFeB)?
MP Materials (NdFeB)?
VAC (NdFeB)?
Quadrant (NdFeB)?
USA Rare Earth (NdFeB)?

~~Hitachi Metals (Ferrite)~~
Electron Energy (SmCo)
Thomas & Skinner(Alnico)
Tengam (Bonded)
Magnet Applications/Bunting-DuBois (Bonded)
Electrodyne(Bonded)
Magnum(Bonded)

2025?

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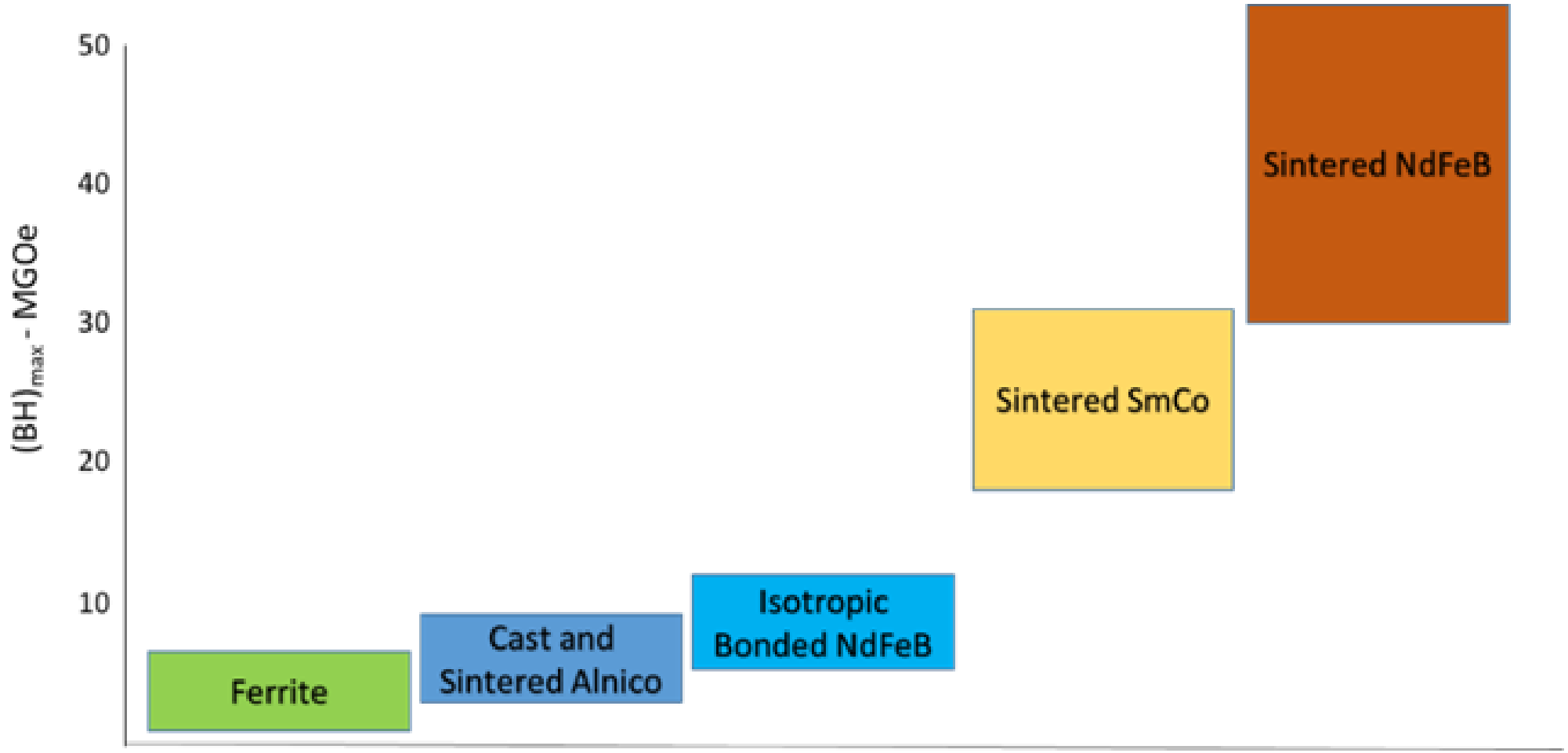
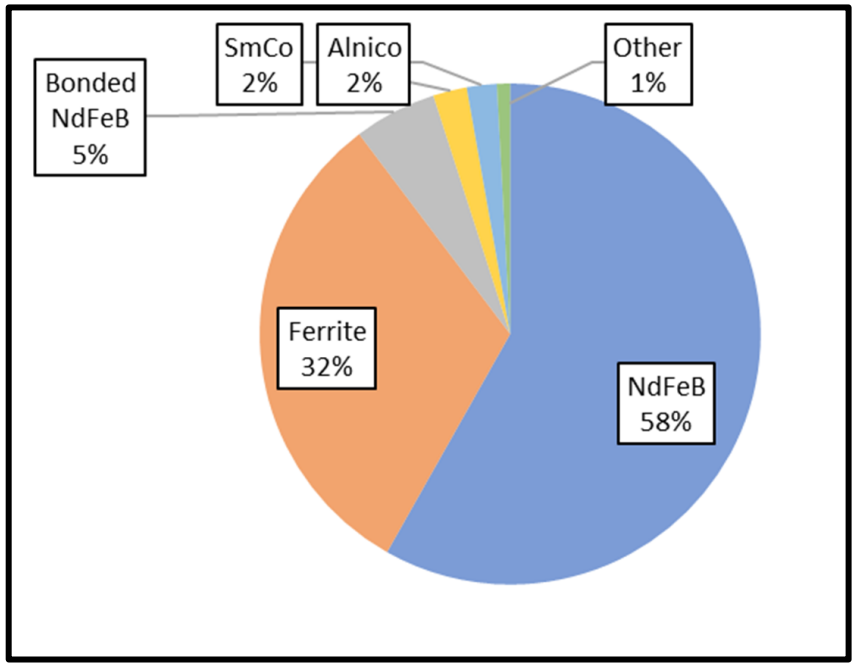
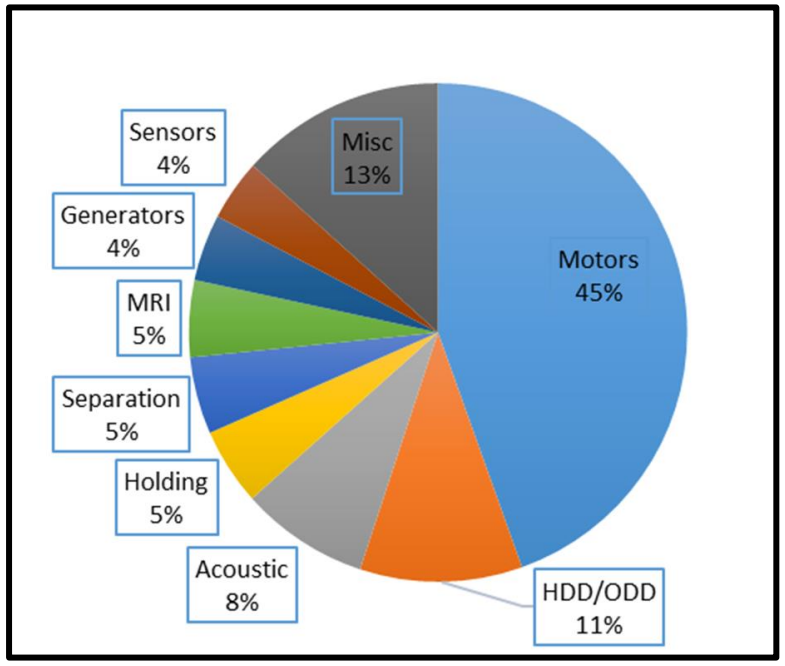
Five Commercially Important Permanent Magnet Types



What Are The Markets And Applications?





	2020	2030	2040
Material	**Weight (000's kg)**	**Weight (000's kg)**	**Weight (000's kg)**
NdFeB	190,000	450,000	600,000
Ferrite	900,000	950,000	1,000,000
Bonded NdFeB	12,000	24,000	34,000
SmCo	4,400	4,700	5,000
Alnico	6,750	6,850	7,000
Other	2200	2,500	3,000

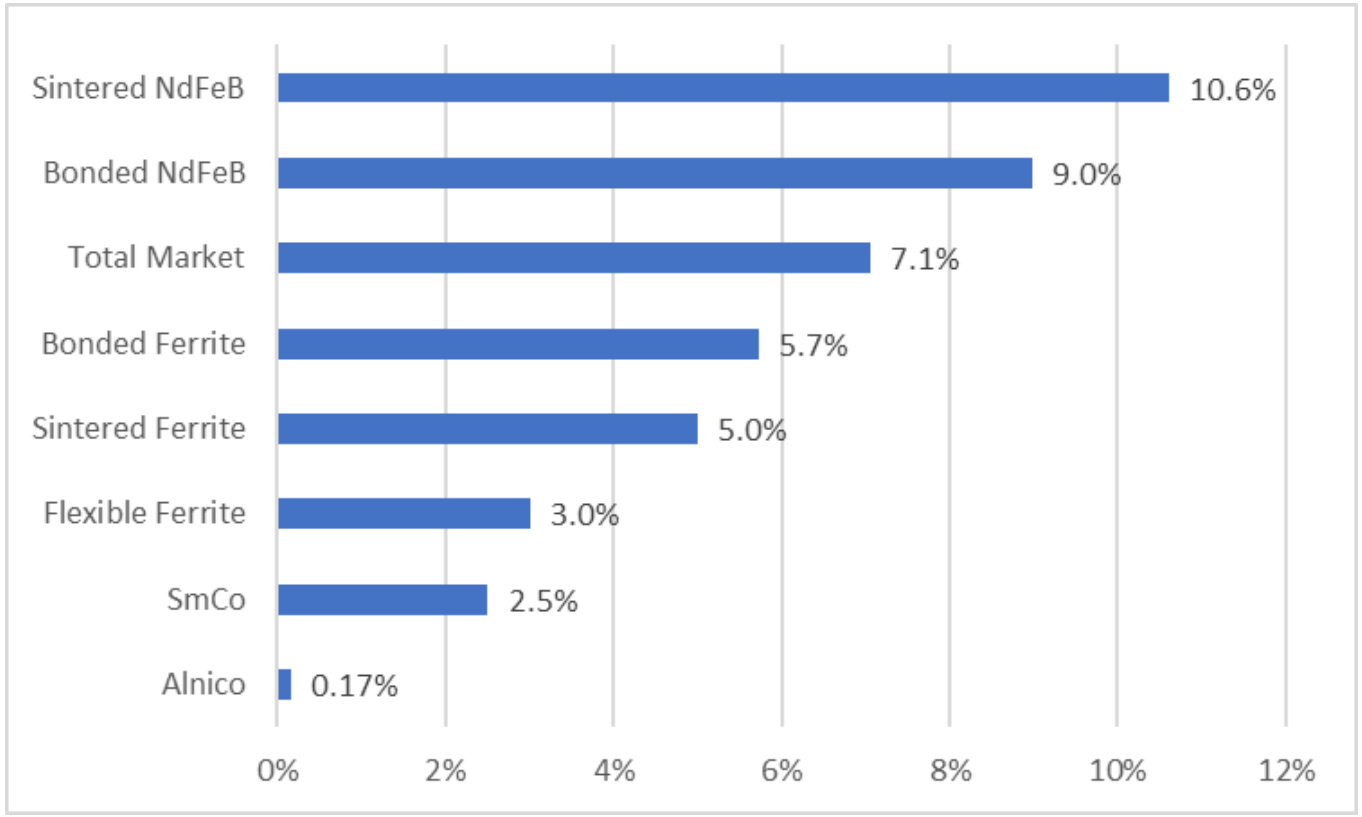
Optimum Price-Performance Metric - Based On Magnet Volume

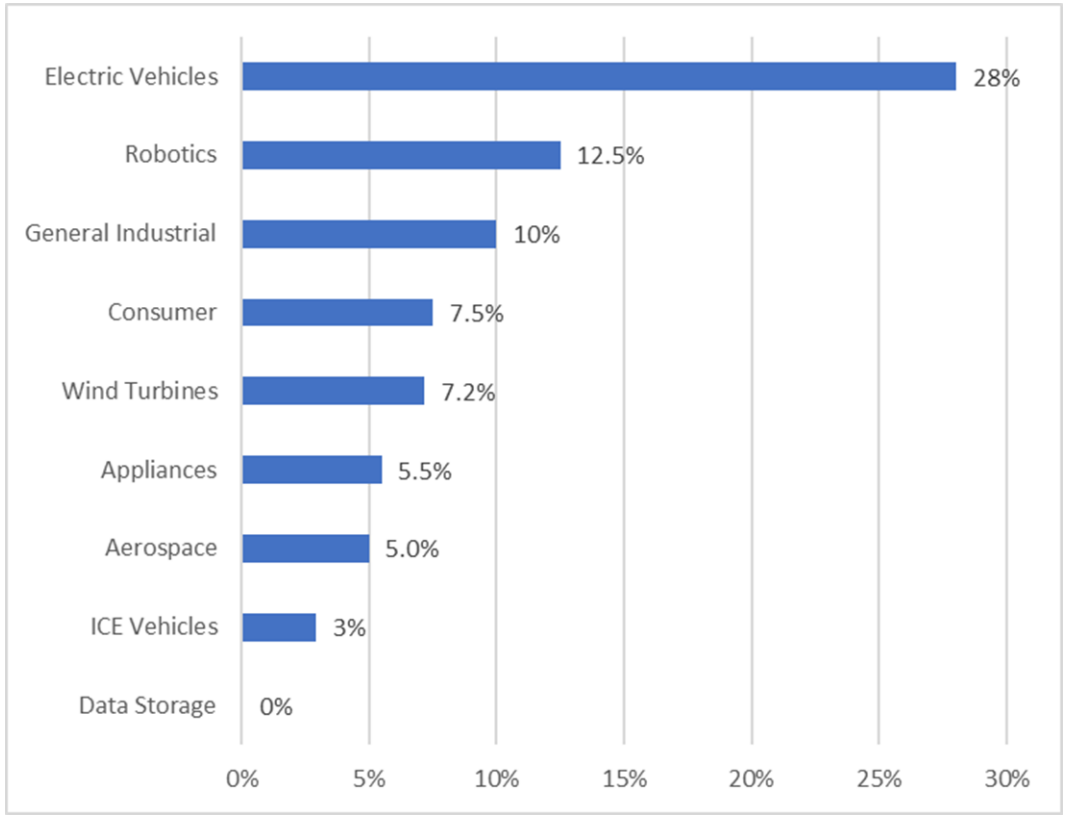
Material	Average $(BH)_{max}$ (MGOe)	Average Price ($/kg)	Density (g/cm^3)	Average Price ($/m^3 x 10^3)	Price/Performance ($/m^3 per MGOe x 10^3)
NdFeB	45	70	7.5	525	12
Ferrite	3.5	6.4	5.0	32	9
Bonded NdFeB	8	91	5.1	464	58
SmCo	25	95	8.4	798	32
Alnico	7	56	7.3	409	58

Production of Permanent Magnets by Country or Region: Metric Tons x1,000

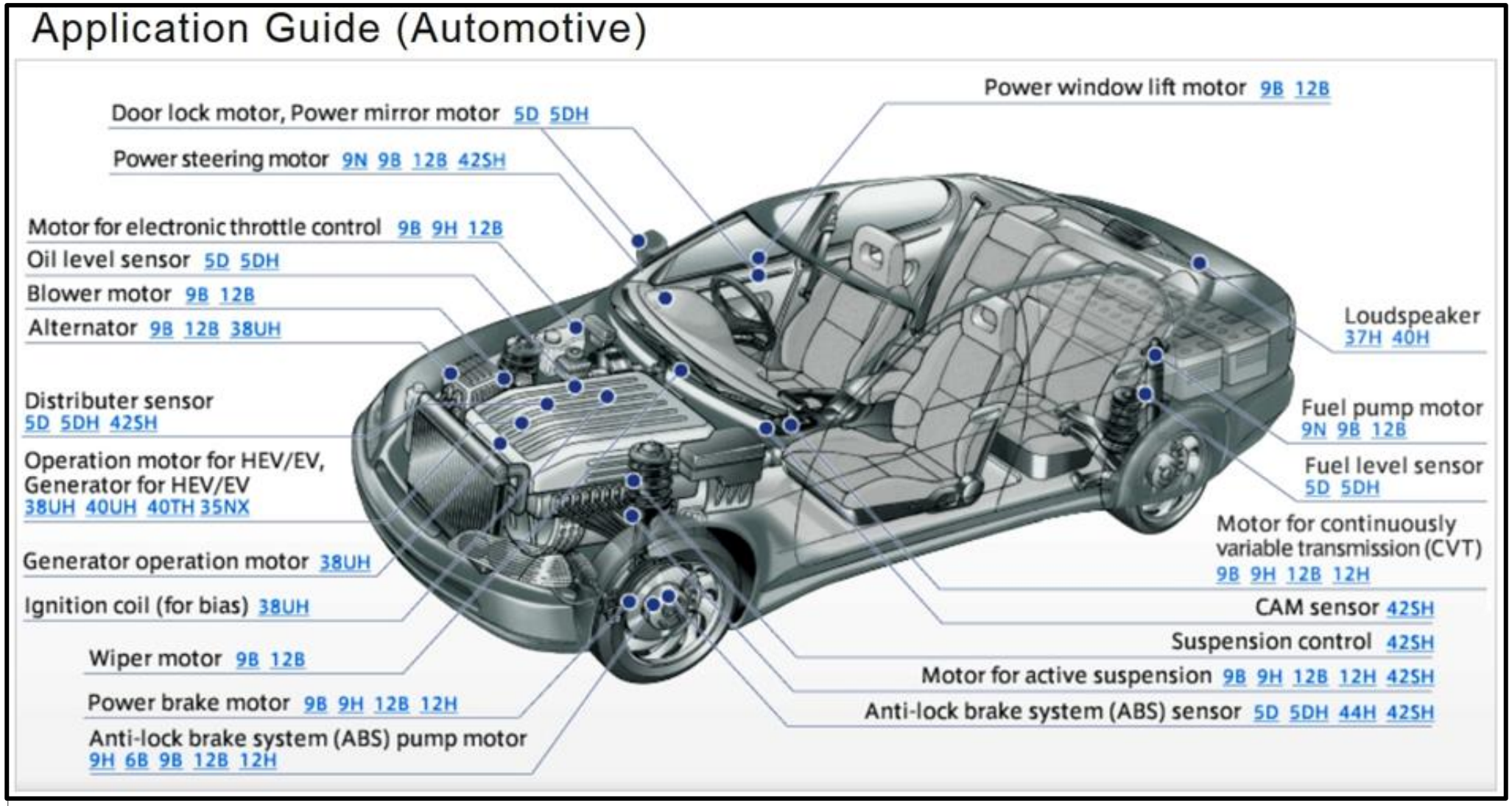
Country or Region	2005	2010	2015	2020	2025	2030
China	485	535	690	805	995	1,170
Japan	100	105	110	110	115	115
USA	70	60	60	55	55	60
Europe	80	65	60	55	65	70
India	55	60	75	75	95	120
SE Asia	85	95	110	115	145	175
South America	45	50	50	50	55	60
All Others	65	70	80	75	90	110
Totals	**985**	**1,040**	**1,235**	**1,340**	**1,615**	**1,880**

Average Annual Growth (AAG) of the Permanent Magnet Market through 2030.





Automotive (ICE and EV) Is The Largest Market For Permanent Magnets



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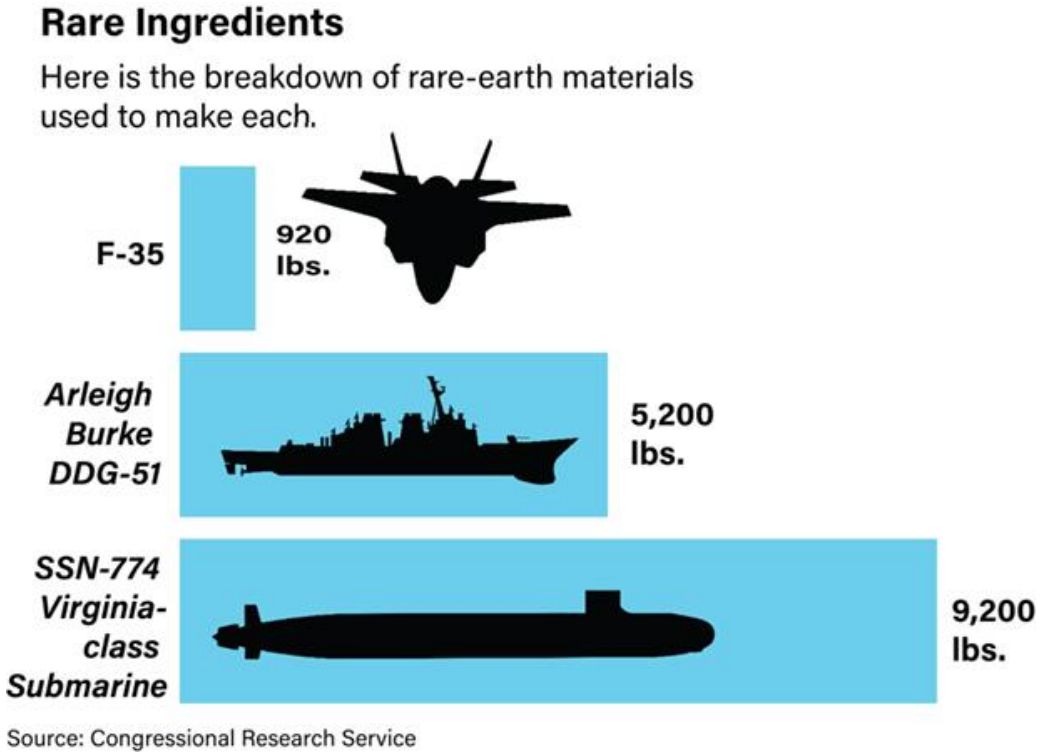
The Rare Earths - Applications

Rare-Earth Elements

Originally produced for the October 2011 issue of *Scientific American*

What Are They Used For?

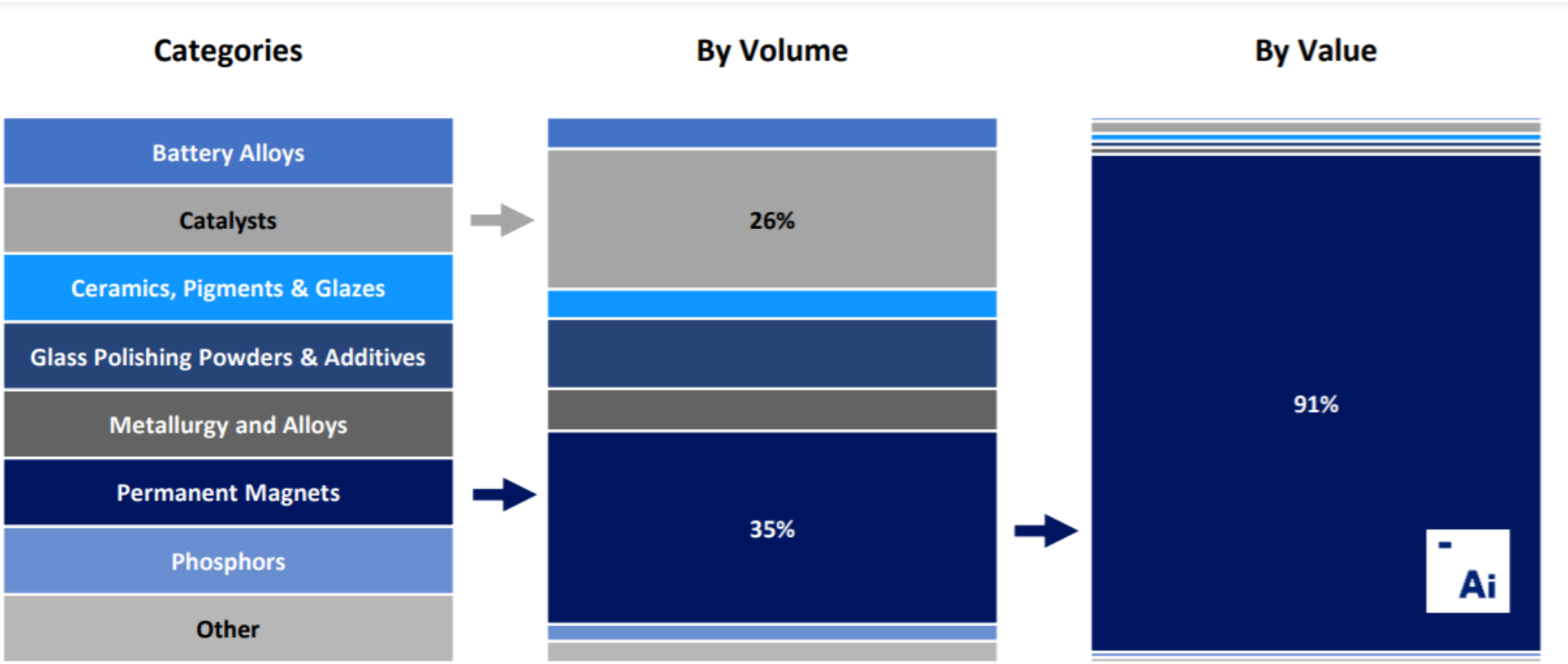
Scandium	Aerospace components, aluminum alloys
Yttrium	Lasers, TV and computer displays, microwave filters
Lanthanum	Oil refining, hybrid-car batteries, camera lenses
Cerium	Catalytic converters, oil refining, glass-lens production
Praseodymium	Aircraft engines, carbon arc lights
Neodymium	Computer hard drives, cell phones, high-power magnets
Promethium	Portable x-ray machines, nuclear batteries
Samarium	High-power magnets, ethanol, PCB cleansers
Europium	TV and computer displays, lasers, optical electronics
Gadolinium	Cancer therapy, MRI contrast agent
Terbium	Solid-state electronics, sonar systems
Dysprosium	Lasers, nuclear-reactor control rods, high-power magnets
Holmium	High-power magnets, lasers
Erbium	Fiber optics, nuclear-reactor control rods
Thulium	X-ray machines, superconductors
Ytterbium	Portable x-ray machines, lasers
Lutetium	Chemical processing, LED lightbulbs



Not a good idea to be totally dependent on Chinese supply chain!

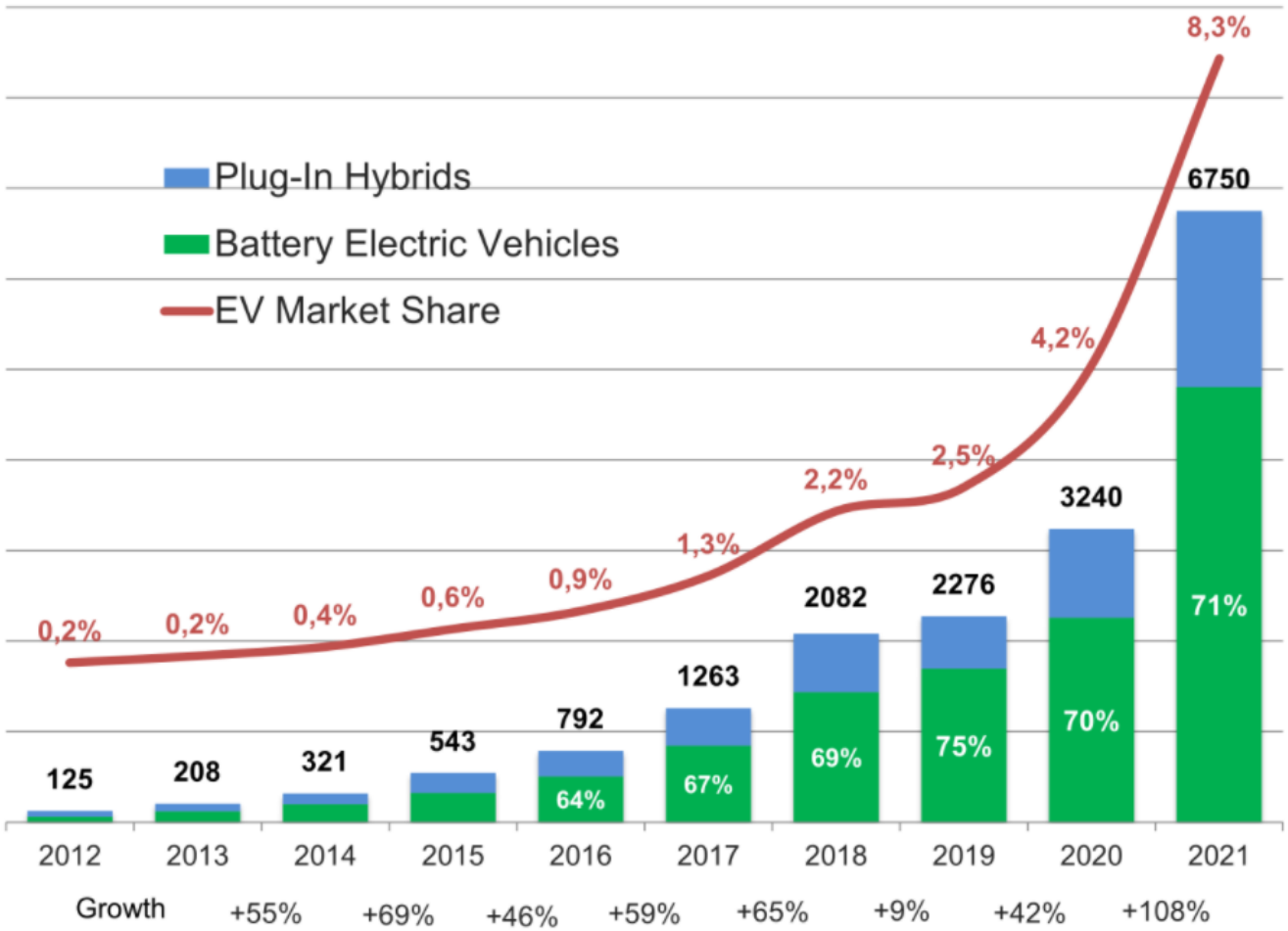
Issue is supply-demand balance

Rare Earths For Magnets Dominate The $'s



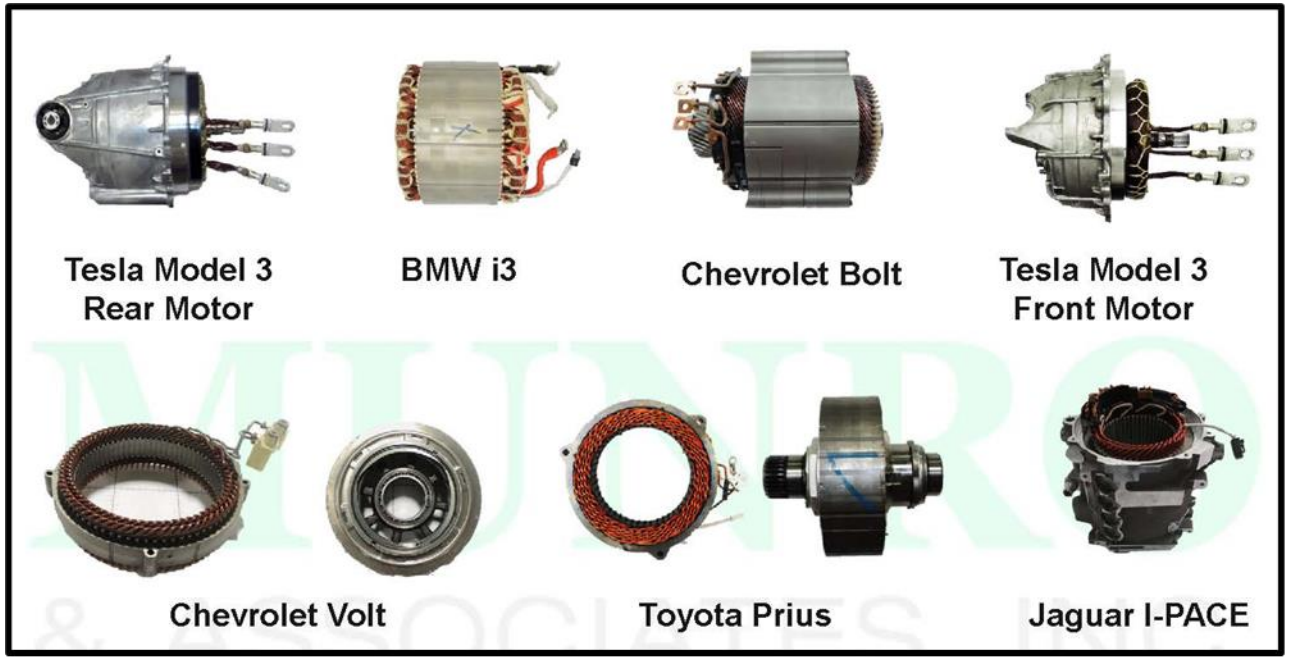
Source: Adamas Intelligence

Global BEV and PHEV Sales ('000s): Is 2021 an Inflection Point?



Source: Evvolumes.com

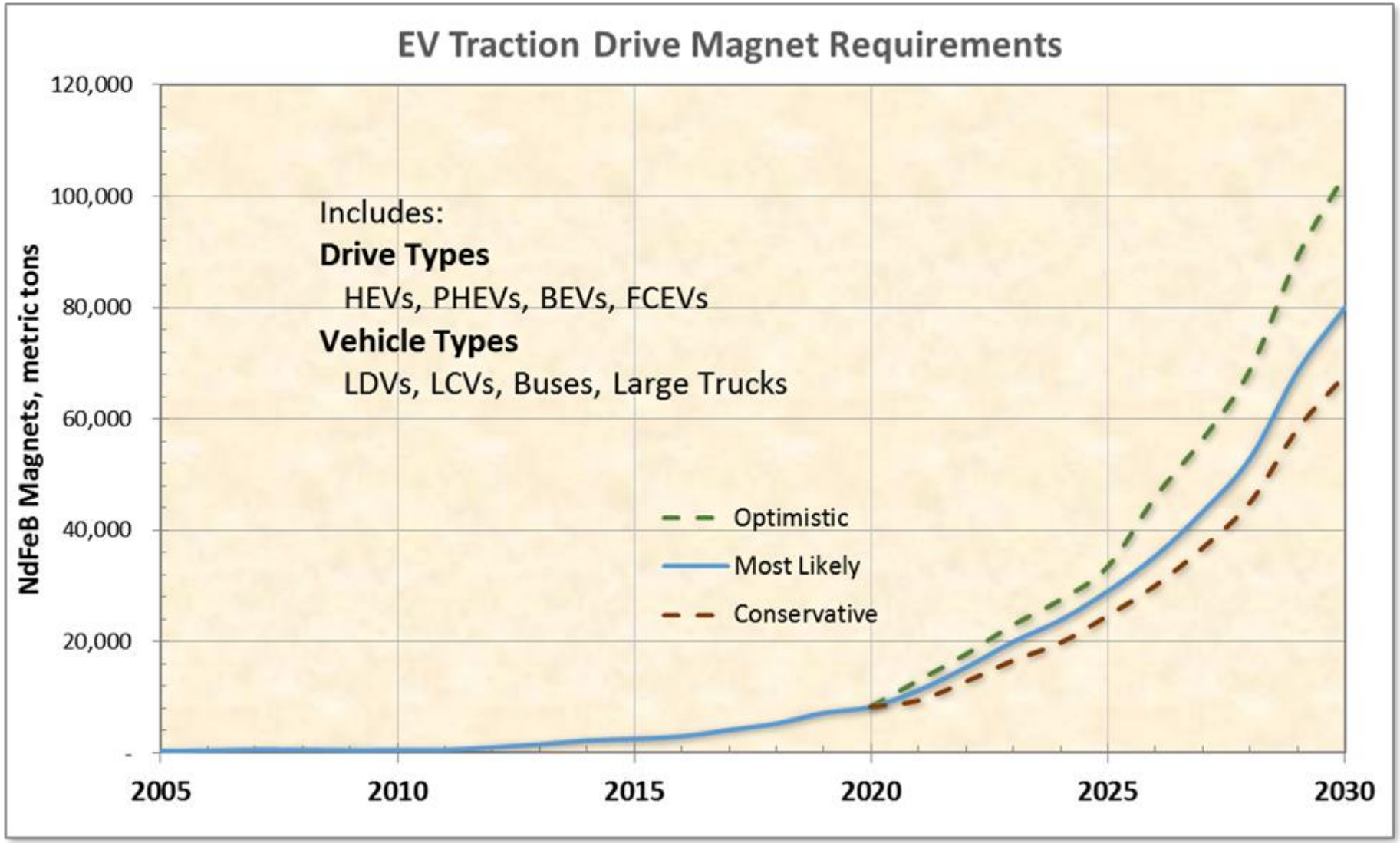
Weight Of Magnets For A Range Of Production EV's



Model	Year	Motor Type	Type	Total weight of Magnets
Tesla Model 3 Rear Motor	2017	PM AC Synchronous	BEV	1.79 kg
BMW i3 Exteneded Range	2014	PM AC Synchronous	BEV	2.01 kg
Chevrolet Bolt	2017	PM AC Synchronous	BEV	1.57 kg
Jaguar iPace	2019	PM AC Synchronous	BEV	1.85 kg
Chevrolet Bolt	2016	PM AC Synchronous	PHEV	0.69 kg
Toytota Prius	2016	PM AC Synchronous	HEV	0.44 kg

Average Magnet Weight For BEV = 1.8 kg
Average Magnet Weight for HEV = 0.57 kg

NdFeB Magnet Requirements to Meet Conversion from ICE to EVs



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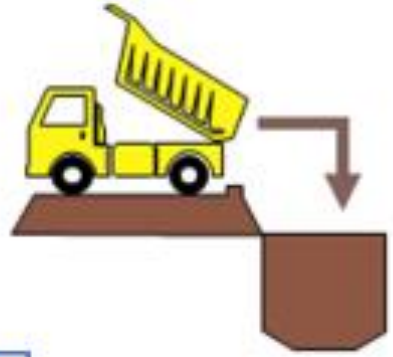
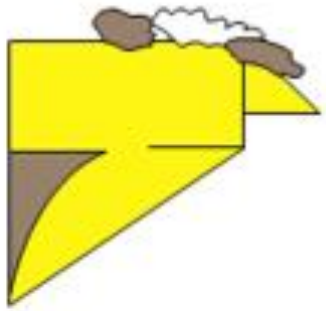
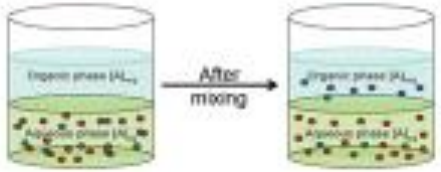
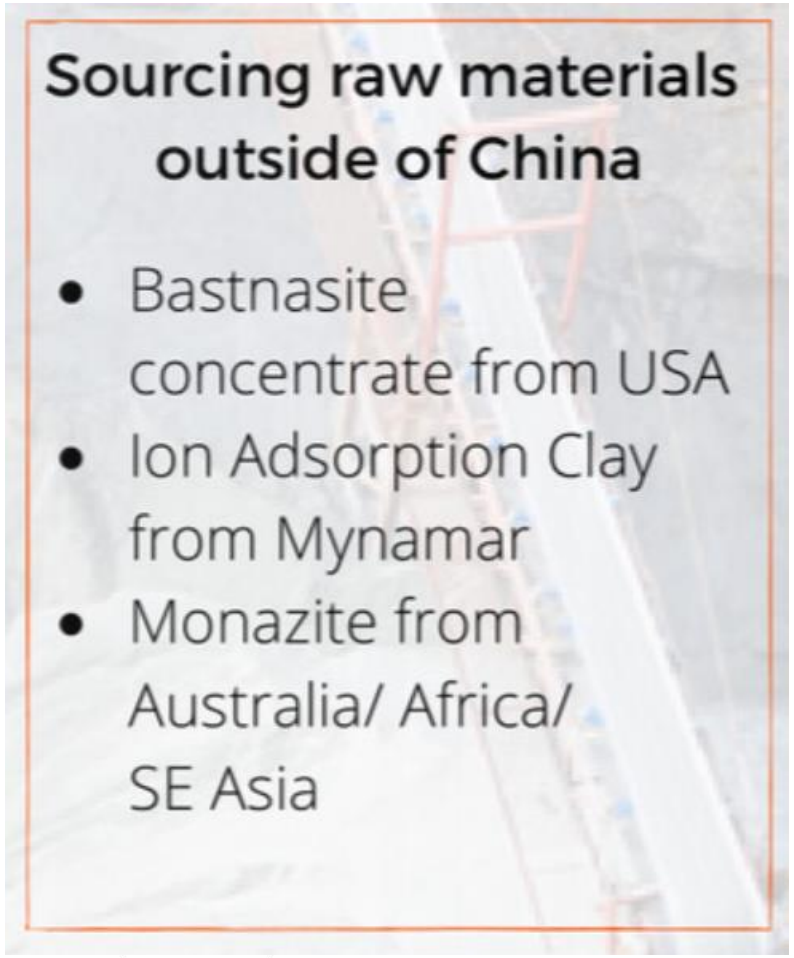
Integrated Rare Earth Magnet Supply Chain

Mine	Mixed REE Concentrate	Separation	Reduction to metal	Alloying and Magnet Making
				
Chinese Global %	60%	60%	85%	75%	>80%

RE Minerals and Major Non-Chinese Sources



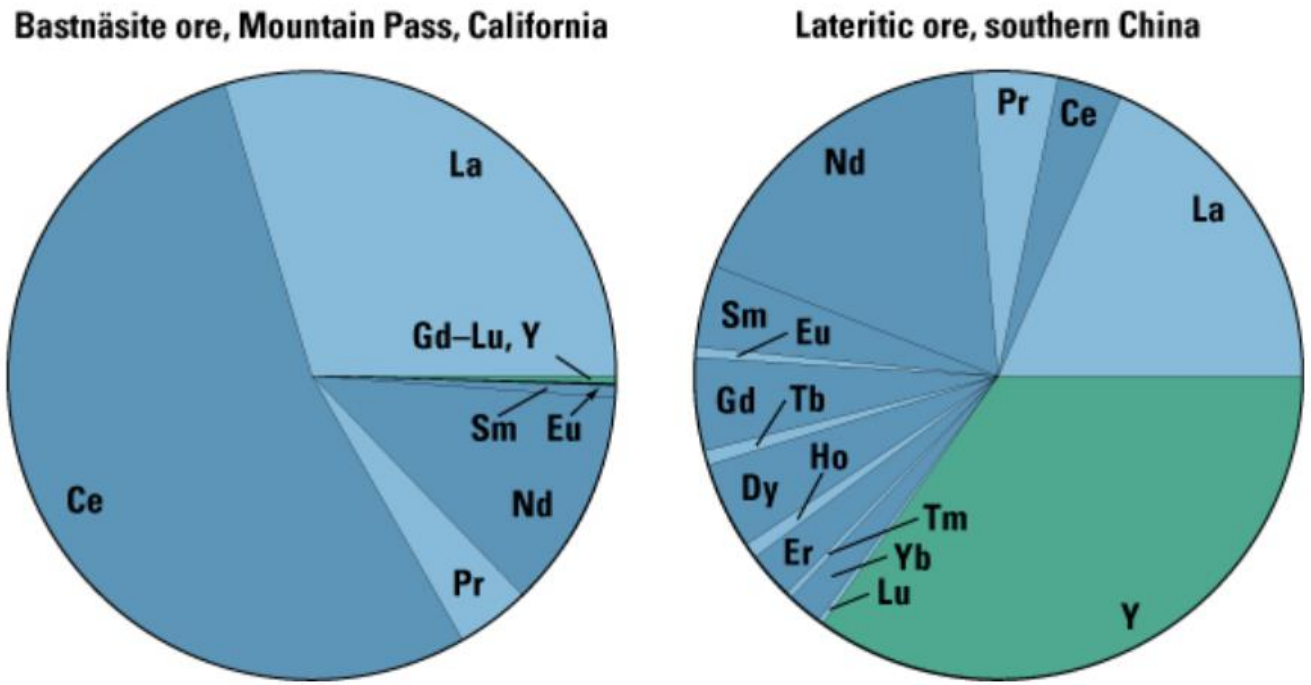
Two major rare-earth mines outside of China are in operation

Mount Weld Mine in Australia – Lynas.

Mountain Pass Mine in the United States – MP Materials.

These two mines together accounted for some 30% of world mined production of rare earths in 2020.

The Dysprosium Problem



It is mostly obtained from lateritic clay deposits in southern China

Almost all of the world's mine production of these elements is in China or Myanmar

Outline

Introduction

The Rare Earths – suddenly in the news.

The Rare Earths – Markets and Demand

Rare Earth Magnet Supply Chain

Summary or “What’s Next?”

Summary or "What's Next?"

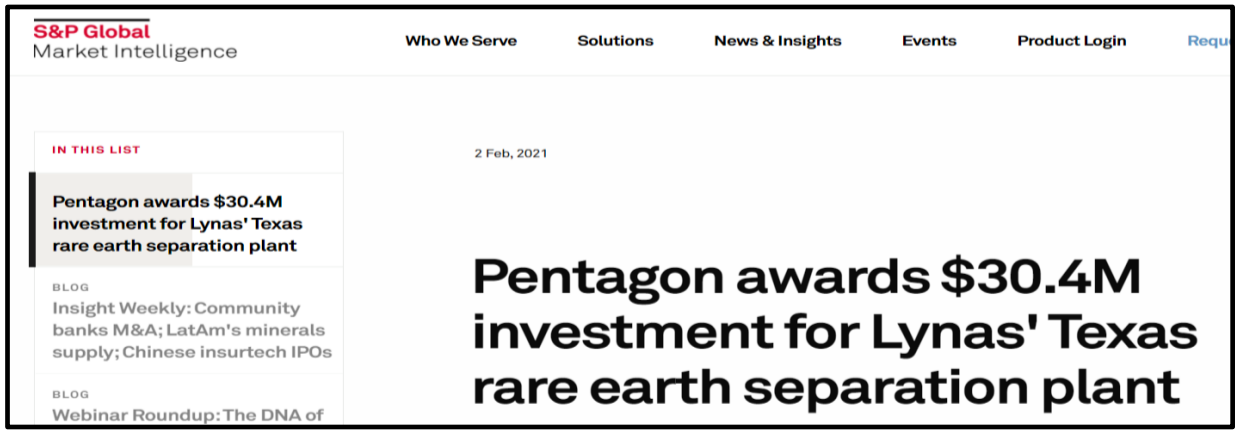
Government Intervention

Reduction of RE consumption

New/Expanding RE Sources/Supply Chains

New lower RE/non-RE Magnet Materials

US Government Get's Involved via DOD, DOE etc.



DOD Announces $28.8 Million Defense Production Act Title III Agreement with Urban Mining Company to Strengthen the Domestic Rare Earth Materials Industrial Base

IMMEDIATE RELEASE

DOD Announces Rare Earth Element Awards to Strengthen Domestic Industrial Base

NOV. 17, 2020

SWALWELL AND RESCHENTHALER INTRODUCE BILL TO INCENTIVIZE AMERICAN-MADE RARE EARTH MAGNETS CRITICAL FOR A MODERN, CLEAN ENERGY ECONOMY

August 10, 2021 | Press Release

LIVERMORE, CA– Reps. Eric Swalwell (CA-15) and Guy Reschenthaler (PA-14) introduced a bipartisan

CMI | Critical Materials Institute
AN ENERGY INNOVATION HUB

Summary or "What's Next?"

Government Intervention

Reduction of RE consumption

New/Expanding RE Sources/Supply Chains

New lower RE/non-RE Magnet Materials

Reduction of RE Consumption

Grain Boundary Diffused heavy rare earth (GBD HRE) grades.

Expansion of cerium and lanthanum grades for use in less-demanding applications.

Modification of applications to reduce the requirement for super high intrinsic coercivity thus reducing HRE needs (specifically Dy or Tb).

Recycling: some amount of recycling has been part of manufacturing NdFeB since commercialization in the mid-1980s. EOL recycling is a minor contribution at present but is expected to grow rapidly in the period between 2025 and 2030.

Uncertainty In Supply Chain Continuity - HREE's

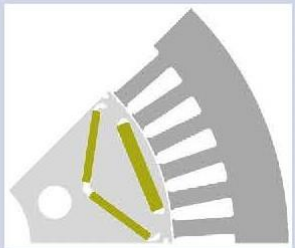
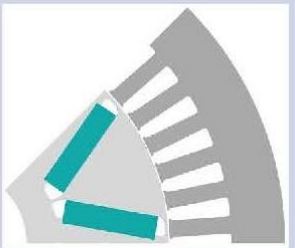
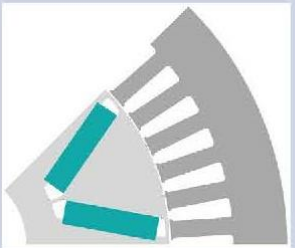
No Magnets, Big Power: BMW's Fifth-Generation Electric Motor

Here's why this motor's old-school tech is seriously impressive, and how it makes the iX M60 scoot.

For latest BMW iX Full EV 2022 Model

Substitution of High-Grade Ferrite for NdFeB in EV Drives

Examples of xEV traction motor designs

	Nd-Fe-B magnets used (Basis of comparison)	High-performance ferrite magnets used [1] (Equivalent motor performance)	High-performance ferrite magnets used [2] (Equivalent motor size and higher rotation speed)
Motor : "1/8 model" ■ Nd-Fe-B magnets ■ High-performance ferrite magnets NMF™-15G			
Max. output	110 kW	110 kW	105 kW
Max. rotation speed	10,000 rpm	10,000 rpm	15,000 rpm
Thickness in axial direction	1 (ref.)	1.4	1.0
Magnet B_r	1 (ref.)	0.37	0.37
Magnet weight	1 (ref.)	1.7	1.2
Motor weight	1 (ref.)	1.3	1.0

*Designed for fixed rotor and stator diameters, taking into account operating temperatures and strength at high speeds.

Reduction of RE Consumption

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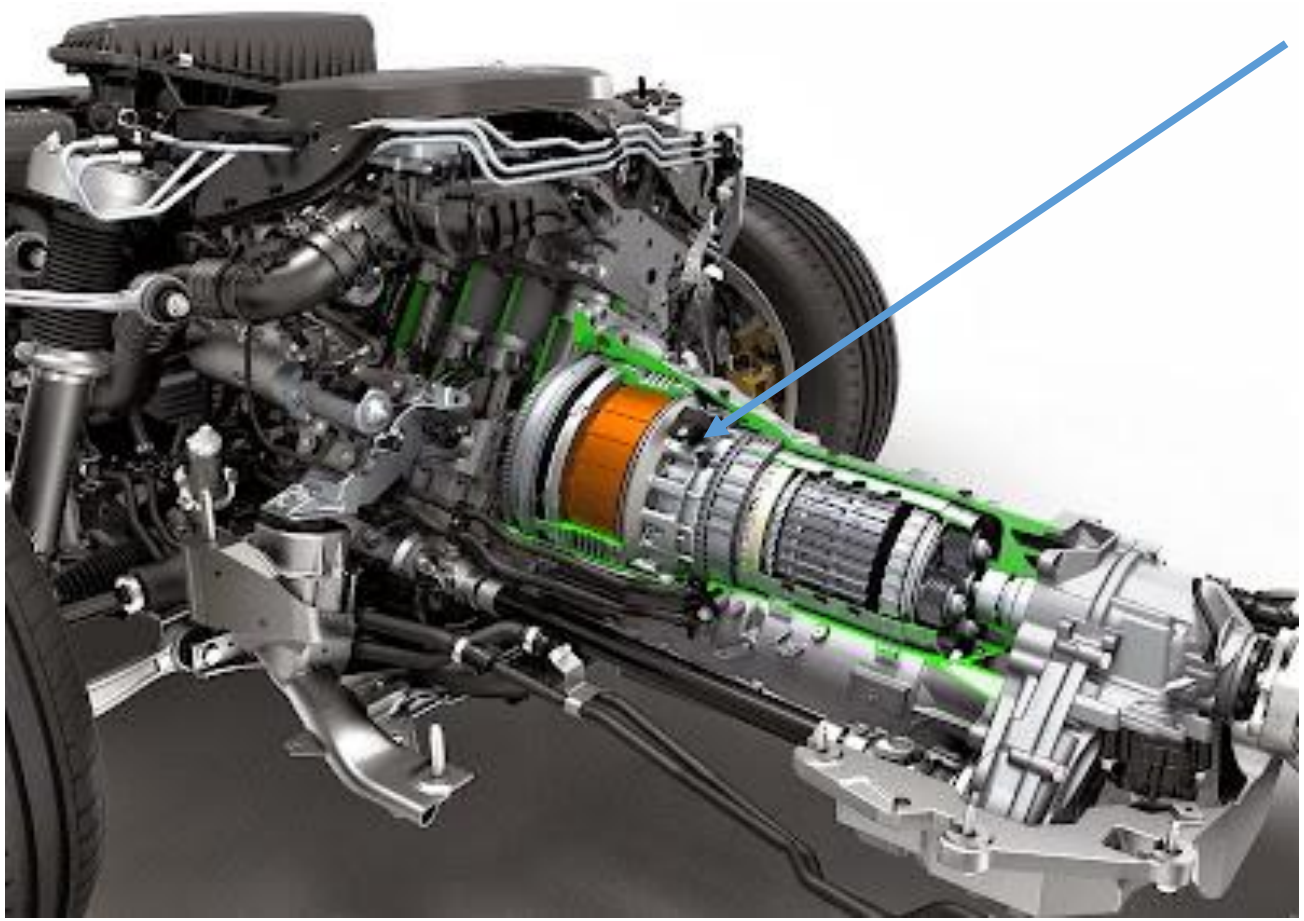
BMW X5 PHEV Power Train - Challenge To Efficiently Remove The Motor



Electric motor between ICE and transmission/gearbox.

Automotive Shredding - We need to develop the Black Box!

Automobile Dismantler

Reusable Parts

Reusable Fluids

Recyclable Materials

Non-Ferrous Metals

Ferrous Metals

Shredder

Scrap Auto Metal

Into NEW Products

Shredder "Fluff"

Separate NdFeB from ferrous scrap

?

Process into Nd, Pr, Dy oxides

Raw material input for NdFeB magnets

Summary or "What's Next?"

Government Intervention

Reduction of RE consumption

New/Expanding RE Sources/Supply Chains

New lower RE/non-RE Magnet Materials

New/Expanding Non-Chinese RE Projects

MP Materials – mine to magnet plans

Lynas Corporation – mine to separation

USA Rare Earth – mine to magnet plans

Energy Materials -Neo Performance Materials

Junior Miners

- ASM formerly Alkane Resources (Australia)
- Arafura Resources, Ltd (Australia)
- Rare Element Resources, Ltd. (USA)
- Leading Edge, formerly Tasman (Sweden)
- Mkango Resources (Malawi)
- Etc.

Novel separation/recycling technologies

- Medallion Resources
- Geomega
- Innovation Metals Corp.
- REECycle

> Neo Performance Materials And Energy Fuels Announce Joint Launch Of U.S.-European Rare Earth Production Initiative
>
> March 1, 2021
>
> *Separated Rare Earth Products Produced in Europe from U.S.-Sourced Feedstock is Expected to Strengthen and Diversify U.S. and European Rare Earth Supply Chains*

Summary

- Lots of private and governmental activities aimed at reestablishing a domestic RE magnet supply chain.
- Essential but MUST address the total supply chain including applications/devices.
- Market drivers are EV, Wind generators, Robotics, FA, Automotive and HVAC.
- Reduction of RE consumption – Is happening.
- New/Expanding RE Sources/Supply Chains – Is happening.
- Need solution for HREE supply-demand in balance.
- New lower RE/non-RE magnet materials – Very difficult to directly replace NdFeB but expect materials with niche applications to be introduced.
- Need economic solution to EOL magnet RECOVERY.
- Today China Does Control Market Prices At Each Key Step.

Thank you for your attention
Any Questions?

Dr. John Ormerod

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