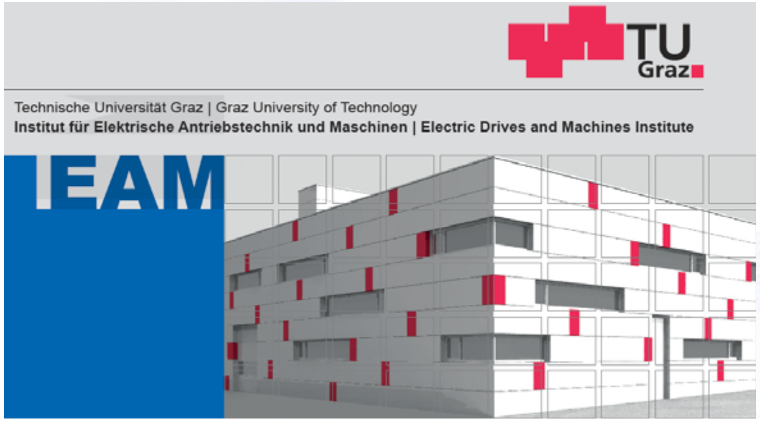
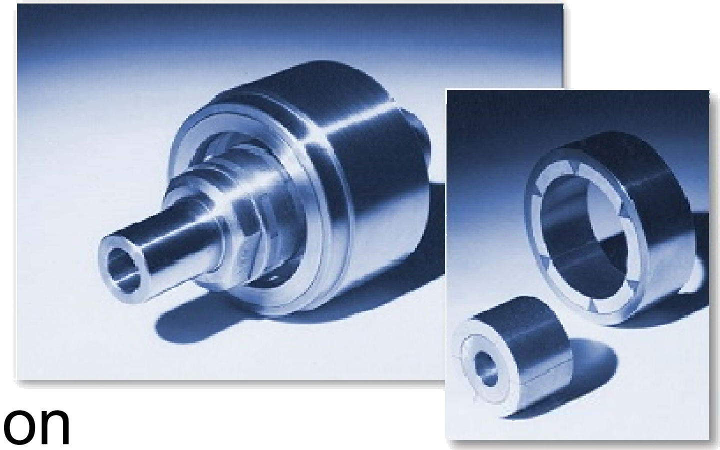
Material Matters

Steve Constantinides, Director of Technology
Arnold Magnetic Technologies Corporation
July 12, 2012



Arnold – What We Manufacture

- Magnet Production, Vertically Integrated
  - SmCo RECOMA® - (Lupfig, Switzerland; Rochester, NY; Ganzhou, China)
  - Alnico - (Marengo, IL)
  - Ferrite (Bonded) - (Marietta, OH; Norfolk, NE)
  - Injection Molded (Bonded) - (Shenzhen, China)
  - Electrical Steels - ARNON ® (Marengo, IL)
  - Electromagnets - (Ogallala, NE)

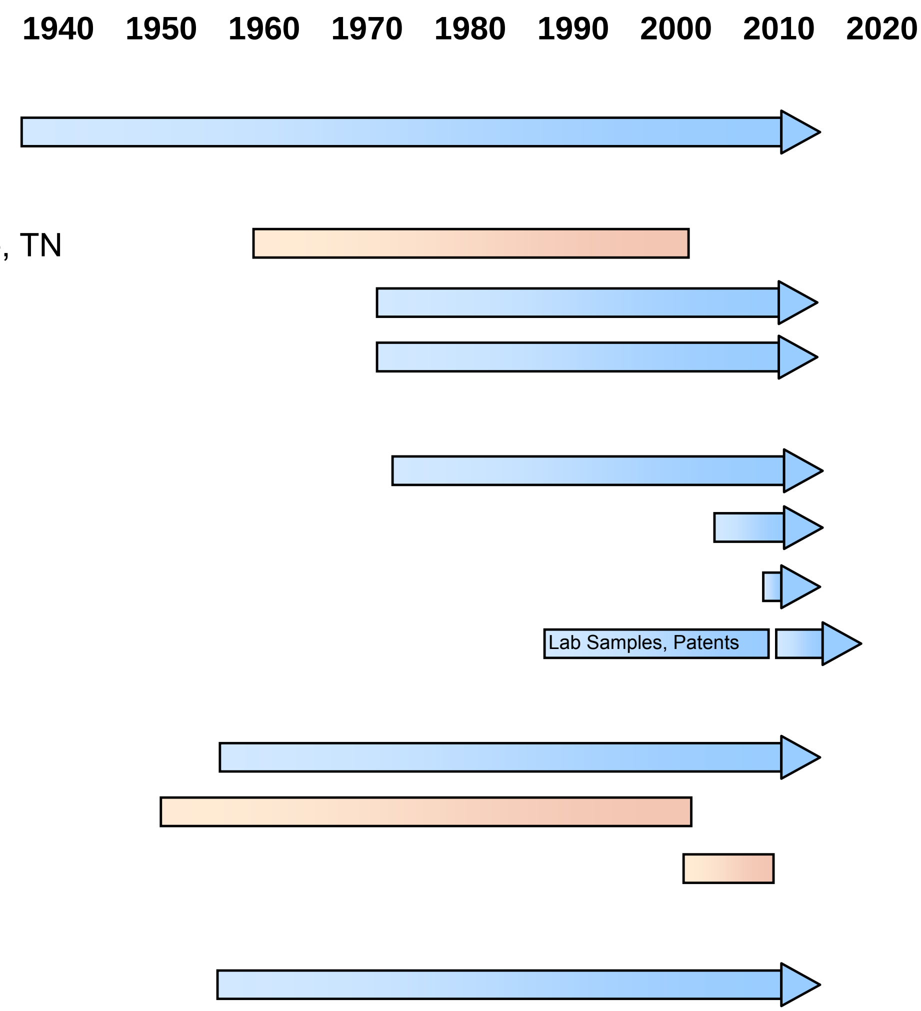


- Fabricated Magnets
  - Slice, grind, EDM
- Assemblies / Value Added Production
  - Precision assembly
    - Complex magnet and assembled shapes
    - Magnetized / unmagnetized assembly
    - High temperature and specialized adhesives
  - Rotor Balancing
  - Encapsulation / sleeving
  - Precision Machining Centers for Magnets AND Components

ARNOLD MAGNETIC TECHNOLOGIES

Arnold Material Knowledge Base

	Mfg Location
ALNICO	
Cast & Sintered alnico	Marengo, IL
FERRITE	
Ferrite (ceramic) magnets	Marengo, IL; Sevierville, TN
Bonded Ferrite	Marietta, OH
	Norfolk, NE
RARE EARTH MAGNETS	
SmCo 1:5 and 2:17	Lupfig, Switzerland
	Ganzhou, China
	Rochester, NY
NdFeB	TBD
SOFT MAGNETICS	
Si-Fe	Marengo, IL
Powder Core Products (Iron,	Marengo, IL
Ferrite, Sendust, Hi-Flux, MPP)	Shenzhen, PRC
ELECTROMAGNETS	
Beam focusing coils	Ogallala, NE



Agenda

- Setting the Picture
  - Energy & Electricity Production and Consumption
- Alternative Energy Production - Wind
- Energy Consumption in Motors
  - PM versus Induction versus Synchronous
  - Motor efficiency
- Motor Materials
  - The Rare Earth Dilemma
  - Prices
  - Availability
  - Alternative Materials and Research

Entropy

Energy

Effective Production

Efficient Use

There are no simple choices
- - only intelligent decisions.

Series of articles submitted by Caterpillar to National Geographic Magazine – 1970's.

Sources of Energy for Electricity Production

Non-renewable

- Oil
- Gas
- Coal / Peat
- Nuclear

Renewable

- Hydro
- Wind
- Bio Fuels and Waste
- Solar
- Geothermal
- Tidal / Wave

Energy Source Material Issues

- Efficiency of fuel extraction & production
  - Net energy balance
    - Example: Ethanol production
- Use of toxic or hazardous materials during exploration and production
  - Environmental impact
    - Example: use of toxic or carcinogenic ingredients in high volume hydro-fracking
- Disposal or storage of end-use by-products (waste)
    - Example: Storage of radioactive waste from nuclear plants
- “Side effects”
  - Affect on cost of other essential products
    - Example: use of corn for bio-fuel increases price of food and animal stocks dependent upon corn for feed
- Byproducts of use
    - Example: carbon dioxide or other noxious gases

Much information about clean energy

http://www.ucsusa.org/clean_energy/clean_energy_101/

ARNOLD
MAGNETIC TECHNOLOGIES

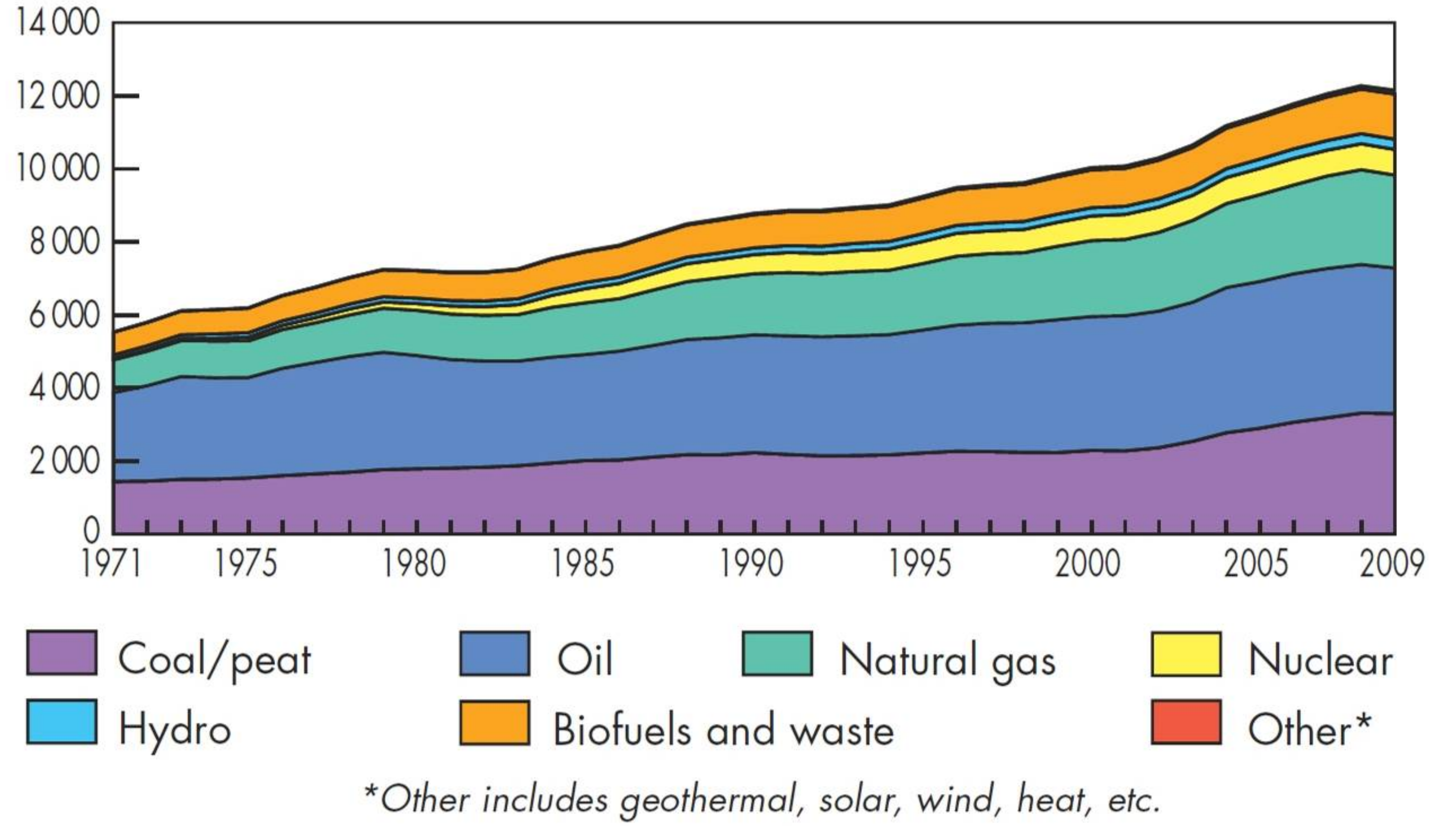
IEA - - The International Energy Agency

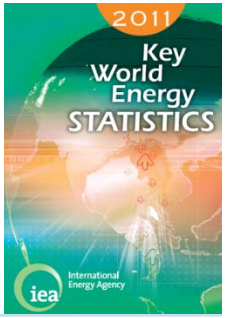
The International Energy Agency is a Paris-based autonomous intergovernmental organization established in the framework of the **Organization for Economic Co-operation and Development (OECD)** in 1974 in the wake of the 1973 oil crisis. The IEA was initially dedicated to responding to physical disruptions in the supply of oil, as well as serving as an information source on statistics about the international oil market and other energy sectors.

The IEA acts as a policy adviser to its member states, but also works with non-member countries, especially China, India and Russia. The Agency's mandate has broadened to focus on the "3Es" of sound energy policy: energy security, economic development, and environmental protection.[1] The latter has focused on mitigating climate change.[2] The IEA has a broad role in promoting alternate energy sources (including renewable energy), rational energy policies, and multinational energy technology co-operation.

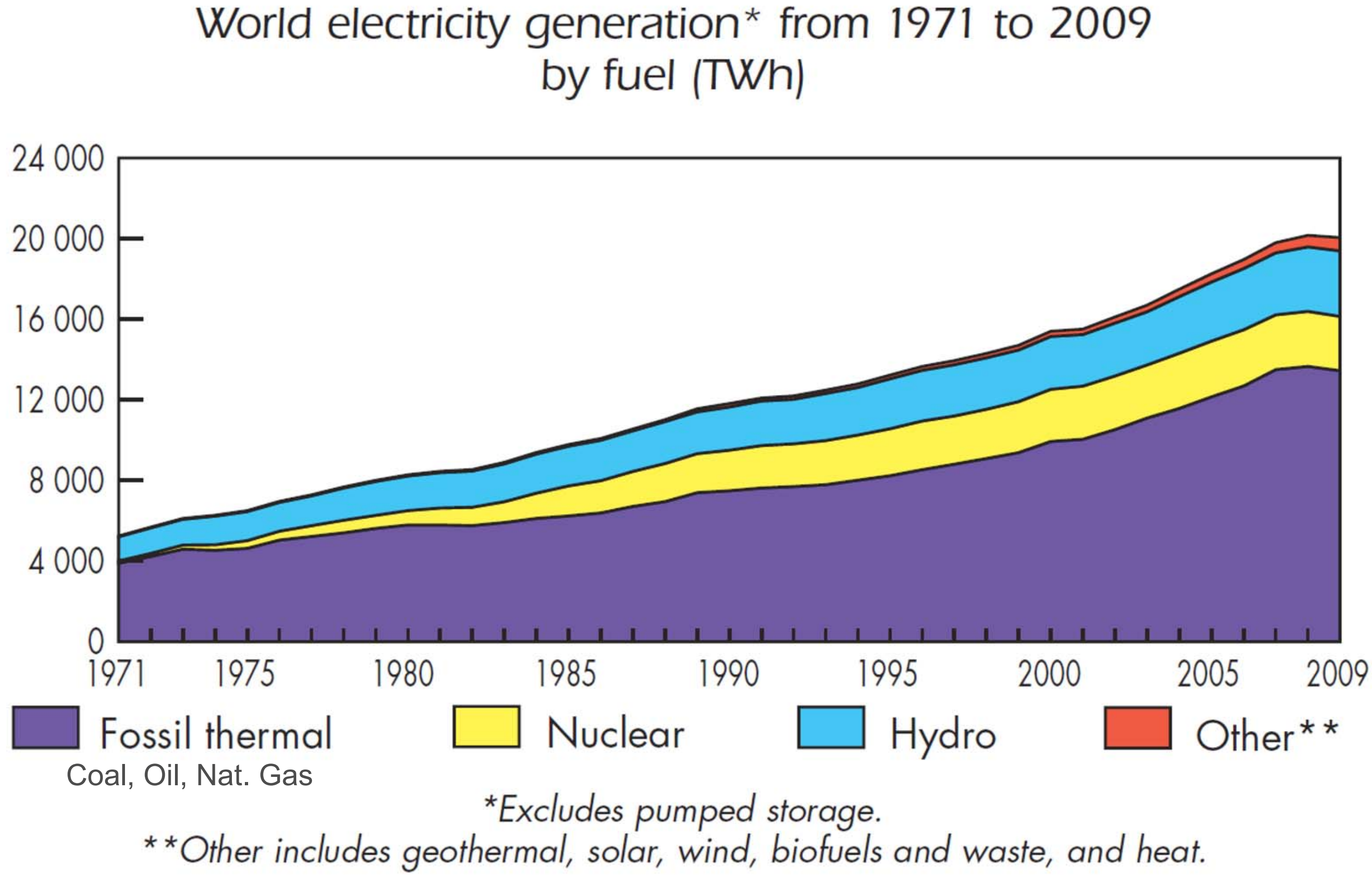
- Australia
- Austria
- Belgium
- Canada
- Czech Republic
- Denmark
- Finland
- France
- Germany
- Greece
- Hungary
- Ireland
- Italy
- Japan
- South Korea
- Luxembourg
- Netherlands
- New Zealand
- Norway
- Poland
- Portugal
- Slovakia
- Spain
- Sweden
- Switzerland
- Turkey
- United Kingdom
- United States

World Total Primary Energy Supply by Fuel

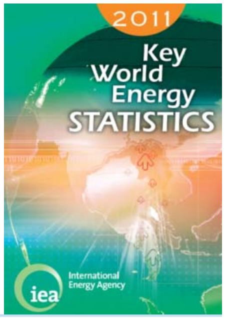




World Electric Generation



Coal, Oil, Nat. Gas



Fuel Used for Production of Electricity

2009

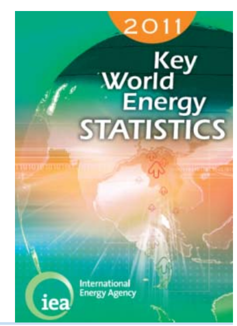
Coal/peat	TWh
People's Rep. of China	2 913
United States	1 893
India	617
Japan	279
Germany	257
South Africa	232
Korea	209
Australia	203
Russian Federation	164
Poland	135
Rest of the world	1 217
World	8 119

3 313

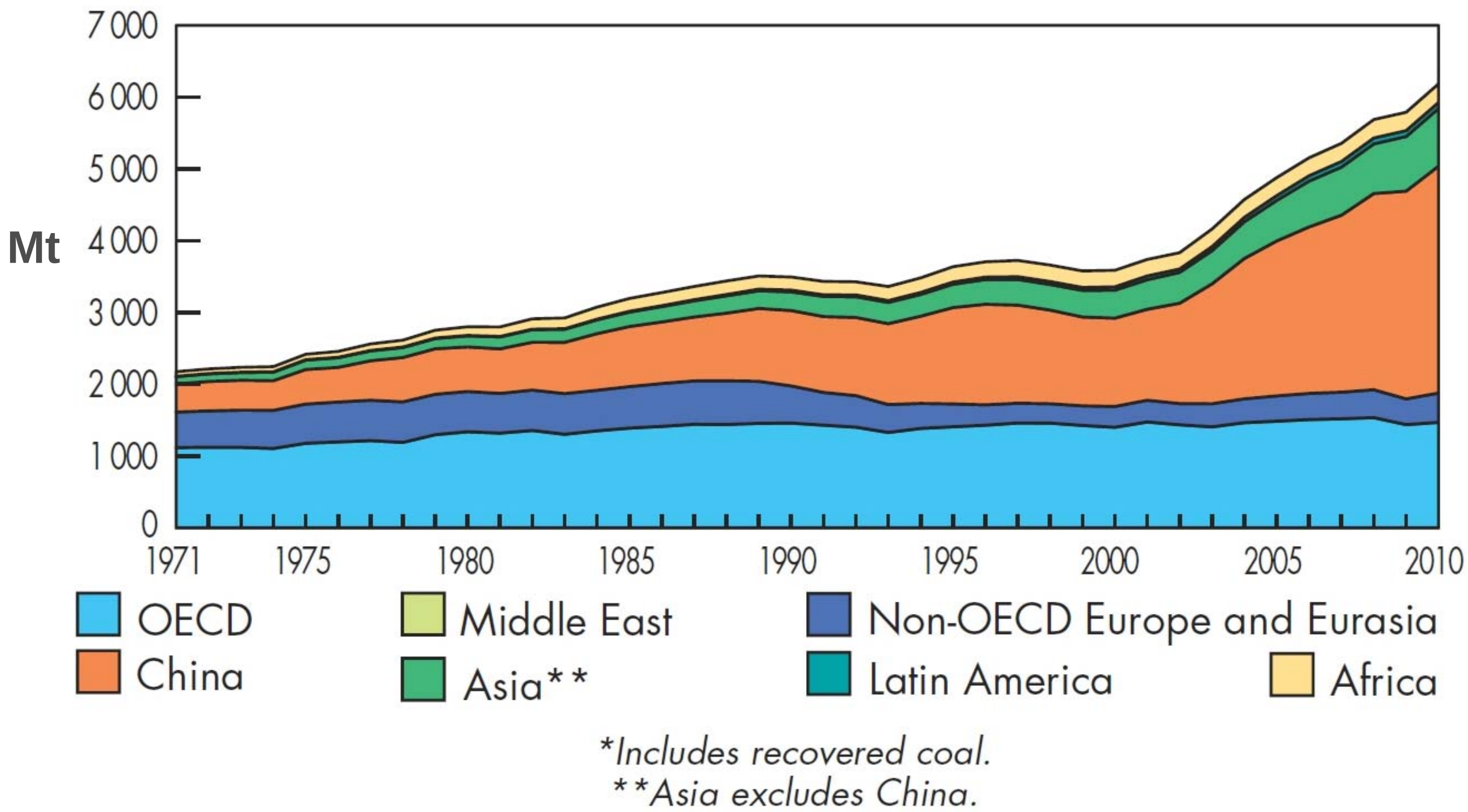
Oil	TWh
Saudi Arabia	120
Japan	92
Islamic Rep. of Iran	52
United States	50
Mexico	46
Iraq	43
Kuwait	38
Pakistan	36
Indonesia	35
Egypt	30
Rest of the world	485
World	1 027

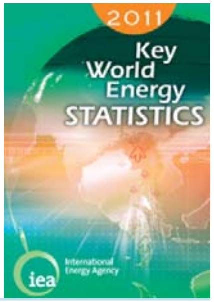
Natural gas	TWh
United States	950
Russian Federation	469
Japan	285
United Kingdom	165
Italy	147
Islamic Rep. of Iran	143
Mexico	138
India	111
Spain	107
Thailand	105
Rest of the world	1 681
World	4 301

We use the fuels which are available to us

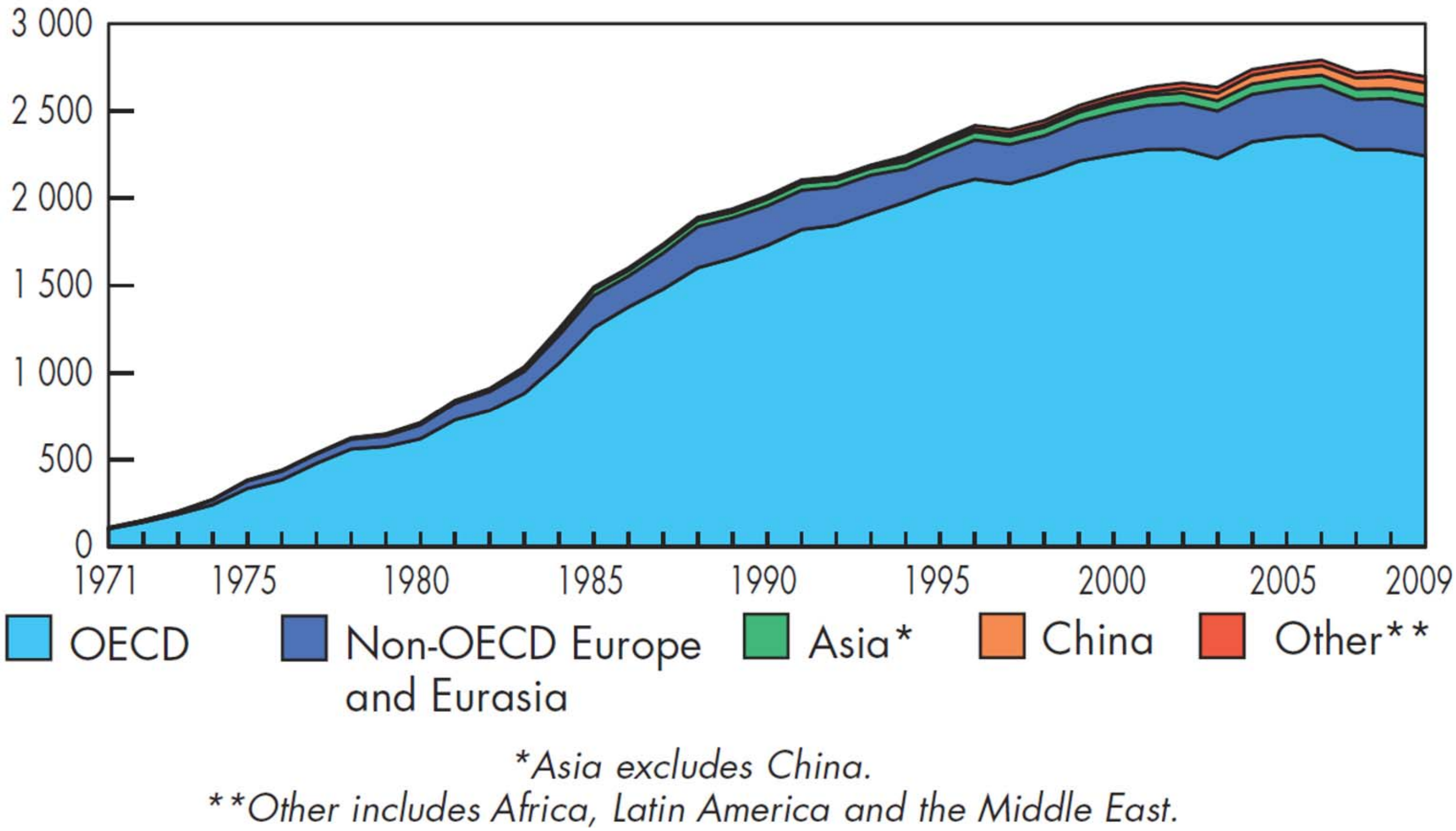


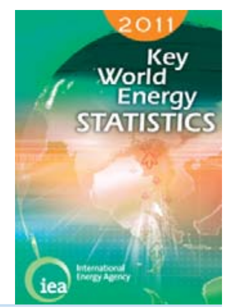
Hard Coal Production by Region



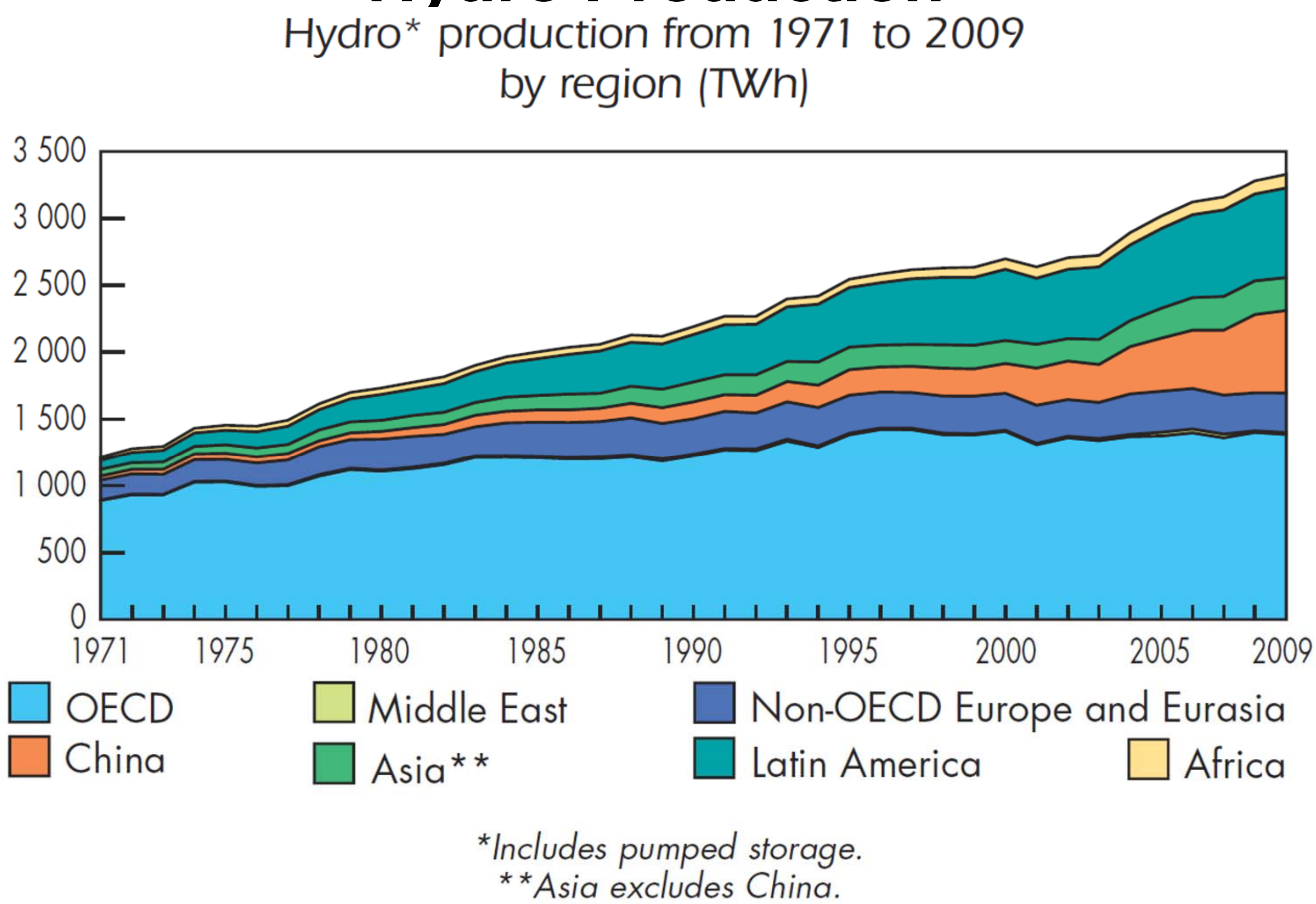


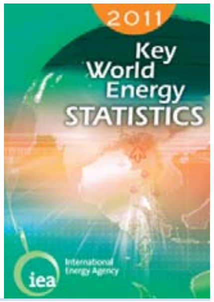
Nuclear Production of Electric Energy





Hydro Production





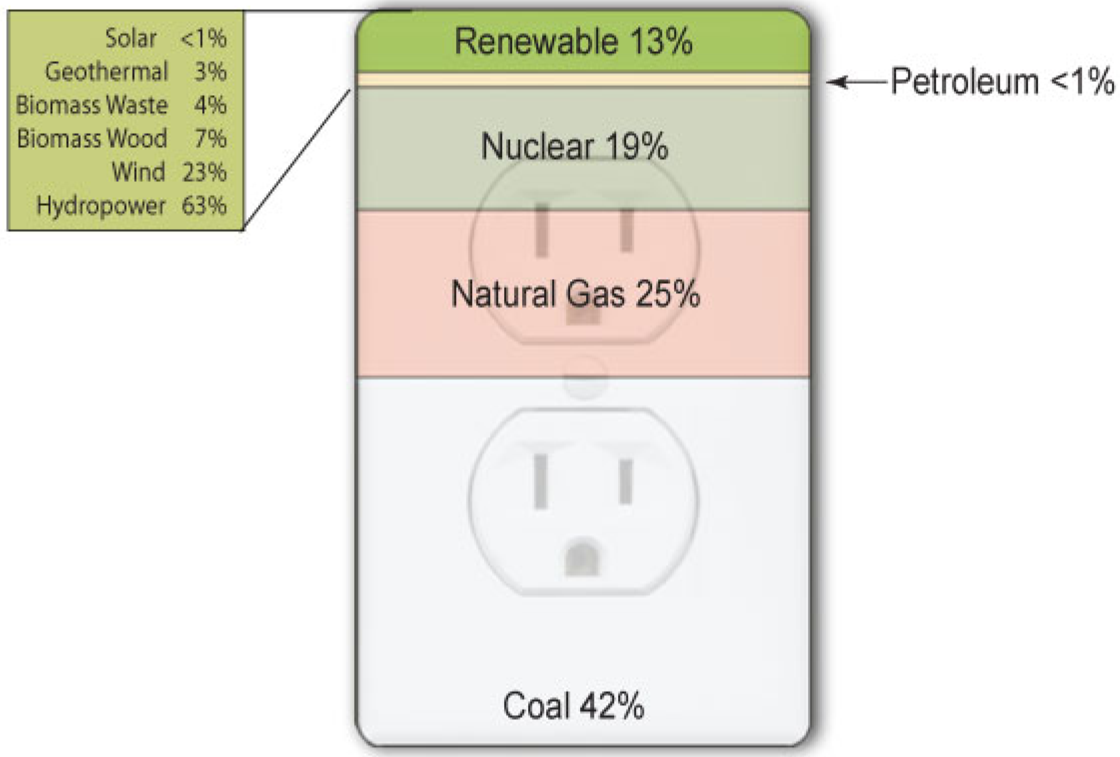
Energy Information Administration

The U.S. Energy Information Administration (**EIA**) is the statistical and analytical agency within the U.S. Department of Energy (**DOE**). EIA collects, analyzes, and disseminates independent and impartial energy information to promote sound policymaking, efficient markets, and public understanding of energy and its interaction with the economy and the environment.

EIA is the Nation's premier source of energy information and, by law, its data, analyses, and forecasts are independent of approval by any other officer or employee of the United States government.

The Department of Energy Organization Act of 1977 established EIA as the primary federal government authority on energy statistics and analysis, building upon systems and organizations first established in 1974 following the oil market disruption of 1973.

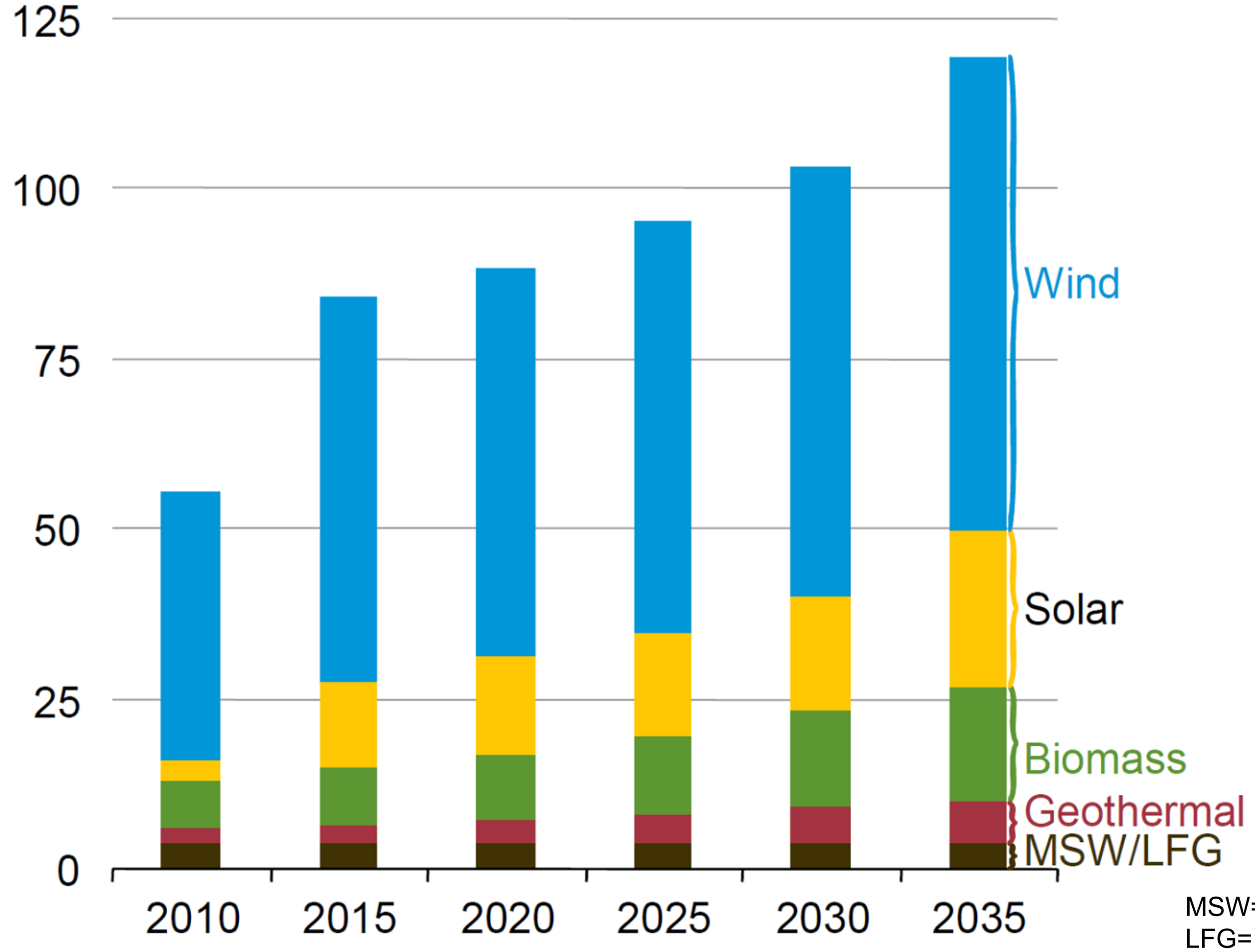
U.S. Sources of Electricity Generation, 2011



Note: Includes utility-scale generation only. Excludes most customer-sited generation, for example, residential and commercial rooftop solar installations

Source: U.S. Energy Information Administration, *Electric Power Monthly* (March 2012). Percentages based on Table 1.1, preliminary 2011 data.

U.S. Non-hydropower renewable electricity generating capacity by energy source, including end-use capacity, 2010-2035 (gigawatts)



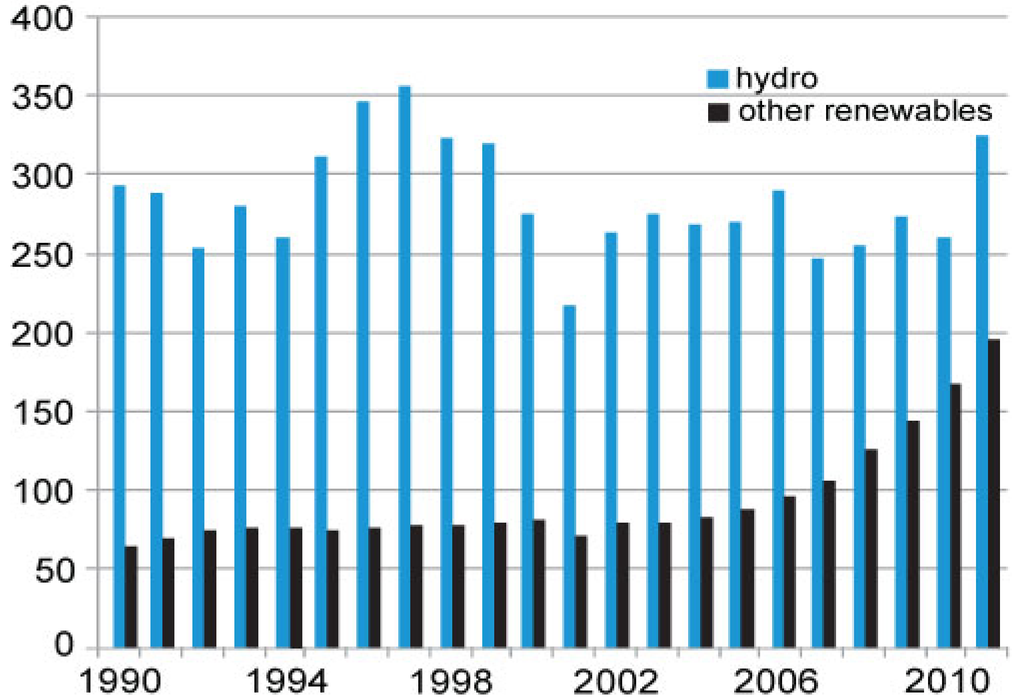
MSW= Municipal Solid Waste
LFG= Land Fill Gas

U.S. Energy Information Administration, Annual Energy Outlook 2012, page 90

ARNOLD MAGNETIC TECHNOLOGIES

U.S. Hydropower and Other Renewable Electricity Generation, 1990-2011

million megawatthours

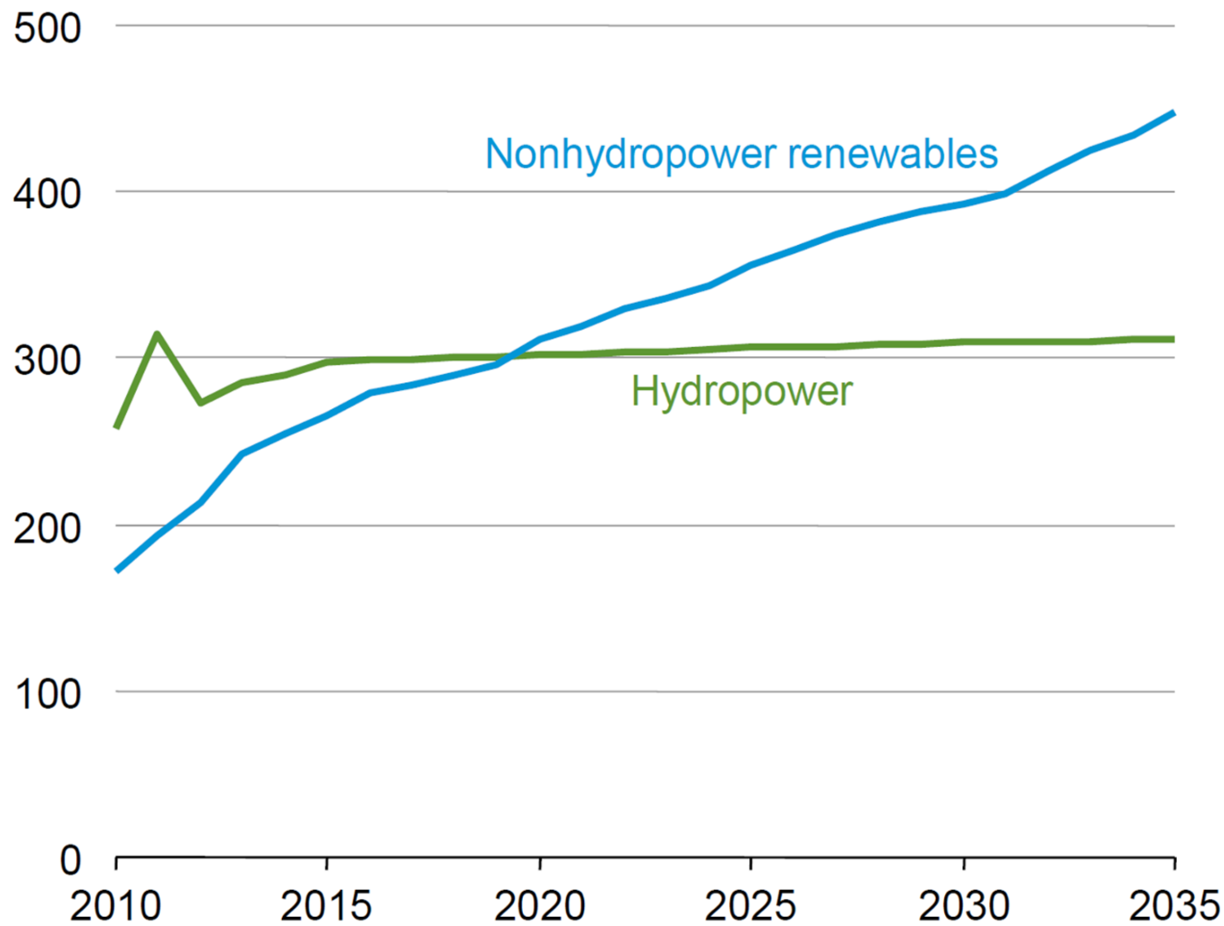


Source: U.S. Energy Information Administration, *Electric Power Annual and Electric Power Monthly* (March 2012) based on preliminary 2011 data.

eia Independent Statistics & Analysis U.S. Energy Information Administration

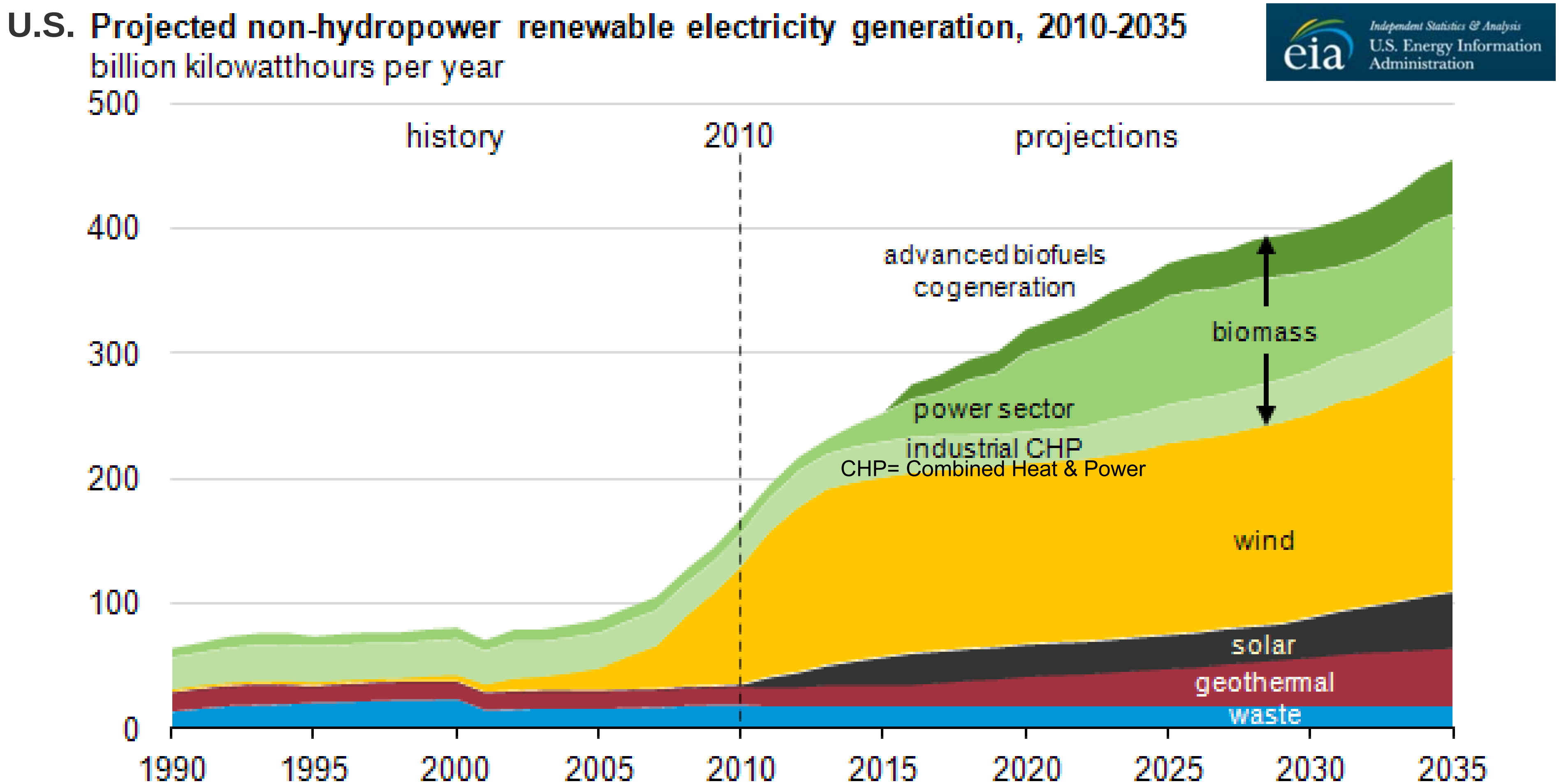
ARNOLD MAGNETIC TECHNOLOGIES

Hydropower and other renewable electricity generation, including end-use generation, 2010-2035 (billion kilowatt-hours)



U.S. Energy Information Administration, Annual Energy Outlook 2012, page 90

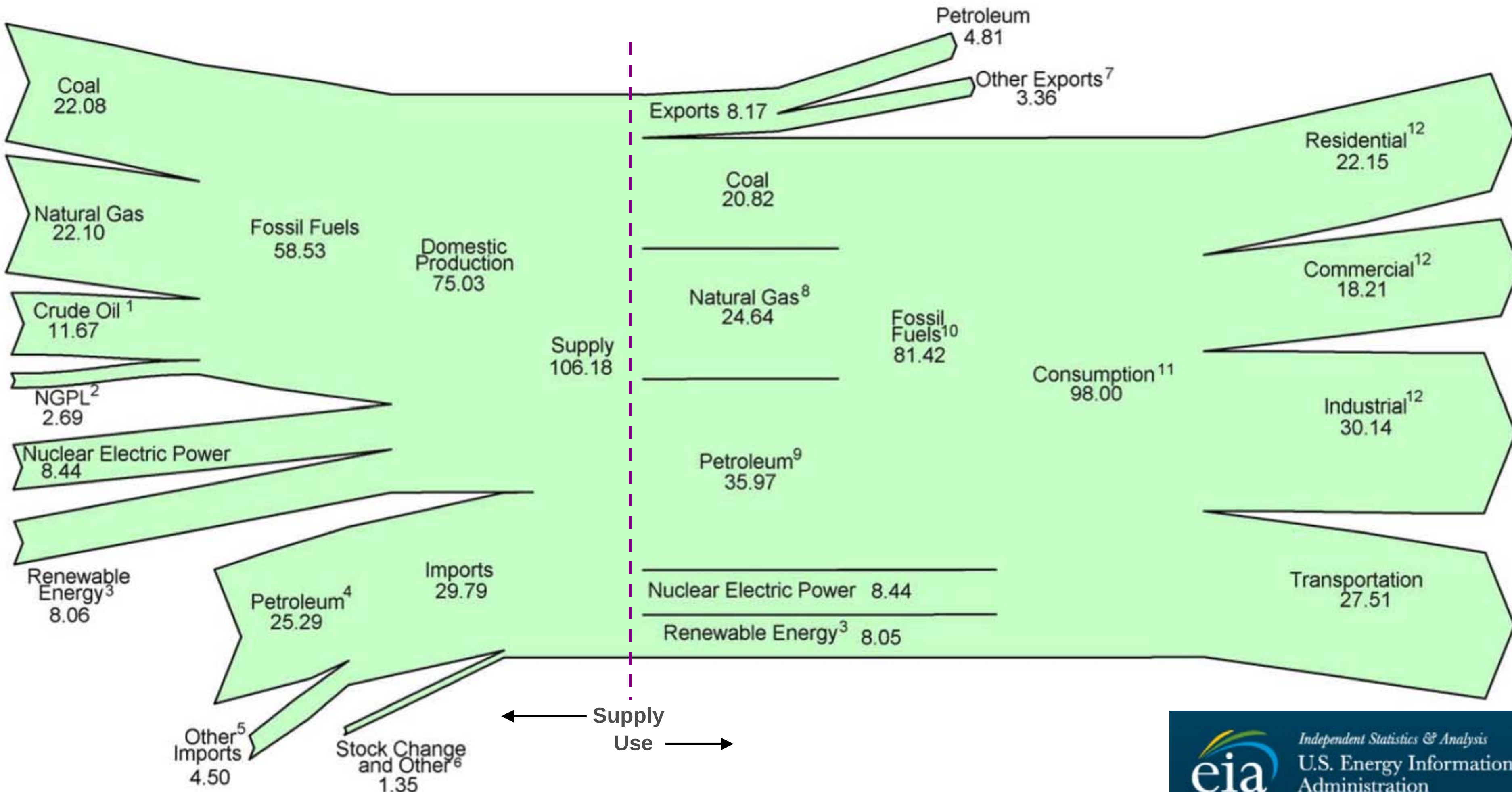
eia Independent Statistics & Analysis U.S. Energy Information Administration



http://205.254.135.7/todayinenergy/detail.cfm?id=5170

Energy Flow, 2010 (quadrillion btu)

Sankey Diagram



Notes to chart: Energy Flow

[1] Includes lease condensate.
[2] Natural gas plant liquids.
[3] Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic, and wind.
[4] Crude oil and petroleum products. Includes imports into the Strategic Petroleum Reserve.
[5] Natural gas, coal, coal coke, biofuels, and electricity.
[6] Adjustments, losses, and unaccounted for.
[7] Coal, natural gas, coal coke, electricity, and biofuels.
[8] Natural gas only; excludes supplemental gaseous fuels.
[9] Petroleum products, including natural gas plant liquids, and crude oil burned as fuel.
[10] Includes 0.01 quadrillion Btu of coal coke net exports.
[11] Includes 0.09 quadrillion Btu of electricity net imports.
[12] Total energy consumption, which is the sum of primary energy consumption, electricity retail sales, and electrical system energy losses. Losses are allocated to the end-use sectors in proportion to each sector's share of total electricity retail sales. See Note, "Electrical Systems Energy Losses," at end of Section 2.

Notes: • Data are preliminary. • Values are derived from source data prior to rounding for publication. • Totals may not equal sum of components due to independent rounding.

Sources: Tables 1.1, 1.2, 1.3, 1.4, and 2.1a.

U.S. Energy Information Administration / Annual Energy Review 2010

Independent Statistics & Analysis
eia U.S. Energy Information Administration

ARNOLD MAGNETIC TECHNOLOGIES

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- Motor Materials
  - The Rare Earth Dilemma
  - Prices
  - Availability
  - Alternative Materials and Research

ARNOLD MAGNETIC TECHNOLOGIES

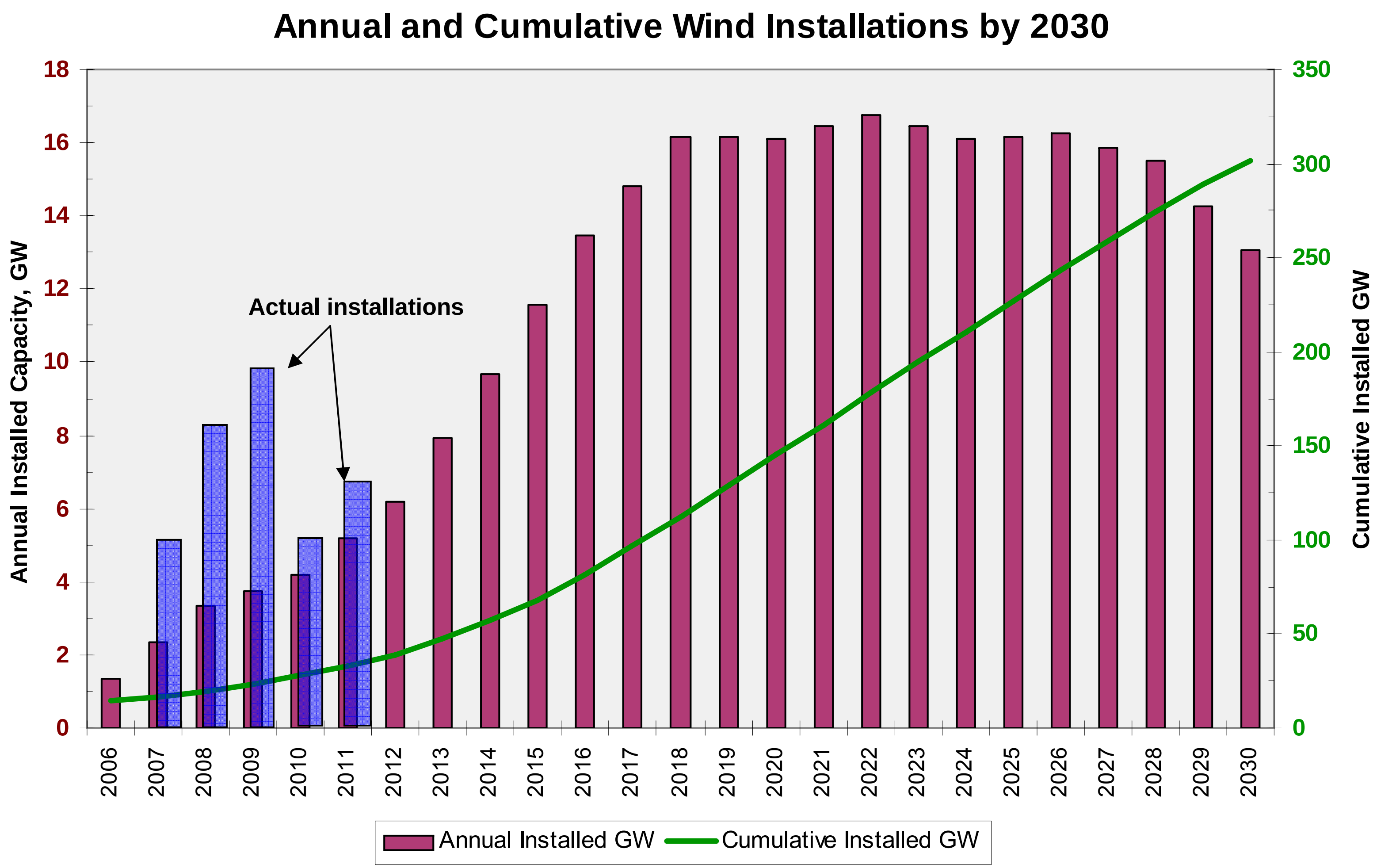
Major Developing Uses for Permanent Magnets

competing for limited resources

- Wind energy
- Transportation
  - Mild hybrids
  - HEV, PHEV
  - EV
  - Electric Bikes
- Consumer goods
  - Air conditioning
  - High efficiency heating (fan motors)
  - Portable hand tools
- Aerospace and military
  - “Drive-by-wire”
  - In wheel traction drives

Wind Power

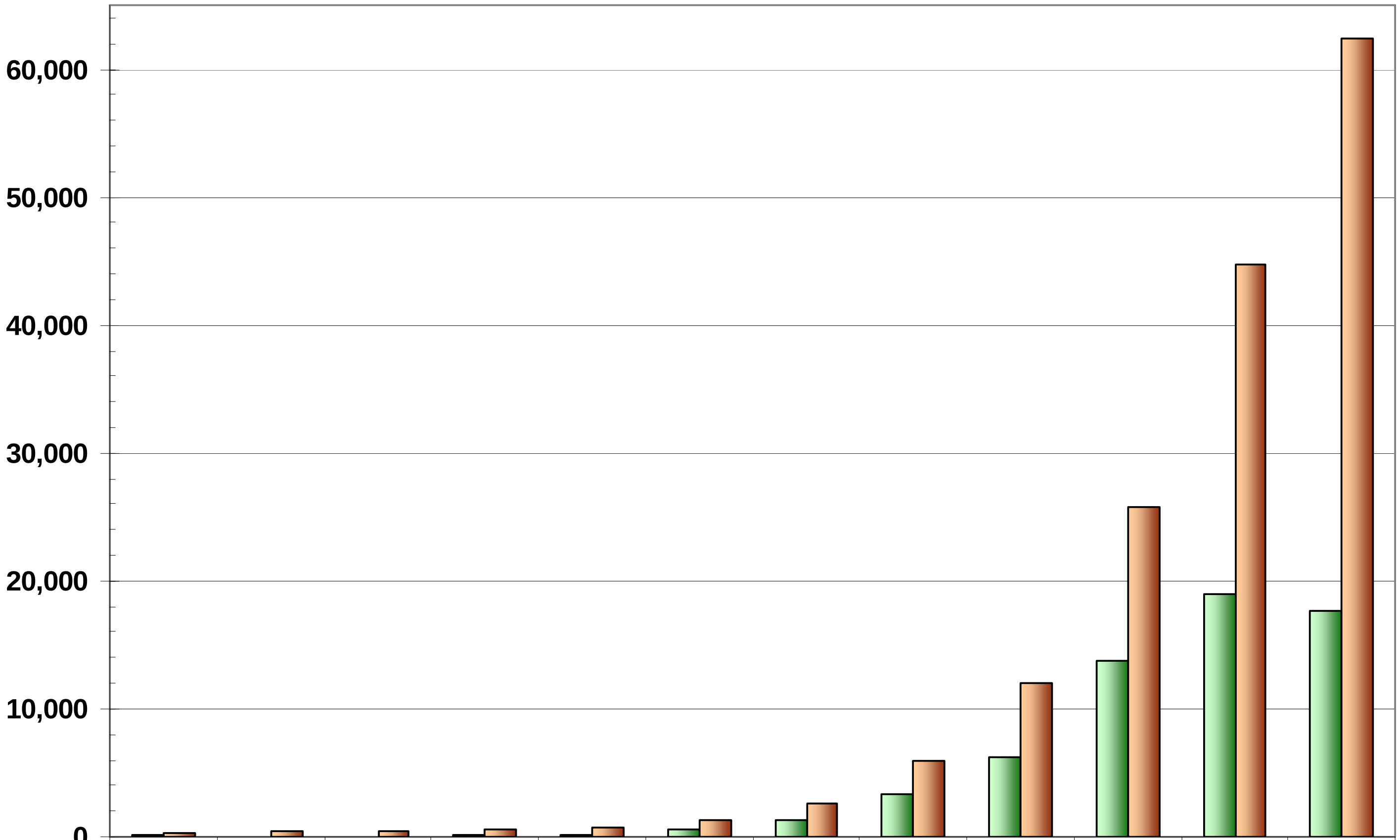
Wind Power Installation - USA



20% Wind Energy by 2030, Increasing Wind Energy's Contribution to U.S. Electricity Supply, AWEA, May 2008

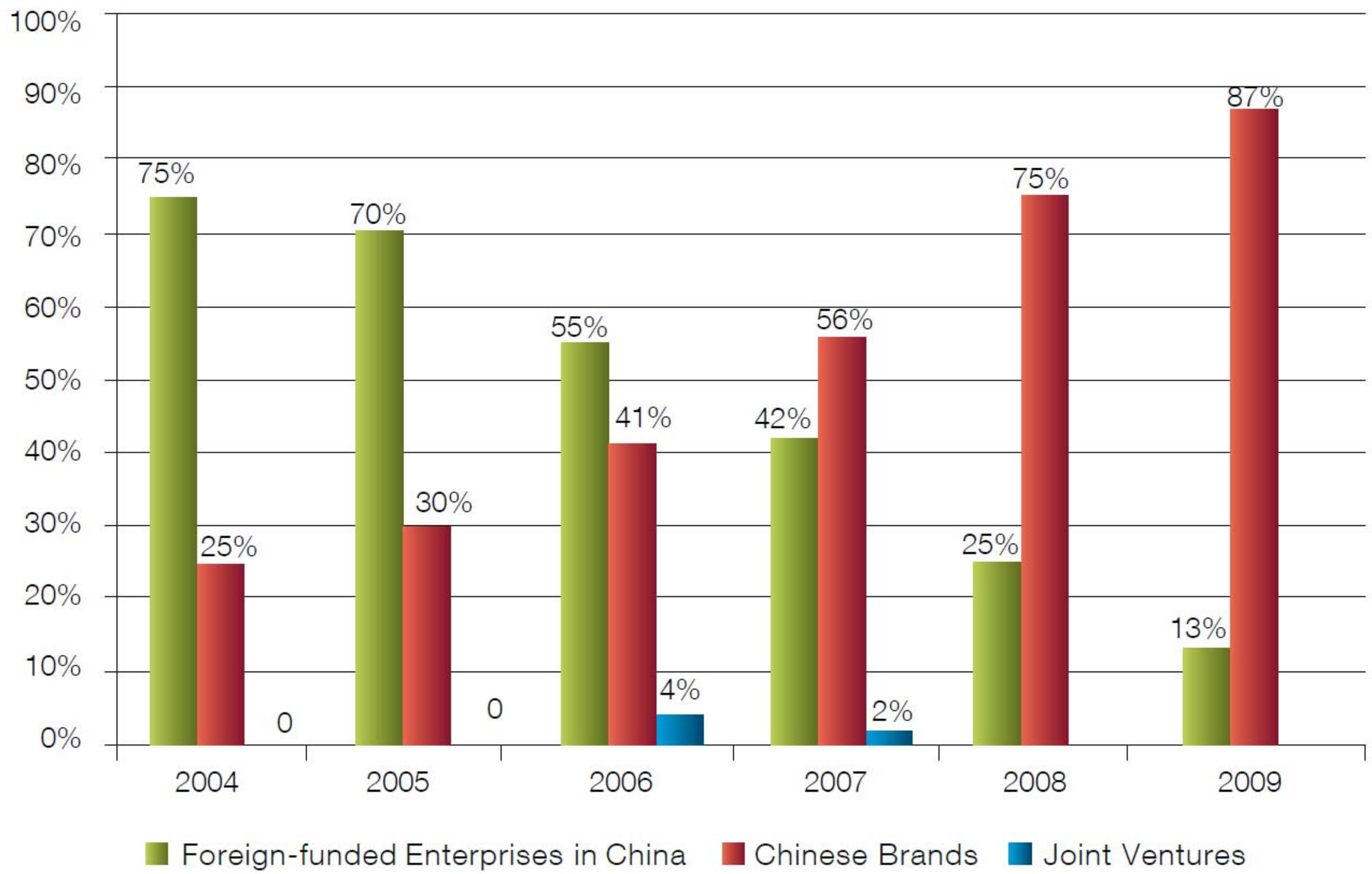
Growth of Wind Power in China

Sources:
CREIA 2010
GWEC 2011

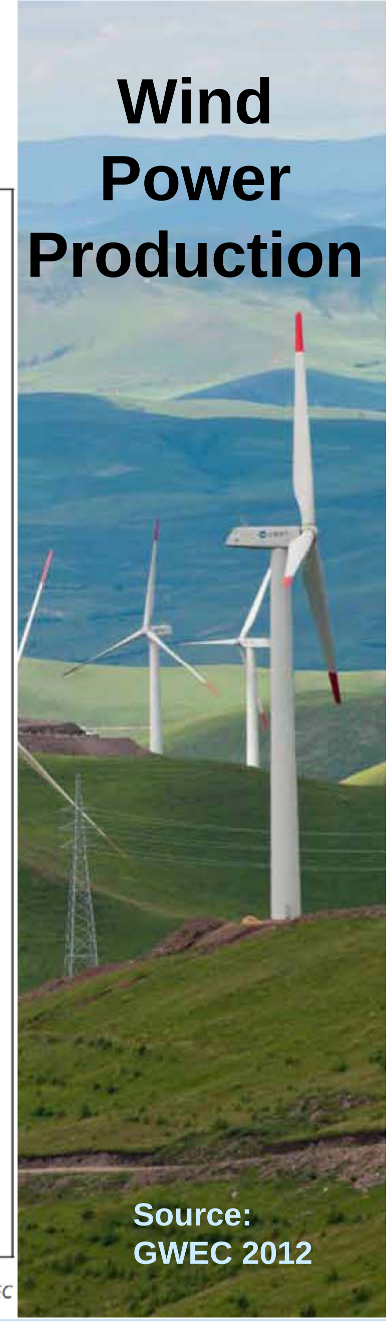


	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Newly Installed Capacity (MW)	73.3	52.7	66.3	98.3	196.8	506.9	1287.6	3311.3	6153.7	13803.3	18928	17631
Cumulative Installed Capacity (MW)	341.6	403.5	469.8	568.1	764.9	1271.8	2559.4	5870.7	12024.4	25827.7	44733	62364

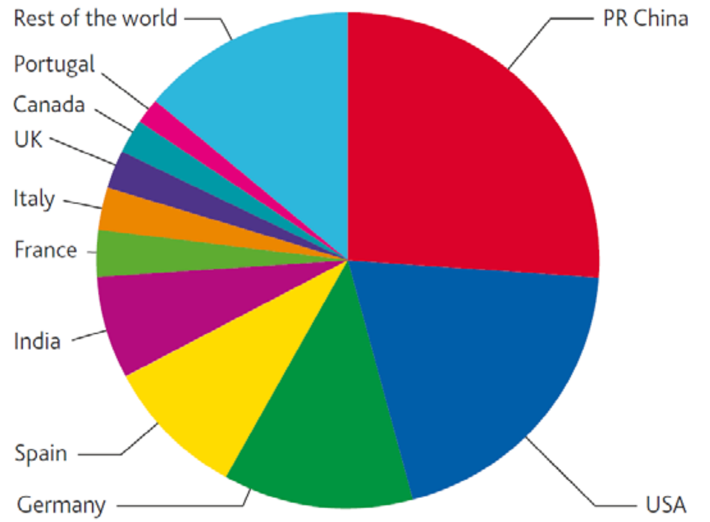
Newly Installed Capacity Market Share between Domestic and Foreign Companies in the Chinese Wind Power Market



ARNOLD MAGNETIC TECHNOLOGIES



Top 10 cumulative capacity Dec 2011

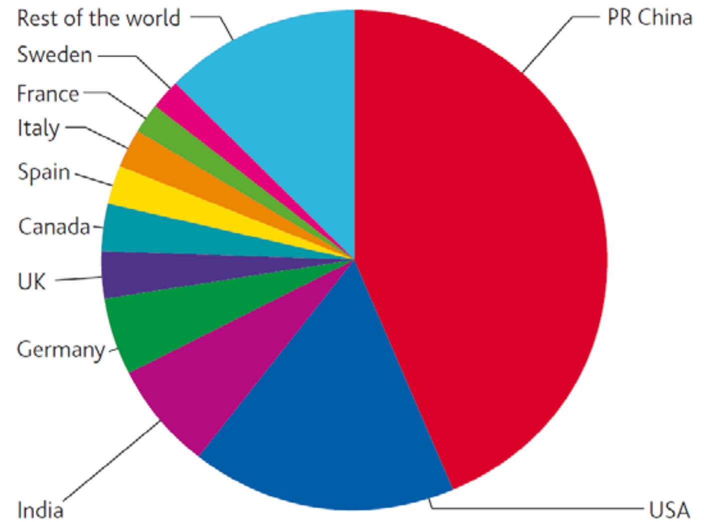


Country	MW	% SHARE
PR China	62,364	26.2
USA	46,919	19.7
Germany	29,060	12.2
Spain	21,674	9.1
India	16,084	6.8
France**	6,800	2.9
Italy	6,737	2.8
UK	6,540	2.7
Canada	5,265	2.2
Portugal	4,083	1.7
Rest of the world	32,143	13.5
Total TOP 10	205,526	86.5
World Total	**237,669**	**100.0**

*** Provisional Figure*

Source: GWEC

Top 10 new installed capacity Jan-Dec 2011



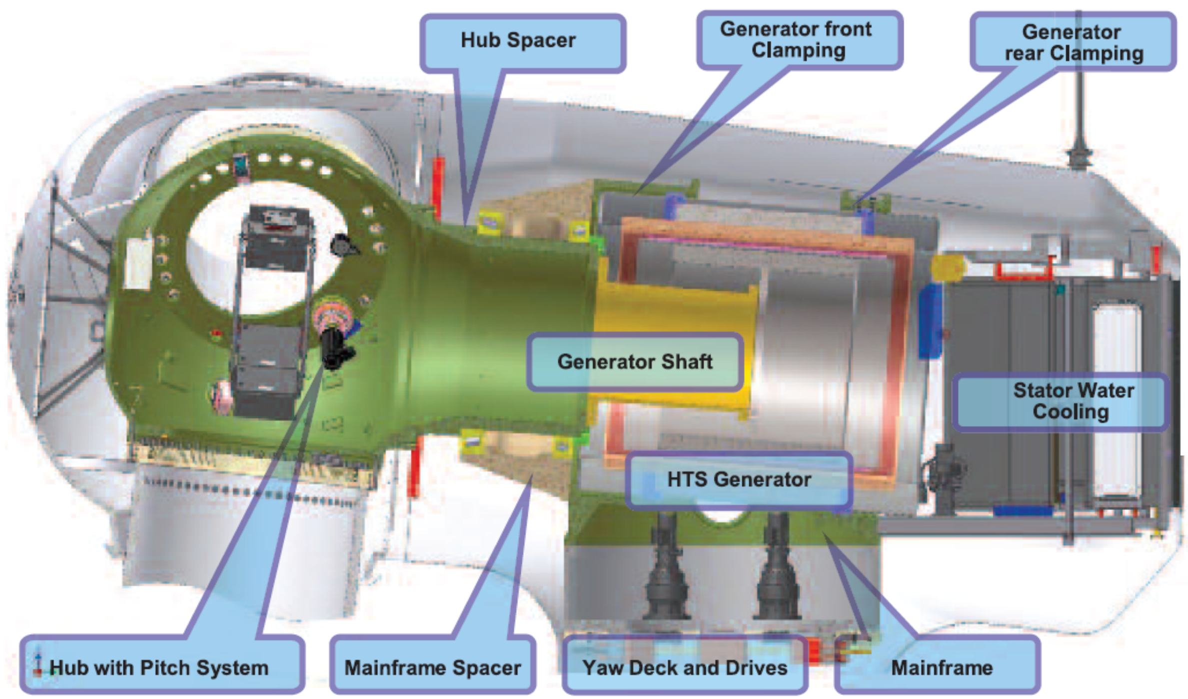
Country	MW	% SHARE
PR China	17,631	43
USA	6,810	17
India	3,019	7
Germany	2,086	5
UK	1,293	3.2
Canada	1,267	3.1
Spain	1,050	2.6
Italy	950	2.3
France**	830	2.0
Sweden	763	1.9
Rest of the world	4,865	12.0
Total TOP 10	35,699	88
World Total	**40,564**	**100.0**

*** Provisional Figure*

Source: GWEC

Wind Technology

The SeaTitan™ Turbine

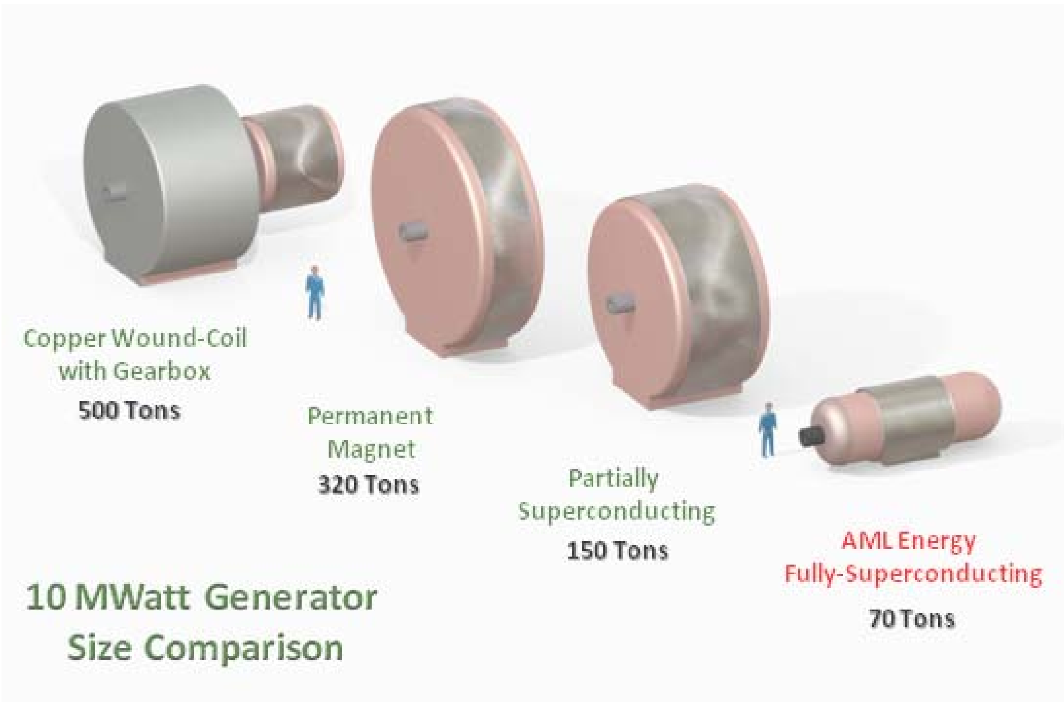


Technical Data (Preliminary)

Rated Power:	10 MW
Rotor Diameter:	190m
Number of blades:	3
Tower height:	125m
Type Class:	TC IB Offshore according to GL Offshore rules
Cut in wind speed:	4m/s
Rated wind speed:	11.5m/s
Cut out wind speed:	30m/s
Ambient survival temp.:	-20 to 50°C
Ambient temp in operation:	-10 to 40°C
Rated speed:	10 RPM
Power control method:	Blade pitching
Position relative to tower:	Upwind

American Superconductor, Sea Titan, superconducting 10 MW generator

Superconducting Wind Power Generation



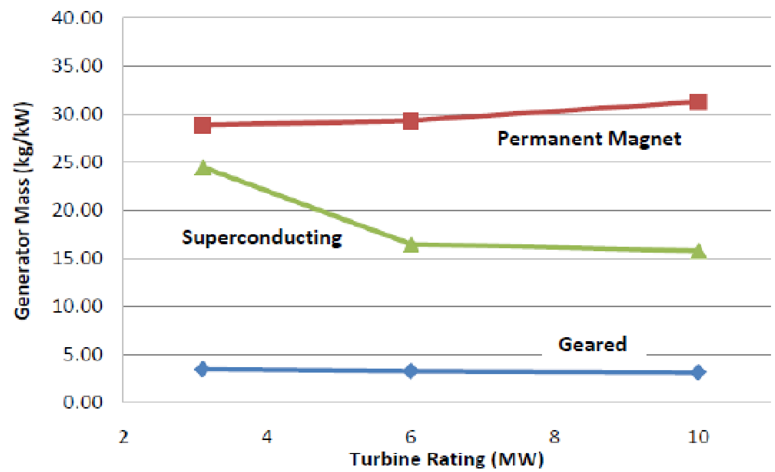
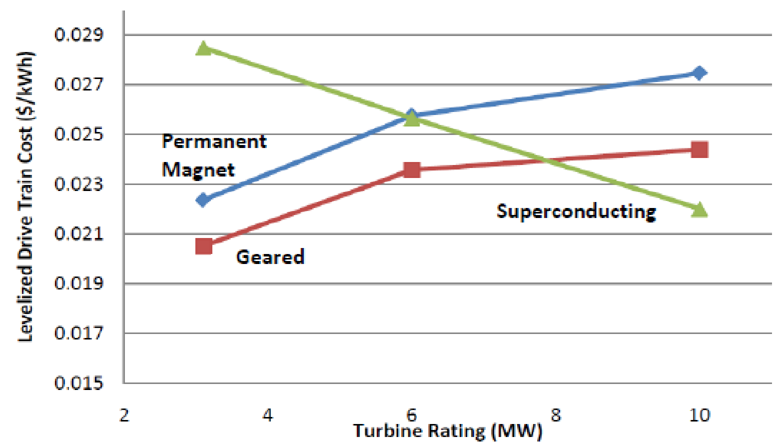


Figure 4a: Wind turbine generator mass for various generator technologies



REACT: Rare Earth Alternatives for Critical Technologies
Mark Johnson, January 10, 2012

ARNOLD MAGNETIC TECHNOLOGIES

Wind Technology Focus

Large Scale Commercial Wind Power

Generator Output in megawatts

< 1.5 MW **10 MW >**

Generator Design	Generator rpm	
Induction No permanent magnets	1800+ rpm	**Land-based** **Older Technology** **China, US, Europe**
Half-speed 165 - 225 kg neo magnets per MW	~800 rpm	**Land or Offshore** **Newest Technology** **US and Europe**
Direct Drive 500 - 650 kg neo magnets per MW	10-12 rpm	**Mostly Offshore** **Newer Technology** **US, Europe**

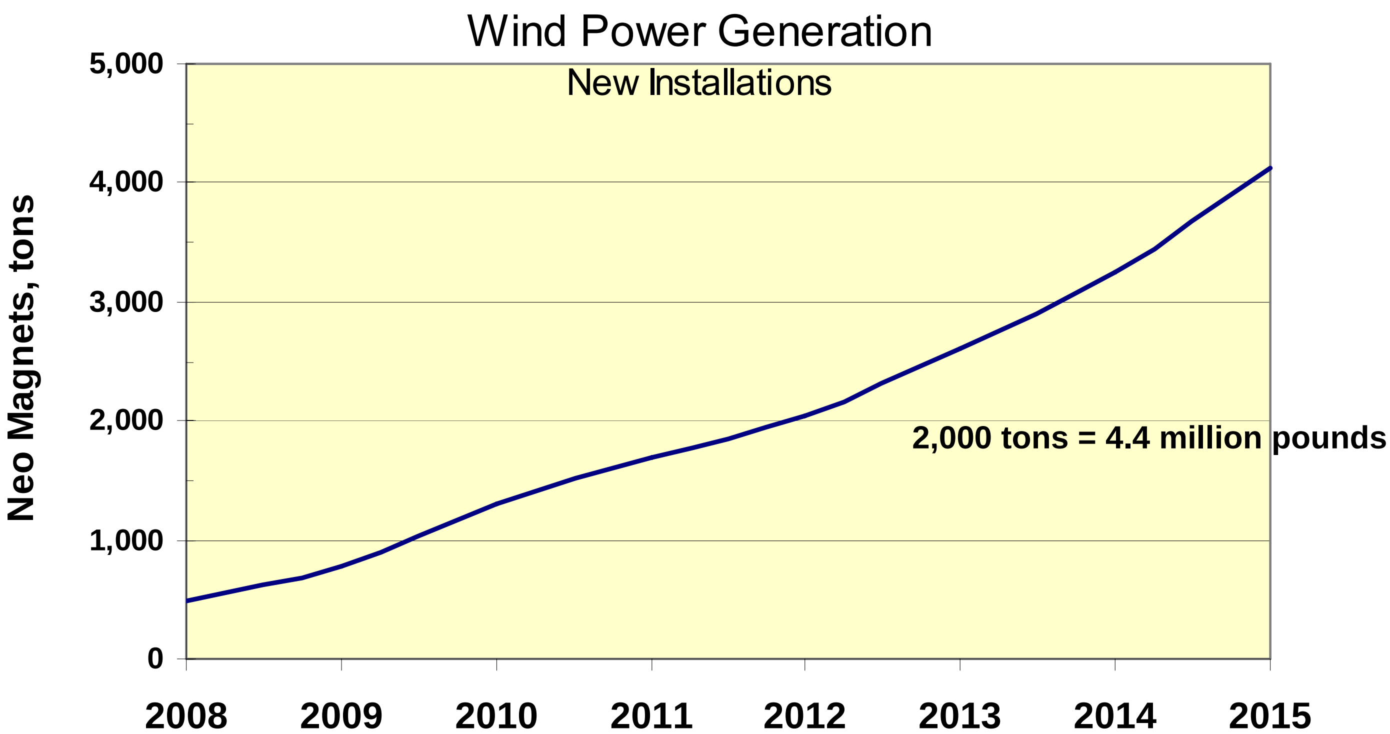
Superconducting Generators ??

Wind Power Requirements for Rare Earths

	2010				2020			
Country	**Installed MW**	**% PM Generators**	**Average kg neo per MW**	**Tons Neo Magnets required**	**Installed MW**	**% PM Generators**	**Average kg neo per MW**	**Tons Neo Magnets required**
China	18,928	25%	600	2,839	10,000	50%	400	2,000
USA	5,115	5%	600	153	15,000	50%	400	3,000
India	2,139	3%	600	39	5,000	10%	400	200
Spain	1,516	3%	600	27	3,000	20%	400	240
Germany	1,493	3%	600	27	1,500	20%	400	120
France	1,086	3%	600	20	1,500	15%	400	90
UK	962	3%	600	17	1,000	15%	400	60
Italy	948	3%	600	17	800	15%	400	48
Canada	690	3%	600	12	800	20%	400	64
Sweden	604	5%	600	18	500	20%	400	40
Rest of World	4,785	3%	600	86	15,000	15%	400	900
Total	**38,265**			**3,255**	**54,100**			**6,760**
Dysprosium requirement at 4.1 weight %				**133**				**277**
Neodymium requirement at 27.5 weight %				**895**				**1,859**

Data sources include: GWEC and China Wind Power 2010

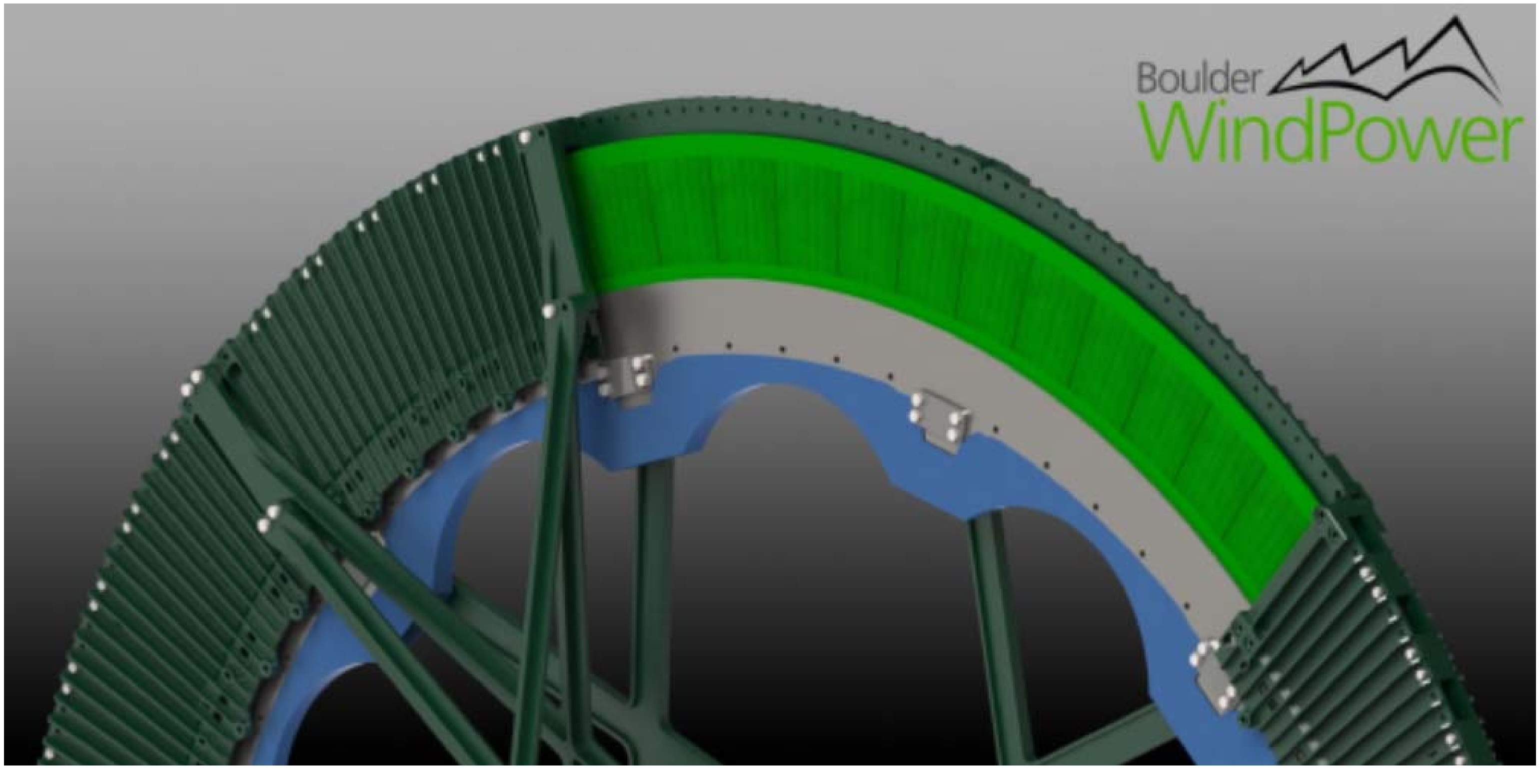
Neo Magnets Required for Wind Power



Data represents a combination of direct and hybrid drives and reflects slower market penetration due to uncertainty about the availability of neo magnets.

Boulder Wind Power

Axial gap, air core, permanent magnet direct drive generator



www.boulderwindpower.com/the-bwp-generator/overview/

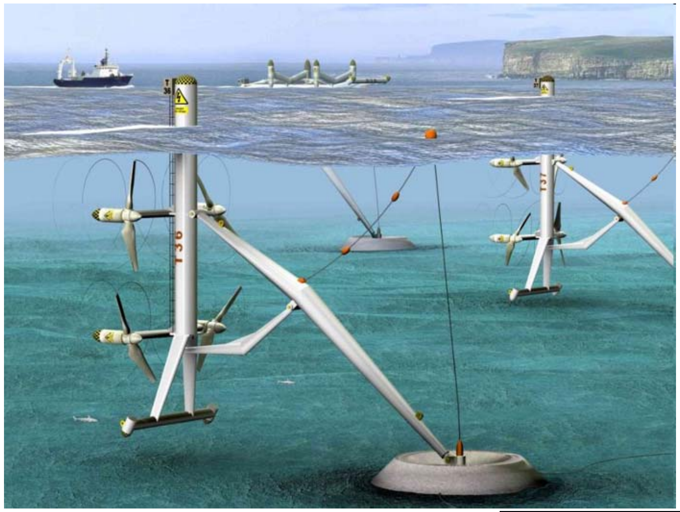
ARNOLD MAGNETIC TECHNOLOGIES

Wind Power - Summary

- Use of wind power is continuing to grow
  - Somewhat slowed due to expiration of government stimulus funding
- Gen-4 designs use permanent magnets to avoid gear box issues
  - Lower cost and weight
  - Less frequent maintenance
  - Reduced noise
  - Reduced incidence of catastrophic failure
- Gen-4 designs are being widely implemented in China
  - Implementation in the ROW is constrained by pricing and availability of Neo magnets
- Alternative technologies are being developed
  - Hybrid (half speed)
  - Superconducting generators
  - Direct drive without steel laminations (e.g., Boulder Wind Power)

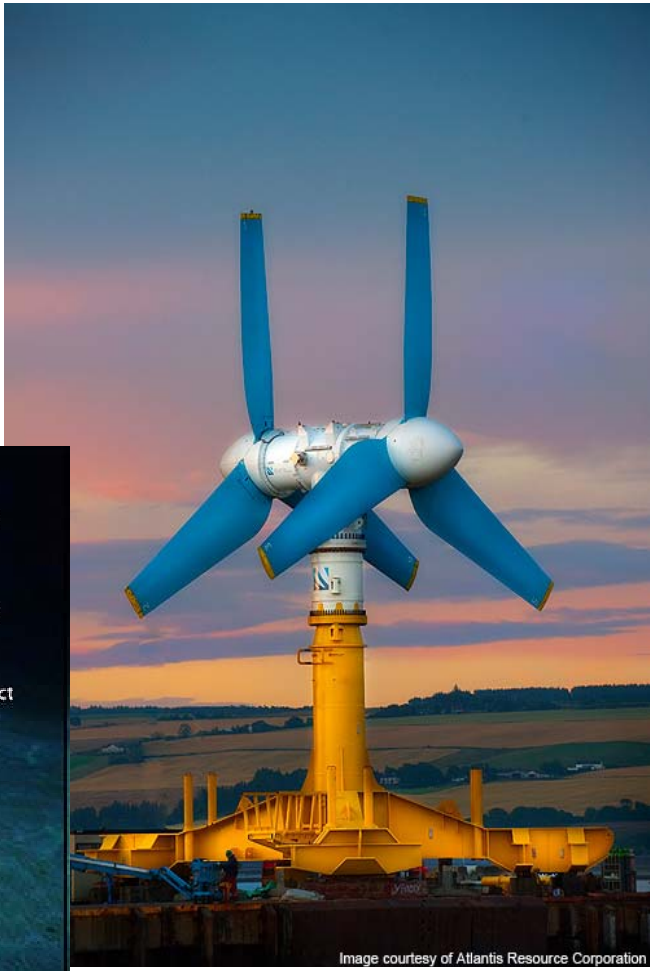
ARNOLD MAGNETIC TECHNOLOGIES

It's Not Just Wind…



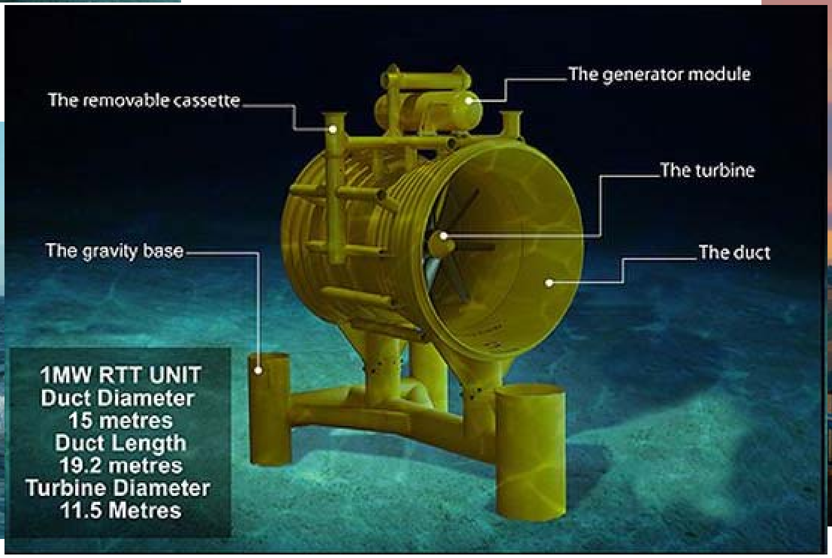
Other sources of renewable electric energy generation

AK-1000 Tidal Turbine
1 and 2 MW, United Kingdom



www.Keetsa.com

Pelamus Wavepower



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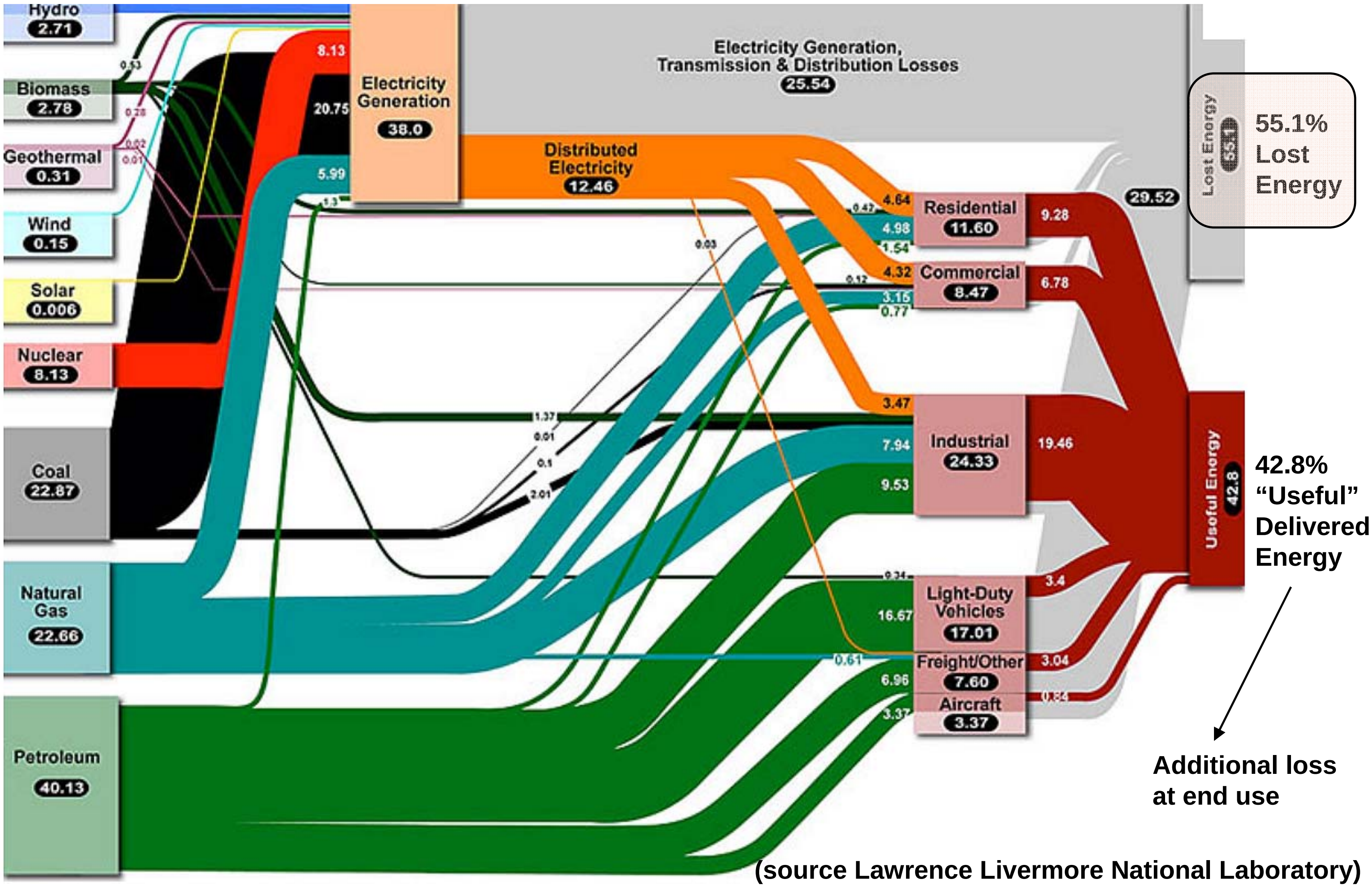
  - Alternative Materials and Research

US energy flow in 2006 in Exajoules

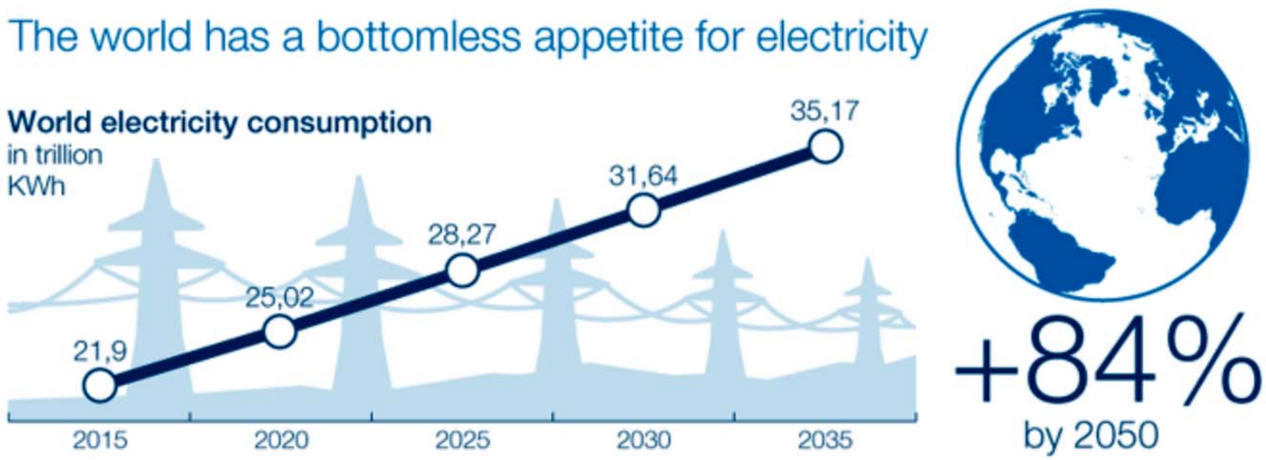
This Sankey diagram shows the sources and use of energy in the United States in 2006 in Exajoules. Electricity generation was mainly done using coal and nuclear. Out of 38 Exajoules of primary energy used to produce electricity, 25.54 Exajoules were wasted in losses, that is 69% of losses, mainly in heat energy. More than half of the energy used in the USA goes into useless losses. That figure is similar across all industrialized countries.

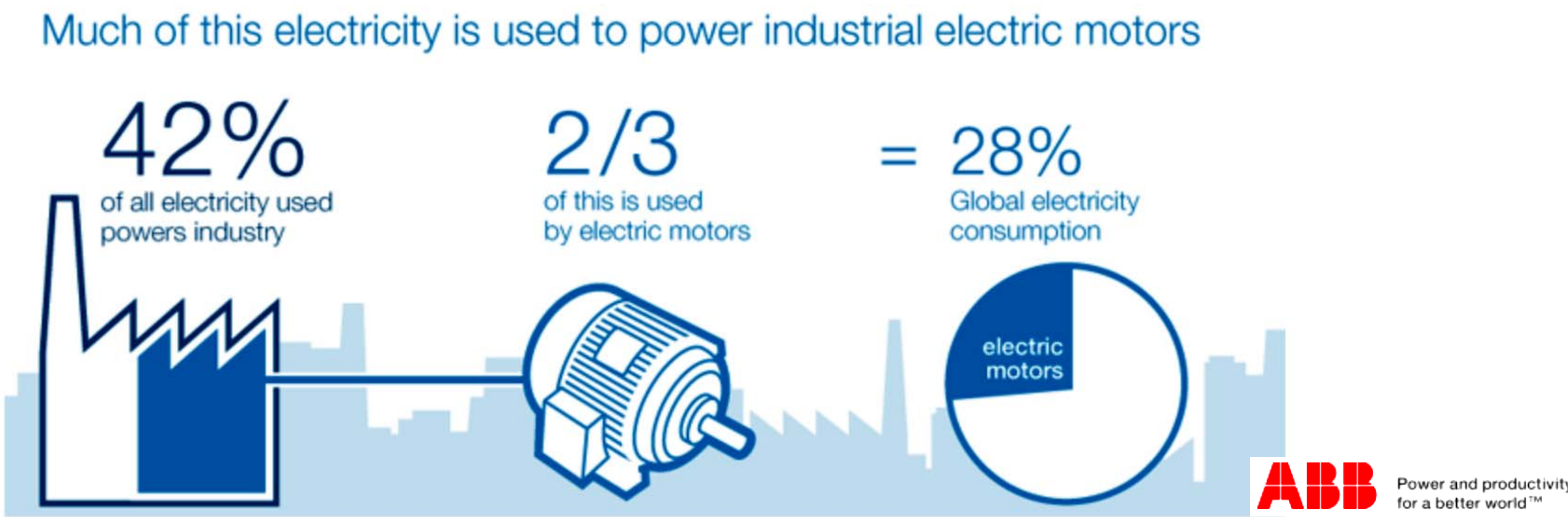


(source Lawrence Livermore National Laboratory)

www.abb.com/product/ap/db0003db004052/ced766241e316af5c12578b00051d2d9.aspx/
www.abb.com/energyefficiency

Power and productivity for a better world™


The world has a bottomless appetite for electricity
World electricity consumption
in trillion
KWh
21,9
25,02
28,27
31,64
35,17
2015
2020
2025
2030
2035
+84%
by 2050



"…~57% of the generated electric energy in the United States is utilized [consumed] by electric motors powering industrial equipment. In addition, more than 95% of an electric motor's life-cycle cost is the energy cost."

The Next Generation Motor, IEEE Industry Applications, January / February 2008, p.37

The industrial energy challenge

300'000'000 industrial electric motors are currently installed worldwide. This figure increases by **10%** each year. Approximately **50%** of these motors are installed in the **US, EU and China.**

50%

of all electric motors are installed in:

economic growth = more electric motors

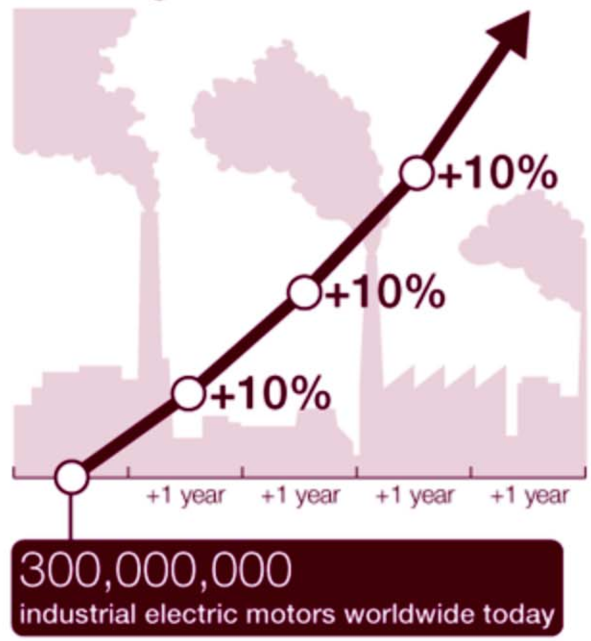
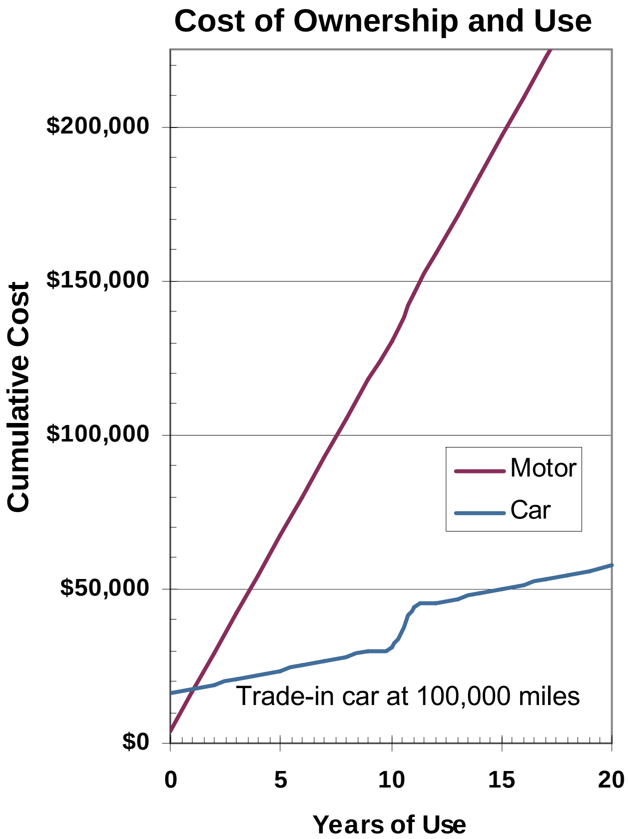


ABB Power and productivity for a better world™

Electric Motor Operating Cost

	Automobile		60 HP* Motor	
Purchase price	$16,000		$4,000	
Annual use	12000	miles	4000	hours
Efficiency	30	mpg	89.20%	
Fuel/energy cost	$3.50	$/gal	$0.056	$/kwh
Annual oper. cost	$1,400		$12,601	
Operating Cost as a % of Purchase Price	**9%**		**315%**	



First Cost is not the Last Cost

*60 HP; equivalent to 50.18 kW capacity
**Based on 2-shift operation

From AEC (North Carolina Alternative Energy Corporation), updated with current gas prices, www.p2pays.org/ref/17/16897.pdf

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MAGNETIC TECHNOLOGIES

Low Voltage* Motor Market

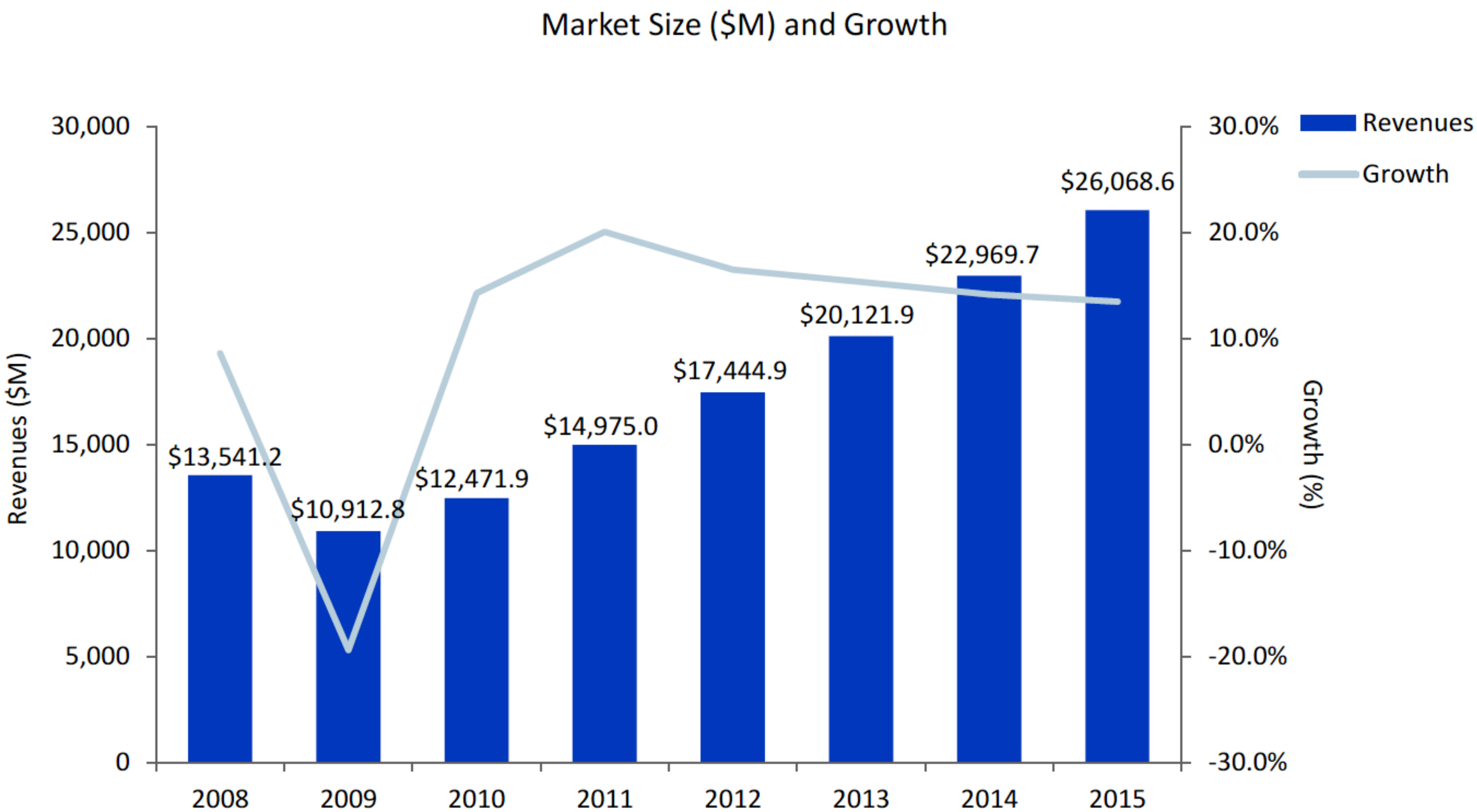
Products Covered:

- IE1 (Standard Efficiency)
  Eff2 and below; Below EPAct
- IE2 (High Efficiency)
  Eff1; EPAct
- IE3 (Premium Efficiency)
  Above Eff1; NEMA Premium
- IE4 (Super Premium Efficiency)
  Much higher than Eff1; Above NEMA Premium
- Other Non-classified
  8 / 10 / 12 pole motors
  >375kW
  Submersible motors
  Fire pump motors
  All motors that fall outside NEMA and/or IEC
- DC Motors

IMSresearch
excellence in market intelligence

* Less than 600 volts

Low Voltage Motors Market



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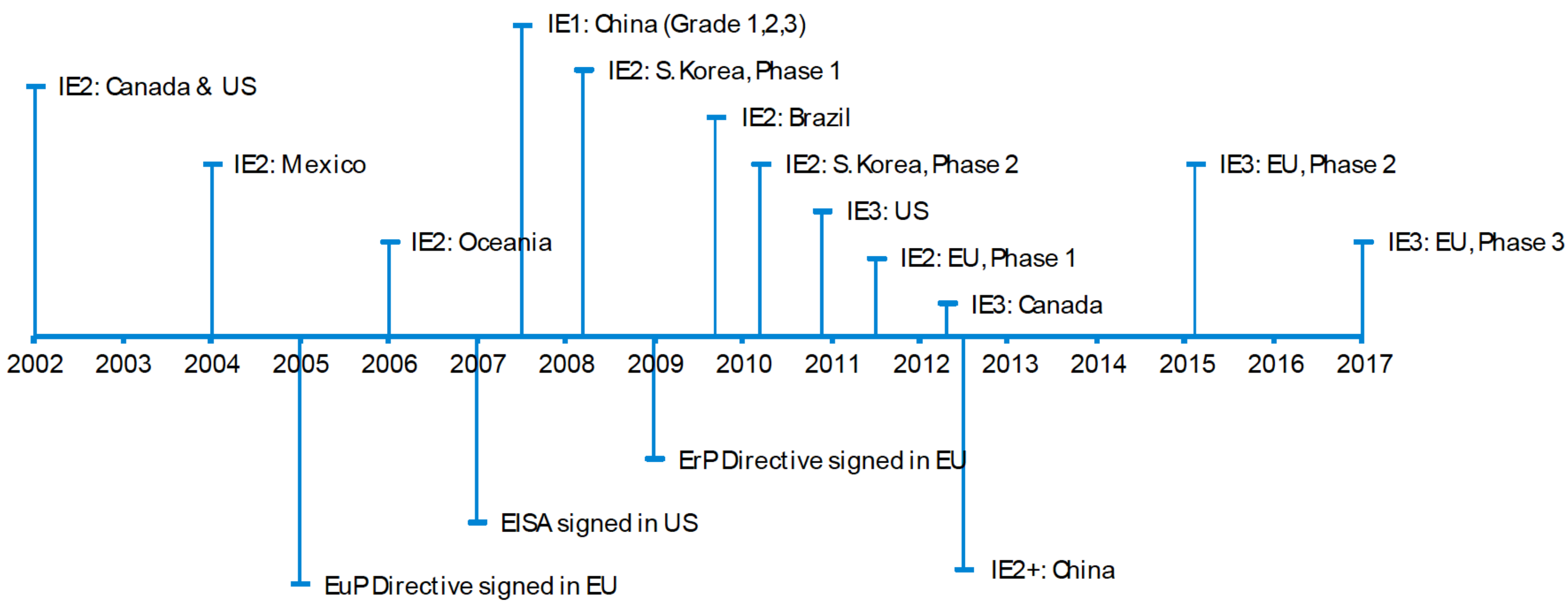
≈ 44 million low voltage motors shipped in 2010

Motor Efficiency Class Transition Timeline



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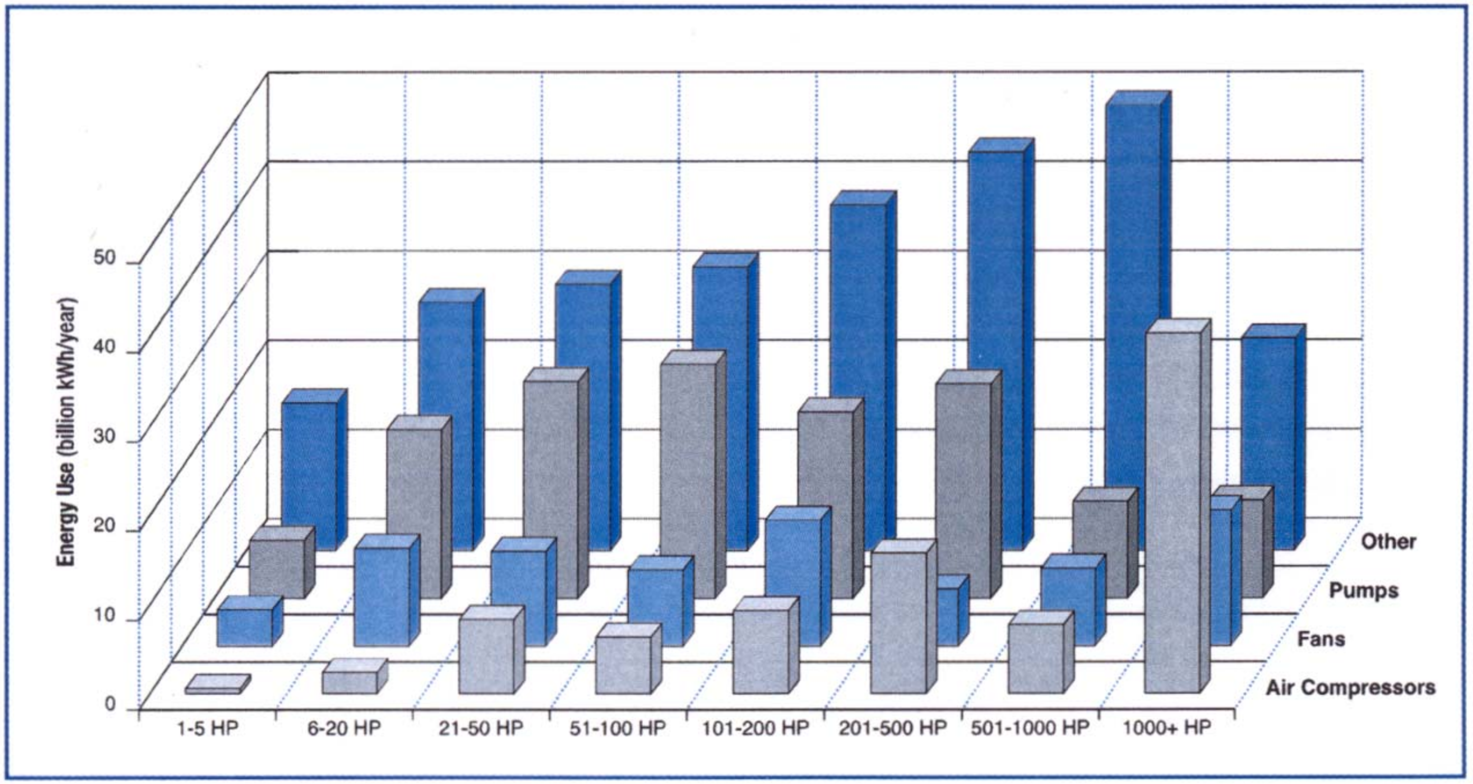
Loss Distribution

COMPARISON OF LOSS DISTRIBUTION BY PERCENT FOR MOTORS TESTED IN THE EASA/AEMT STUDY [12].

Losses	Two-Pole Average	Four-Pole Average	Design Factors Affecting Losses
Core losses (W_c)	19%	21%	Electrical steel, air gap, saturation, supply frequency, condition of interlaminar insulation
Friction and windage losses (W_{fw})	25%	10%	Fan efficiency, lubrication, bearings, seals
Stator I2R losses (W_s)	26%	34%	Conductor area, mean length of turn, heat dissipation
Rotor I2R losses (W_r)	19%	21%	Bar and end ring area and material
Stray load losses (W_l)	11%	14%	Manufacturing processes, slot design, air gap, condition of air gap surfaces and end laminations

Increased Efficiency versus Increased Reliability, IEEE Industry Applications, January / February 2008, p.33

Energy Consumption by Motor Size



Motor system energy consumption (Adapted from information in the *United States Industrial Electric Motor Systems Market Opportunities Assessment*, available online at www.eere.energy.gov/industry/bestpractices/.)

http://www1.eere.energy.gov/manufacturing/tech_deployment/pdfs/39157.pdf

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U.S. Energy Policy Act* Efficiency Targets

Nominal Full-Load Efficiency	OPEN MOTORS			CLOSED MOTORS		
Number of Poles	6	4	2	6	4	2
Motor Horsepower						
1	80.0	82.5	-	80.0	82.5	75.5
1.5	84.0	84.0	82.5	85.5	84.0	82.5
2	85.5	84.0	84.0	86.5	84.0	84.0
3	86.5	86.5	84.0	87.5	87.5	85.5
5	87.5	87.5	85.5	87.5	87.5	87.5
7.5	88.5	88.5	87.5	89.5	89.5	88.5
10	90.2	89.5	88.5	89.5	89.5	89.5
15	90.2	91.0	89.5	90.2	91.0	902
20	91.0	91.0	90.2	90.2	91.0	90.2
25	91.7	91.7	91.0	91.7	92.4	91.0
30	92.4	92A	91.0	91.7	92.4	91.0
40	93.0	93.0	91.7	93.0	93.0	91.7
50	93.0	93.0	92A	93.0	93.0	92.4
50	93.6	93.6	93.0	93.8	93.6	93.0
75	93.6	94.1	93.0	93.6	94.1	93.0
100	94.1	94.1	93.0	94.1	94.5	93.6
125	94.1	94.5	93.6	94.1	94.5	94.5
150	94.5	95.0	93.6	95.0	95.0	94.5
200	94.5	95.0	94.5	95.0	95.0	95.0

Increasing Efficiency Targets

75.5%

95.0%

* EPAct

Additional Motor Efficiency Information

- Energy Efficient Electric Motor Selection Handbook
  - www.wbdg.org/ccb/DOE/TECH/ce0384.pdf
- Buying an Energy Efficient Electric Motor
  - www1.eere.energy.gov/industry/bestpractices/pdfs/mc-0382.pdf
- Consortium for Energy Efficiency
  - www.cee1.org/ind/mot-sys/mtr-ms-main.php3
- Efficient Electric Motor Systems for Industry
  - www.osti.gov/bridge/servlets/purl/10112522-FoENQM/webviewable/10112522.PDF
- Efficient Electric Motor Systems: SEEEM
  - www.asiapacificpartnership.org/BATF/BATF%20Projects%20Workshops/Motors%20WS-SEEEM-brunner.pdf
- Development of Ultra-Efficient Electric Motors
  - www.osti.gov/bridge/servlets/purl/928973-hsePV1/928973.PDF
- Electric Motor Systems in Developing Countries: Opportunities for Efficiency Improvement
  - www.osti.gov/bridge/servlets/purl/10187187-n23Ohm/native/10187187.PDF

Agenda

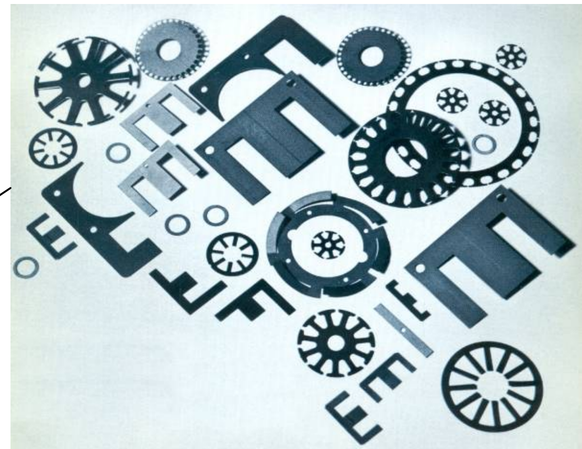
- Setting the Picture
  - Energy & Electricity Production and Consumption
- Alternative Energy Production - Wind
- Energy Consumption in Motors
  - PM versus Induction versus Synchronous
  - Motor efficiency
- Motor Materials
  - The Rare Earth Dilemma
  - Prices
  - Availability
  - Alternative Materials and Research

Motor Materials

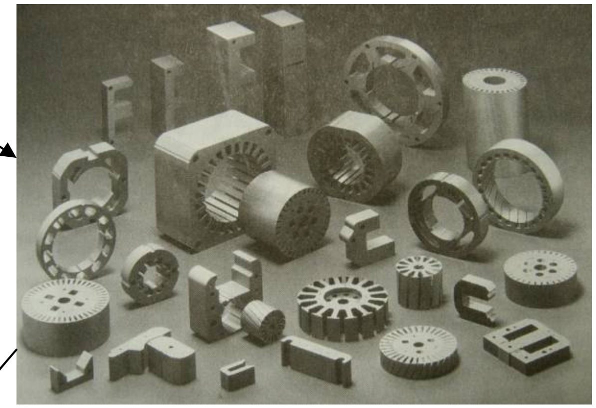
- Steel (electrical)
- Copper and/or Aluminum
- Permanent Magnets
  - Ferrite
  - SmCo
  - NdFeB
  - Alnico
- Power Electronics

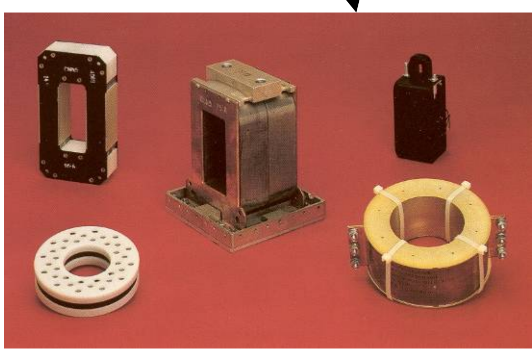
Two Main Applications for Electrical Steel

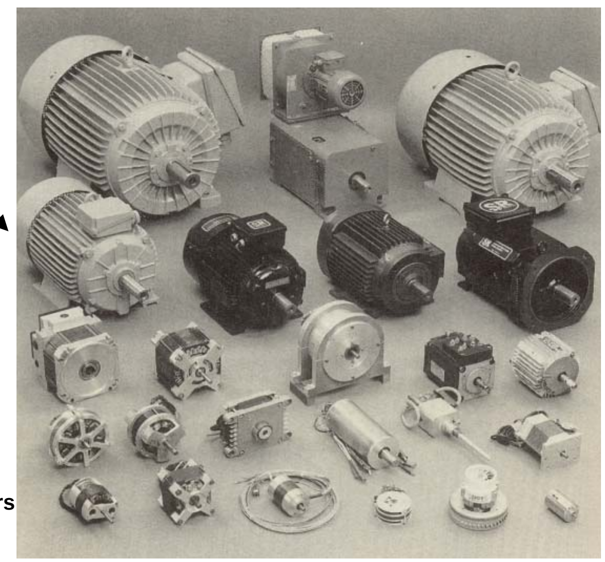
Transformers and Motors



Handbook of Small Electric Motors







Switched Reluctance Motors
and their Control, p.154
T.J.E. Miller

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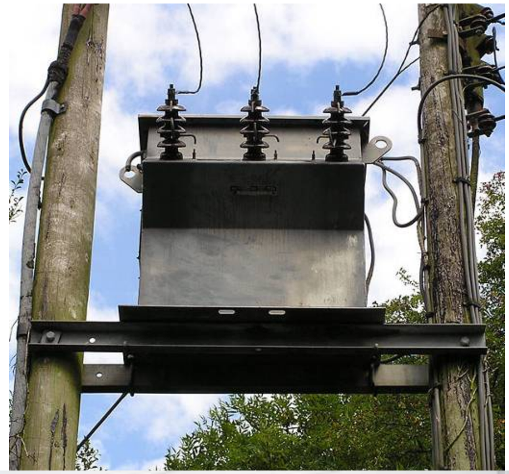
Transformers

Transformers can be small enough for installation onto circuit boards or as large as a house



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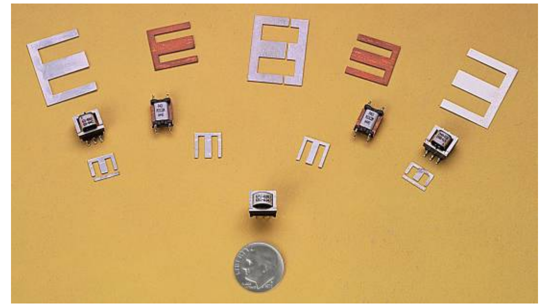
Transformers: Examples

From
Small

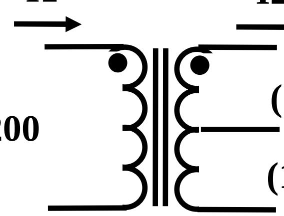


Photograph courtesy of Magnetic Metals

To
Large

Photographs courtesy of ABB

I1 I2



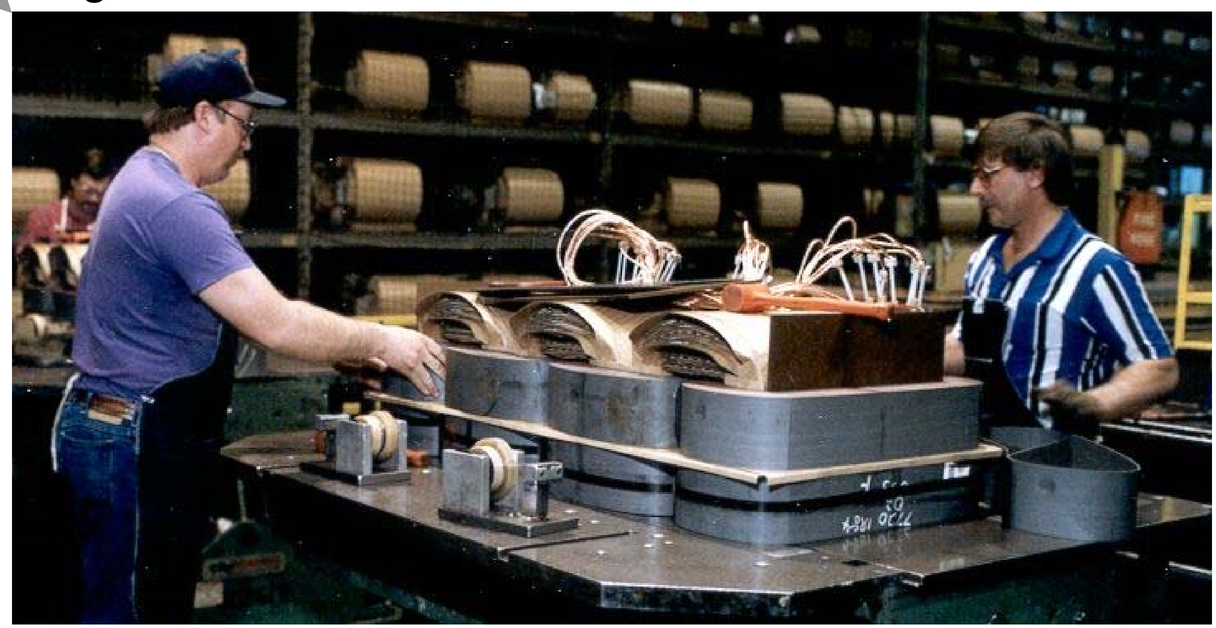
V1 = 7200 volts

(1/2)V2 = 120 volts

(1/2)V2 = 120 volts

30 :1
N:1

V2 = 240 volts
Center-Tapped



Silicon Steel 3-Phase Transformer

Widely Available Materials

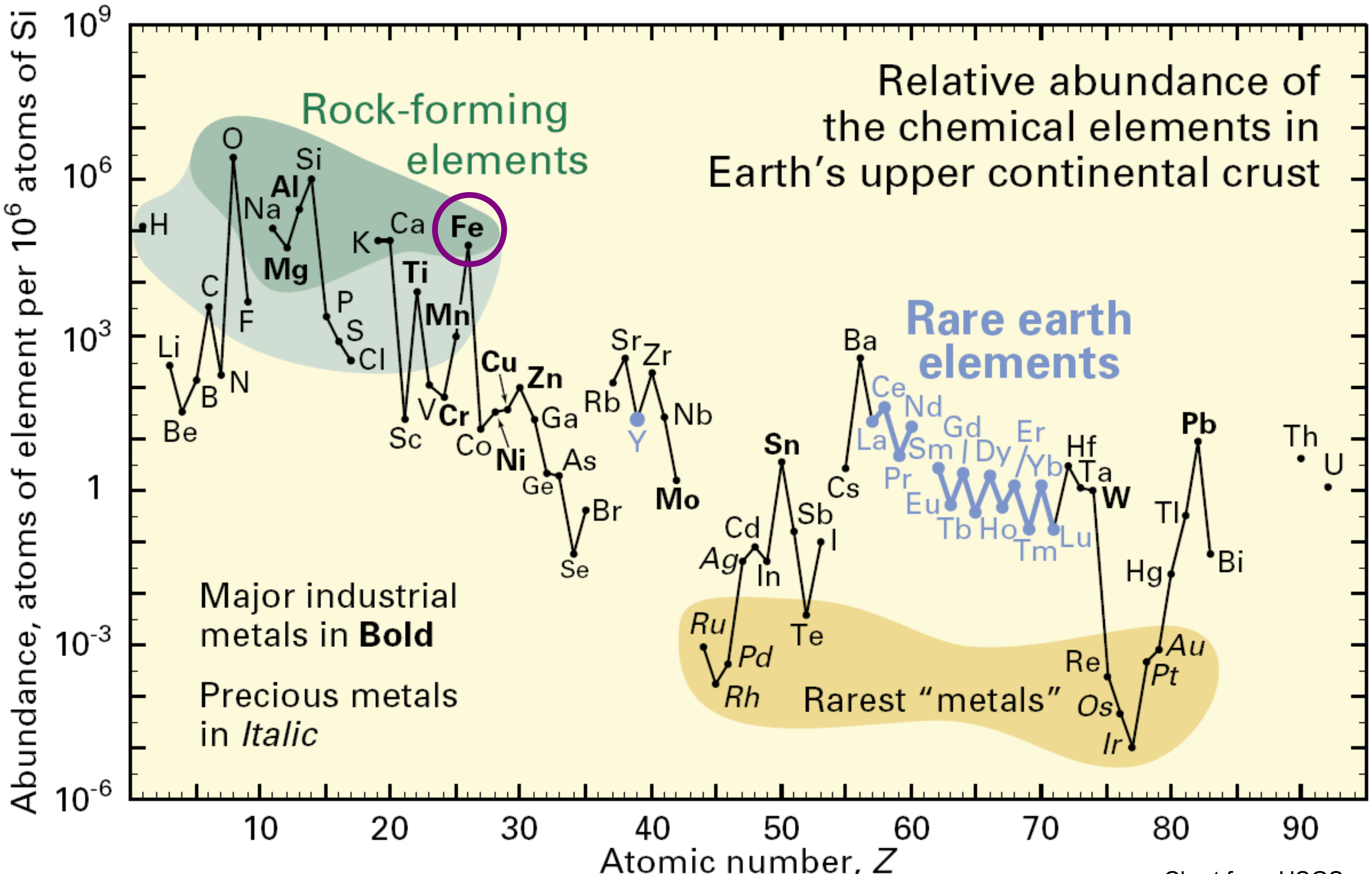
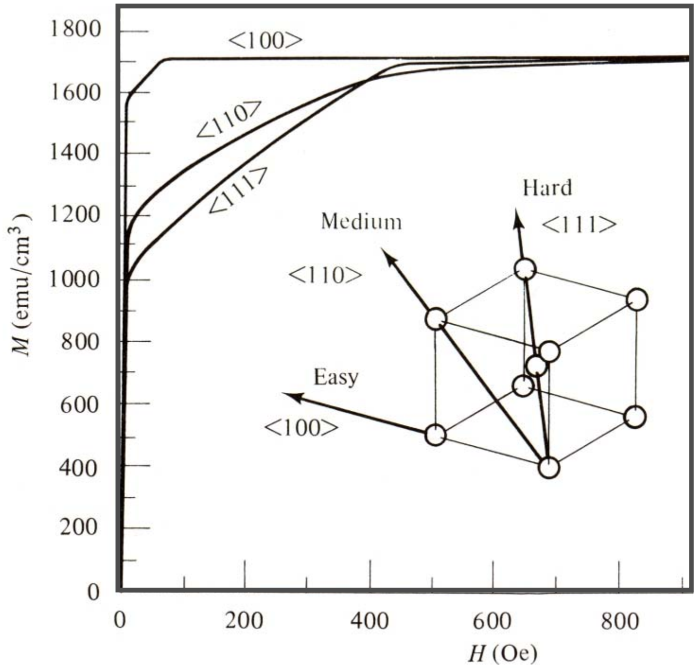
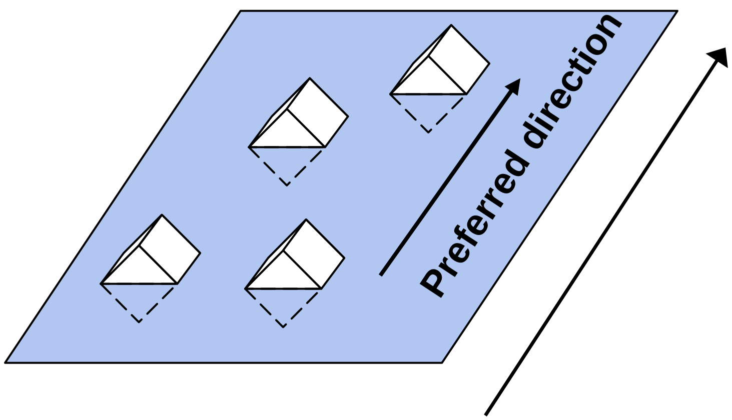


Chart from USGS: www.USGS.org

Understanding the Structure of Electrical Steel



Magnetization curves for single crystals of iron (by Honda and Kaya)



Directional Properties of Si-Steel (GOES)

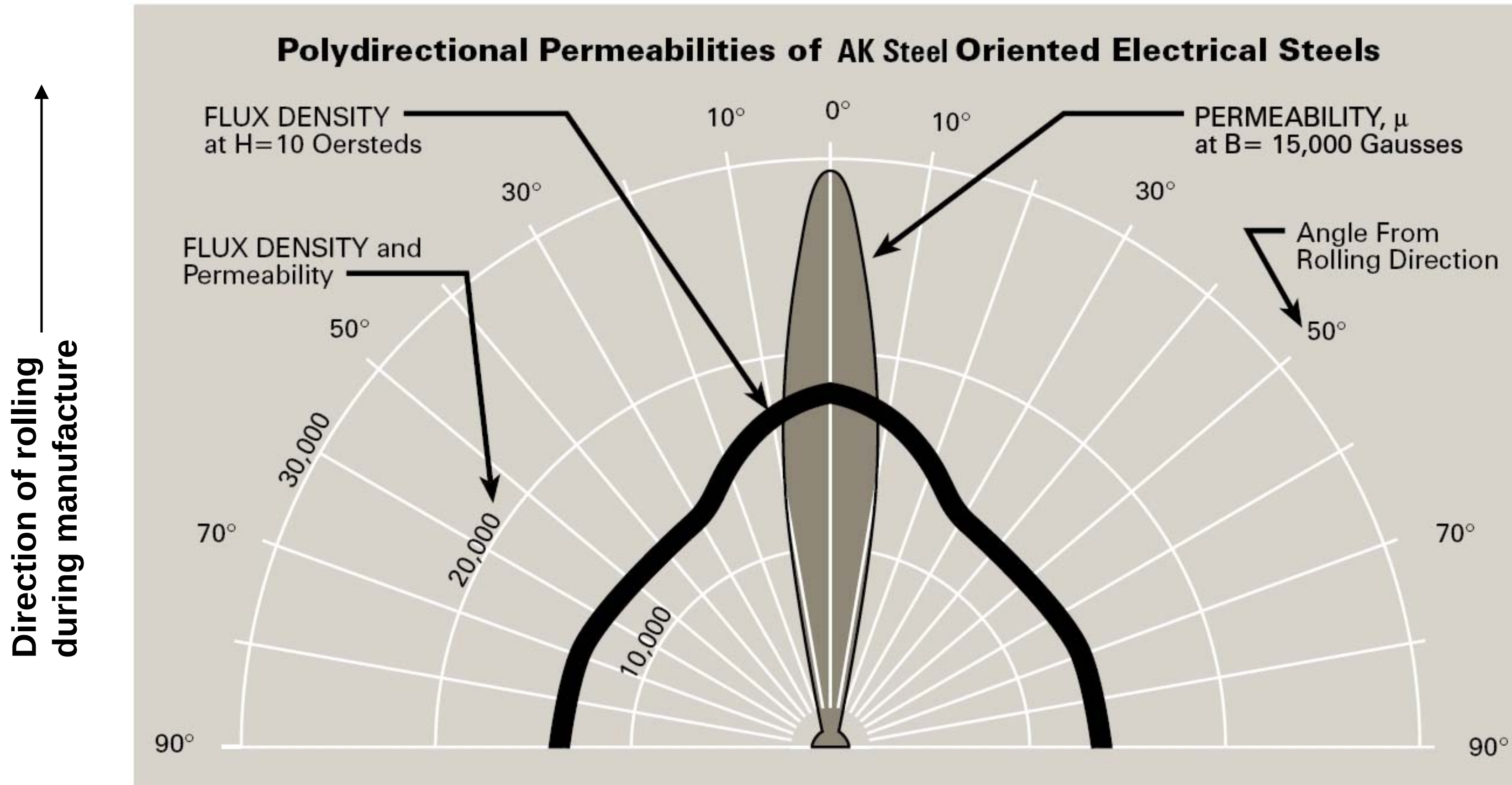
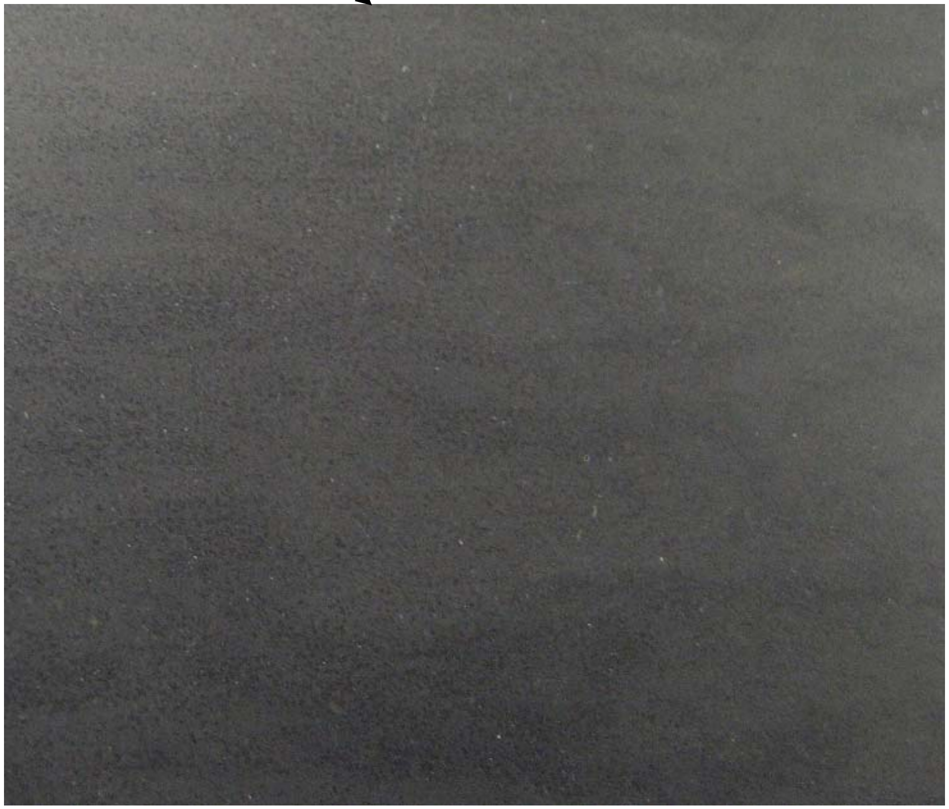


Figure 3. Tests made on Epstein samples cut at various angles to rolling direction, stress annealed after shearing. Negligible joint effects. Assumed density 7.65 grams per cubic centimeters.

GOES versus NGOES

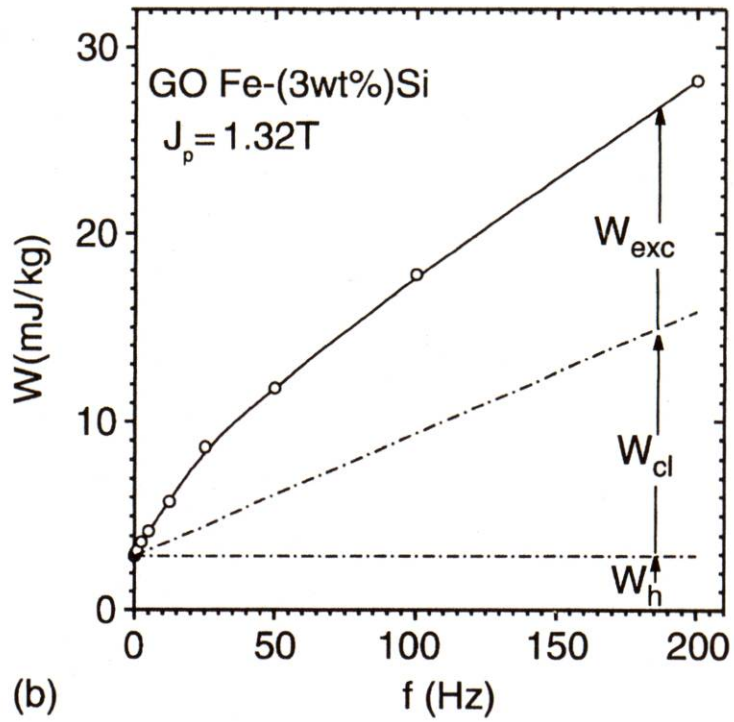
Grain Oriented Electrical Steel **versus** **Non-grain Oriented Electrical Steel**



Direction of rolling during manufacture →

Core Loss Mechanisms

Silicon Steel Core Loss



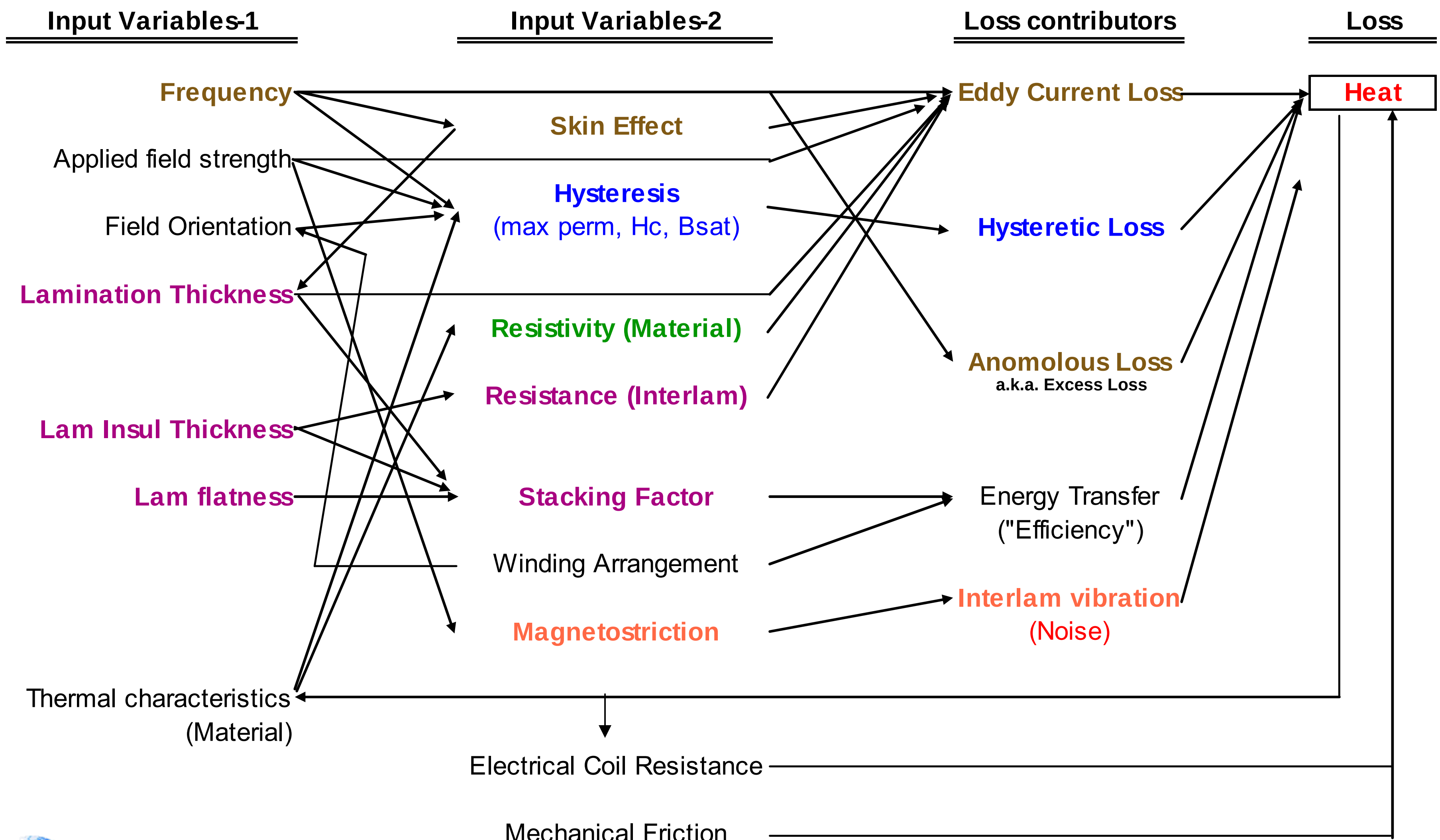
$W = W_h + W_{cl} + W_{exc}$ Where Classical Loss is $$W_{cl} = \frac{\pi^2}{6} \frac{\sigma d^2 J_p^2 f}{\delta}$$

Measurement and Characterization of Magnetic Materials, Fausto Fiorillo, p.31

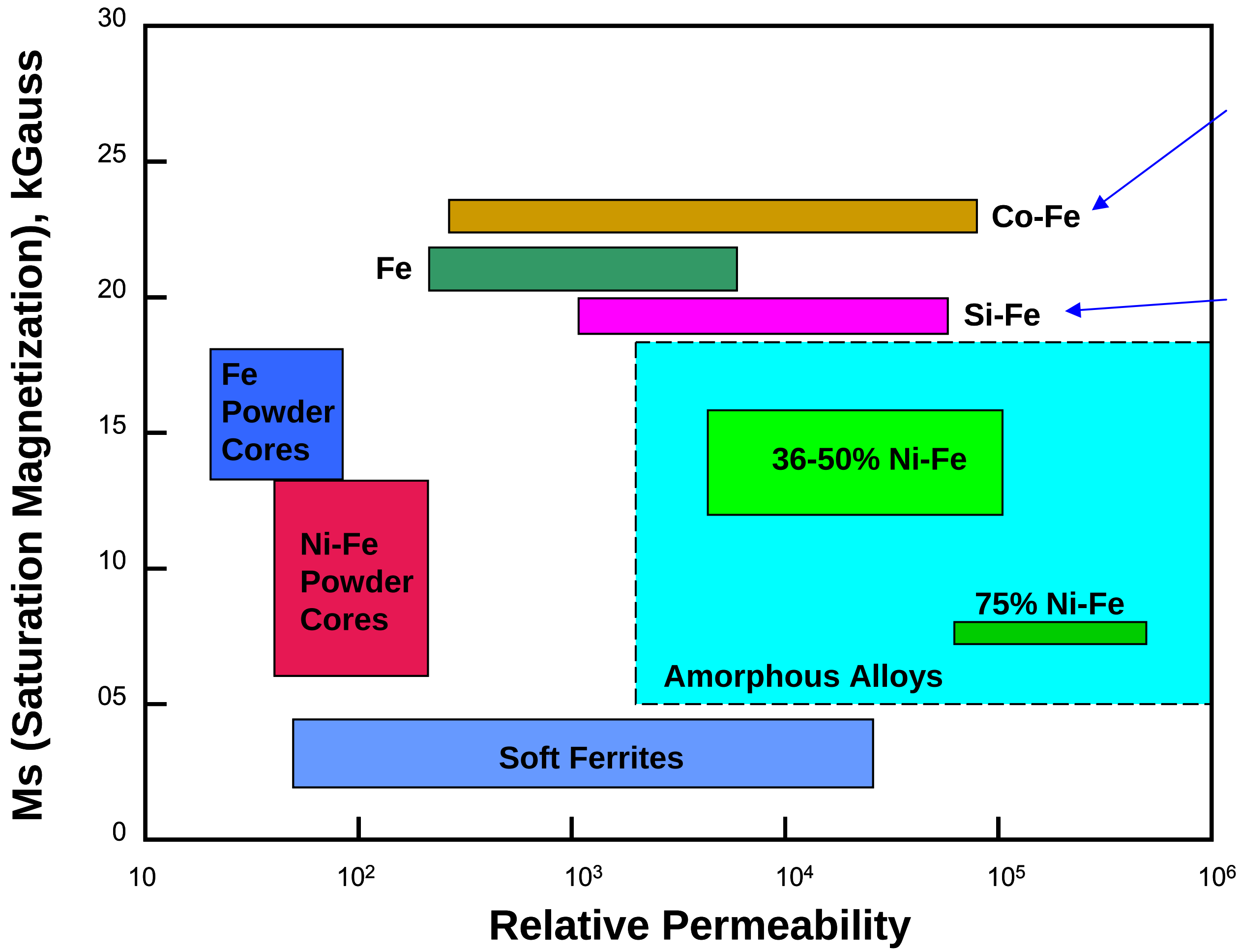
ARNOLD MAGNETIC TECHNOLOGIES

1. Magnetic Hysteresis
2. Eddy Current
3. Laminations Characteristics
4. Magnetostriction
5. Material Resistivity

Motor Loss Variables by Categories



Comparing Material Properties



Co-Fe: Outstanding performance but at a high price

Si-Fe: Excellent performance at a reasonable price

Copper / Aluminum

- Two main uses
  - Copper in the windings of the stator (and rotor – brushed type)
  - Aluminum in the rotor of induction motors
- Neither copper nor aluminum is considered a critical material or in short supply, however...
  - Price swings regularly occur due to supply-demand imbalance
  - Aluminum is present in the earth’s crust in higher quantity than copper (next slide): about 8 000x more Al than Cu

Bauxite (aluminum) mine

Open pit copper mines

Widely Available Materials

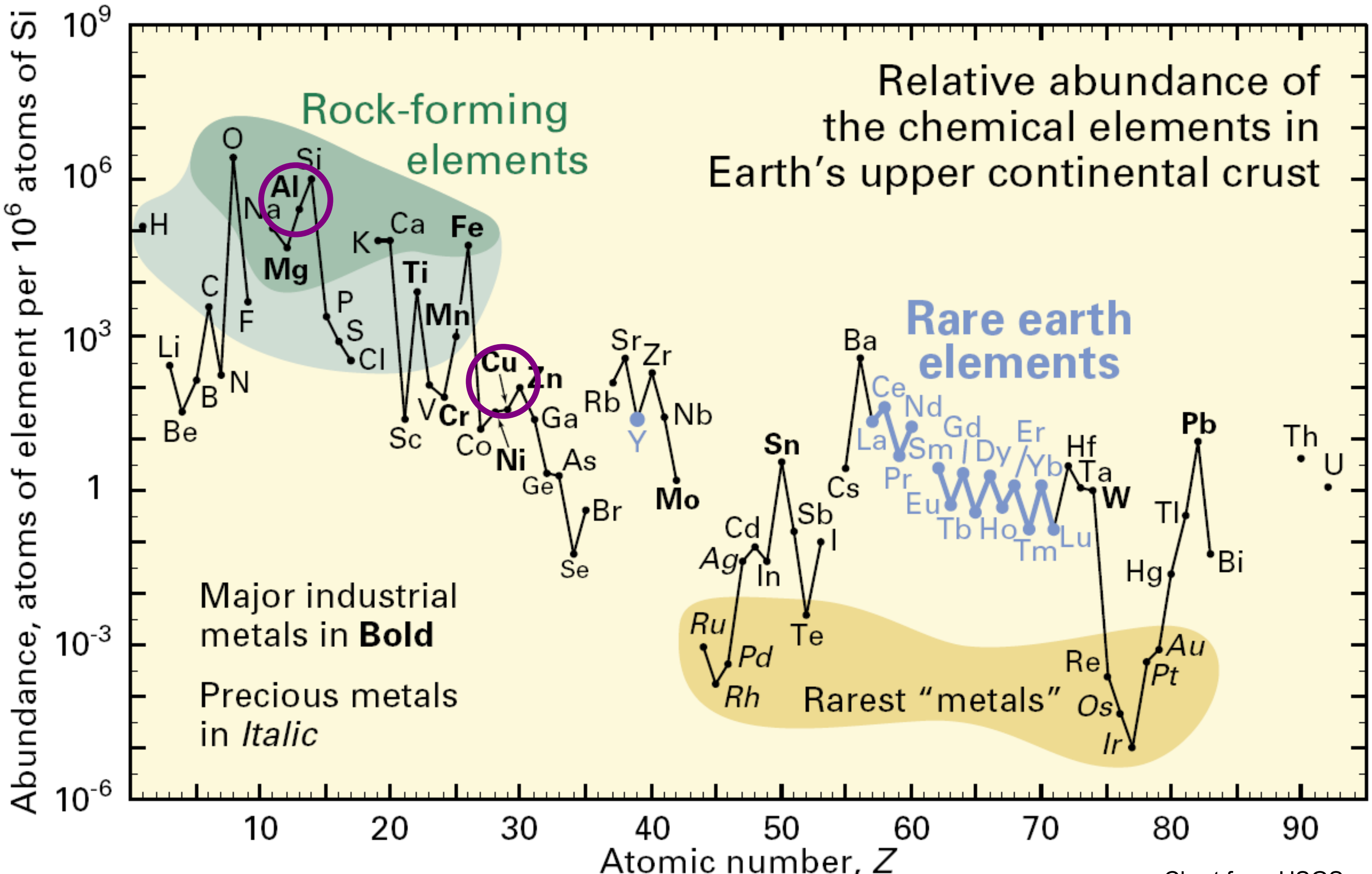


Chart from USGS: www.USGS.org

ARNOLD MAGNETIC TECHNOLOGIES

Magnets – many choices!

The 4 most widely used commercial permanent magnets (→ Alnico, Ferrite*, NdFeB, SmCo**)

	Alloy Products			Bonded Magnets			
Material	Cast	Extruded or Rolled	Sintered, Fully Dense	Injection Molded	Compression Bonded	Flexible	Rigid Extruded
Alnico	Y		Y	Y			
FeCrCo	Y	Y					
Ferrite*			Y	Y		Y	Y
NdFeB		(Y)	Y	Y	Y	Y	(Y)
SmCo**			Y	Y	(Y)		
Si-Fe		Y			SMCs		
SmFeN				Y			
Vicalloy		Y					
Hybrids				Y	Y	Y	

* Ferrite refers to strontium ferrite permanent magnets

** SmCo refers to either SmCo5 or Sm2Co17

SMC = Soft magnetic composite

What makes a magnet *good*?

Requirements depend upon the application

- Flux density (Br)
- Energy Product (BHmax)
- Resistance to demagnetization (Hcj)
- Usable temperature range
- Magnetization change with temperature (RTC)
- Demagnetization (2^{nd} quadrant) curve shape
- Recoil permeability (minimal - close to one)
- Corrosion resistance
- Physical strength
- Electrical resistivity
- Magnetizing field requirement
- Available sizes, shapes, and manufacturability
- Raw material cost and availability

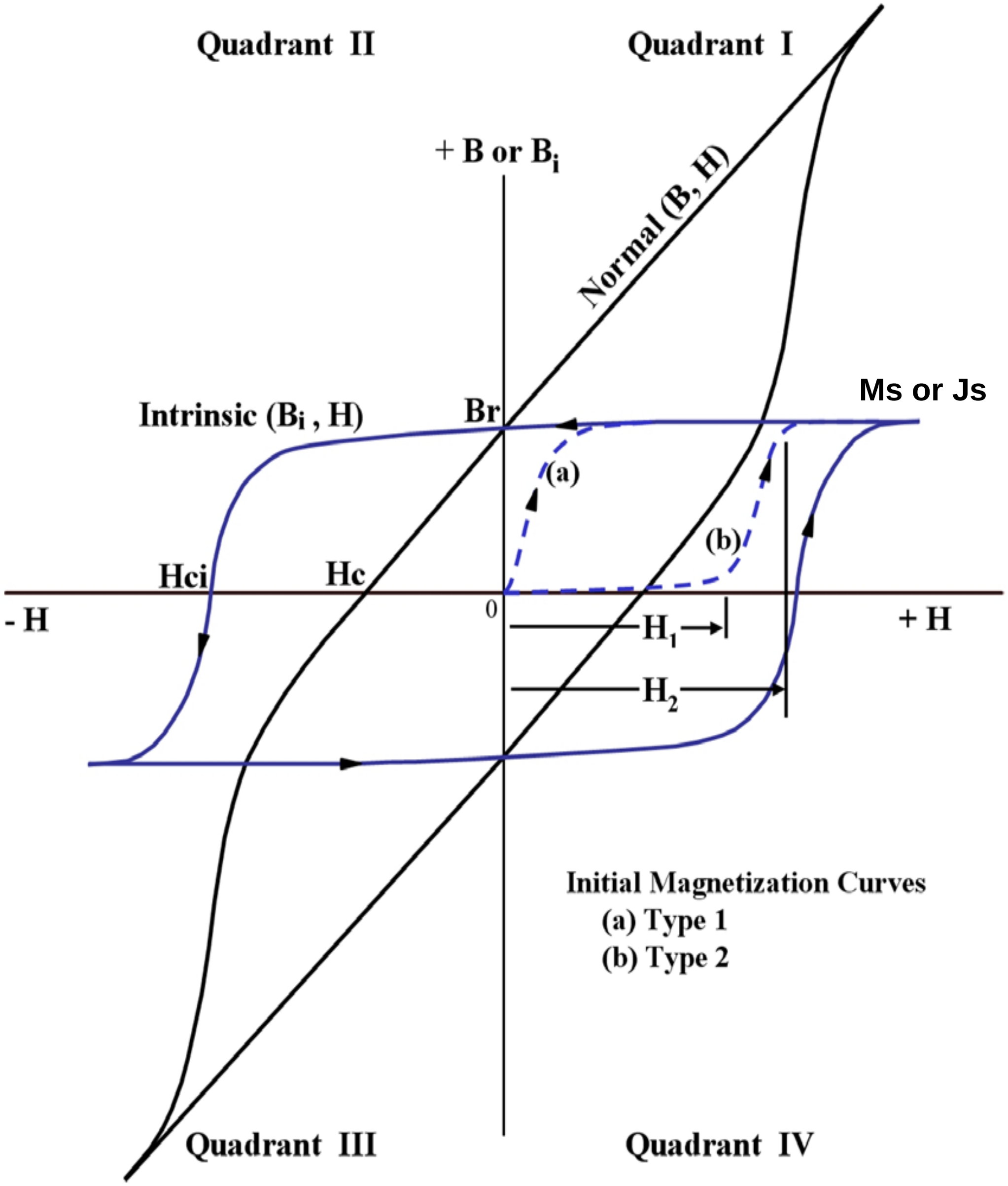
Directional Indicators

Competitive Values

Characteristic	Units	Alnico 5-7	Alnico 9	Ferrite 8	Ferrite 9	SmCo 1:5	SmCo 2:17	NdFeB 33EH	NdFeB 48M	Indicator
Flux density (Br)	Tesla	1.35	11200	0.39	0.45	0.9	1.1	1.15	1.39	> is better
Energy Product (BHmax)	kJ/m^3	60	84	28	37	175	230	230	370	> is better
Resistance to demagnetization (Hcj)	kA/m	59	115	245	370	2400	1600	2400	1115	> is better
Usable temperature range	ºC	4 K to 520 ºC	4 K to 520 ºC	-40 to 150 ºC	-40 to 150 ºC	4 K to 520 ºC	4 K to 520 ºC	150 K to 200 ºC	150 K to 100 ºC	minimum -40 to 200 ºC
Induction change with temperature (RTCof Br)	%/ºC	-0.02	-0.01	-0.2	-0.18	-0.045	-0.035	-0.11	-0.12	< is better
2nd quadrant Normal curve shape		Curved	Curved	Straight	Straight	Straight	Straight	Straight	Straight	Straight
Recoil permeability	B / H	2	1.3	1.04	1.04	1.03	1.05	1.04	1.05	~1
Corrosion resistance		Excellent	Excellent	Outstanding	Outstanding	Good	Good	Fair	Fair	Outstanding
Physical strength	MPa	55	55	65	70	120	120	285	285	> 50 also "tough"
Electrical resistivity	μΩ • cm	47	50	10^6	10^6	55	90	180	180	> is better
Magnetizing field requirement	kA/m	120	240	480	800	2000	4000	2700	2700	Less than 4000
Coefficient of Termal Expansion	$\%/ ºC\times10^{-6}$	11.5	11	10 to 15	10 to 15	7 to 14	11 to 13	7.5 to -0.1	7.5 to -0.1	< 15
Approx Current Price (ballpark estimates)	$/kg	$40	$45	$8	$15	$120	$100	$200	$150	< is better
Relative Cost at 20 °C	$/MGOe	$5.3	$4.3	$2.3	$3.2	$5.5	$3.5	$6.9	$3.2	< is better
Relative Cost at 200 °C	$/MGOe	$5.7	$4.4	$5.6	$7.1	$6.5	$3.9	$10.8	n/a	< is better

Magnetic Hysteresis

- "H" is the applied magnetic field
- "B" is the measured, induced field ("induction")
- Normal curve is a measurement of the applied plus the induced field
- The Intrinsic curve is a measure of only the induced field and represents the magnetic properties of the magnet under test
- The dashed lines represent starting with an unmagnetized material
- Once magnetized, the material will be driven around the hysteresis loops represented by the solid lines



Source: ASTM A977-07 – Standard Test Method for magnetic properties of high coercivity permanent magnet materials

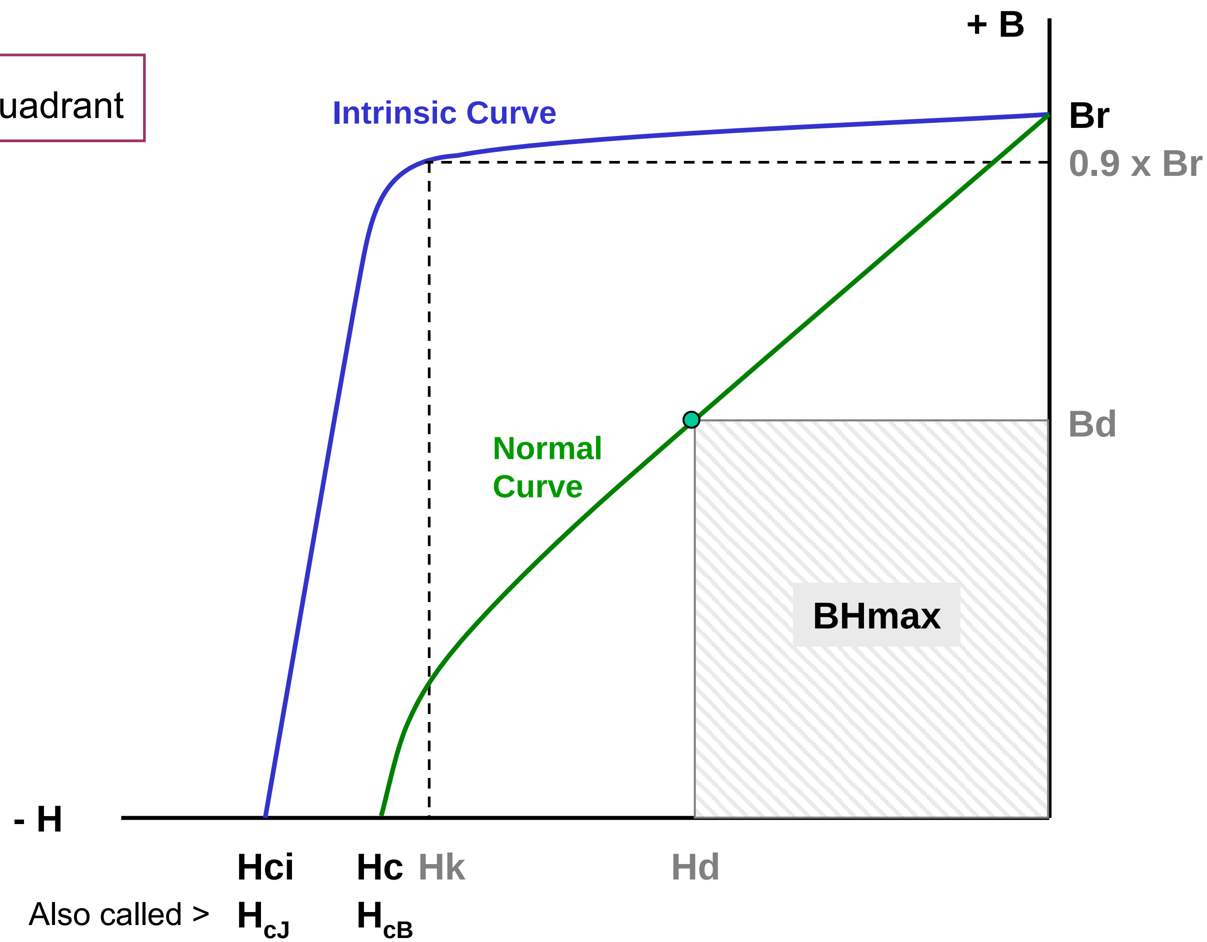
Permanent Magnet Key Characteristics

2nd Quadrant

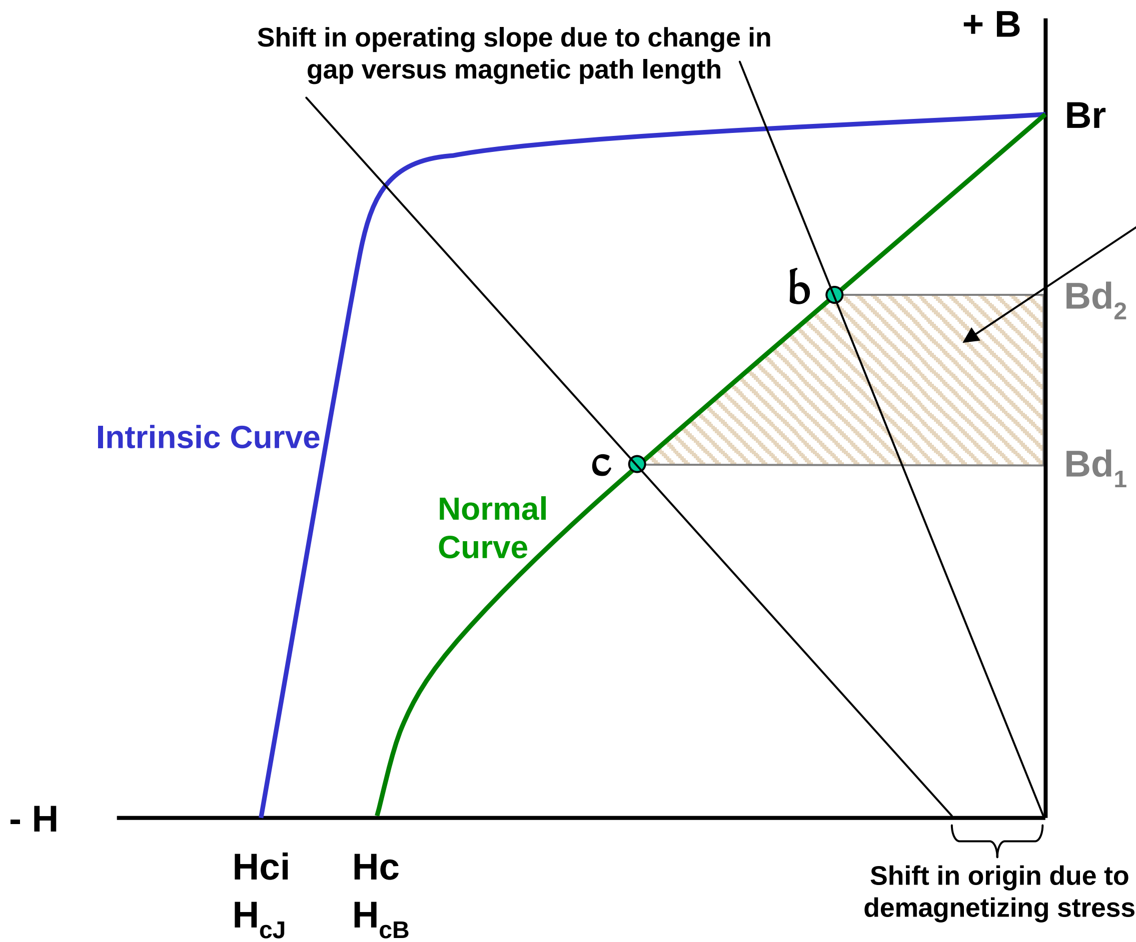
Energy product is related to Br

BHmax ~ $Br^2 / (4 \cdot \mu_r)$
μ_r ~ 1.05

When Normal curve from Br to Operating Point is Linear



Energy Stored in a Magnet



$$-\int_b^c B\,dH - \int_b^c H\,dB = -[BH]_b^c$$

References

1. R. J. Parker, *Advances in Permanent Magnetism*, John Wiley & Sons, New York, 1990, pp. 141-143
2. P. Campbell, *Permanent Magnet Materials and Their Application*, Cambridge University Press, 1994, pp.16-17
3. P. Campbell, Comments on Energy Stored in Permanent Magnets, IEEE Transactions on Magnetics, Col. 36, No. 1, January 2000

ARNOLD MAGNETIC TECHNOLOGIES

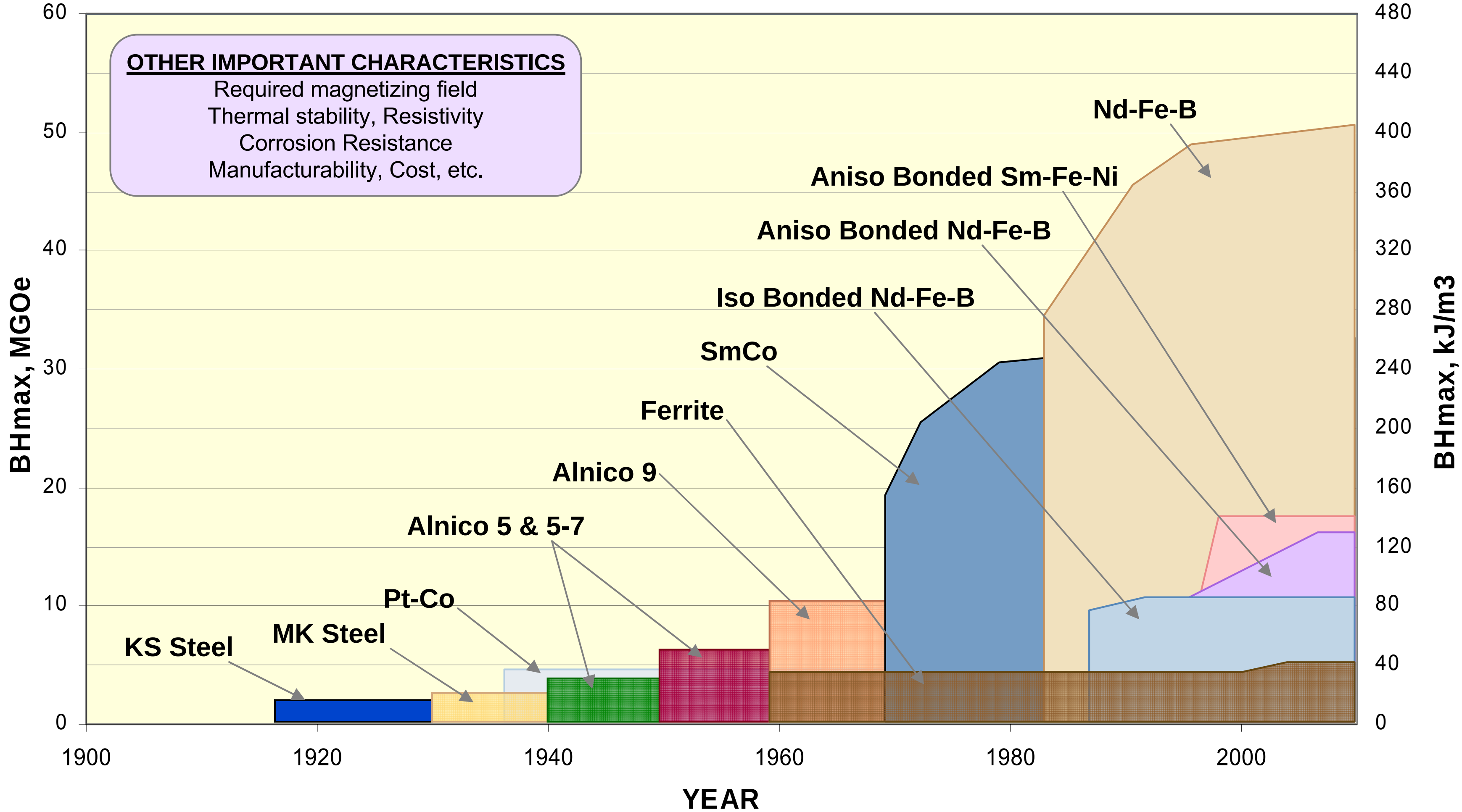
Permanent Magnet Development Timeline

- Permanent Magnets have been developed to achieve
  - Higher Br and Energy Product (BHmax)
  - Greater resistance to demagnetization (Hci)
- Most are still in production
  - Exceptions
    - ***Lodex*** *was discontinued due to use of hazardous materials in production and in the product*
    - ***Cunife*** *has been replaced by FeCrCo*
    - ***PtCo*** *is a specialty item made in very limited quantities due to it's high material cost*

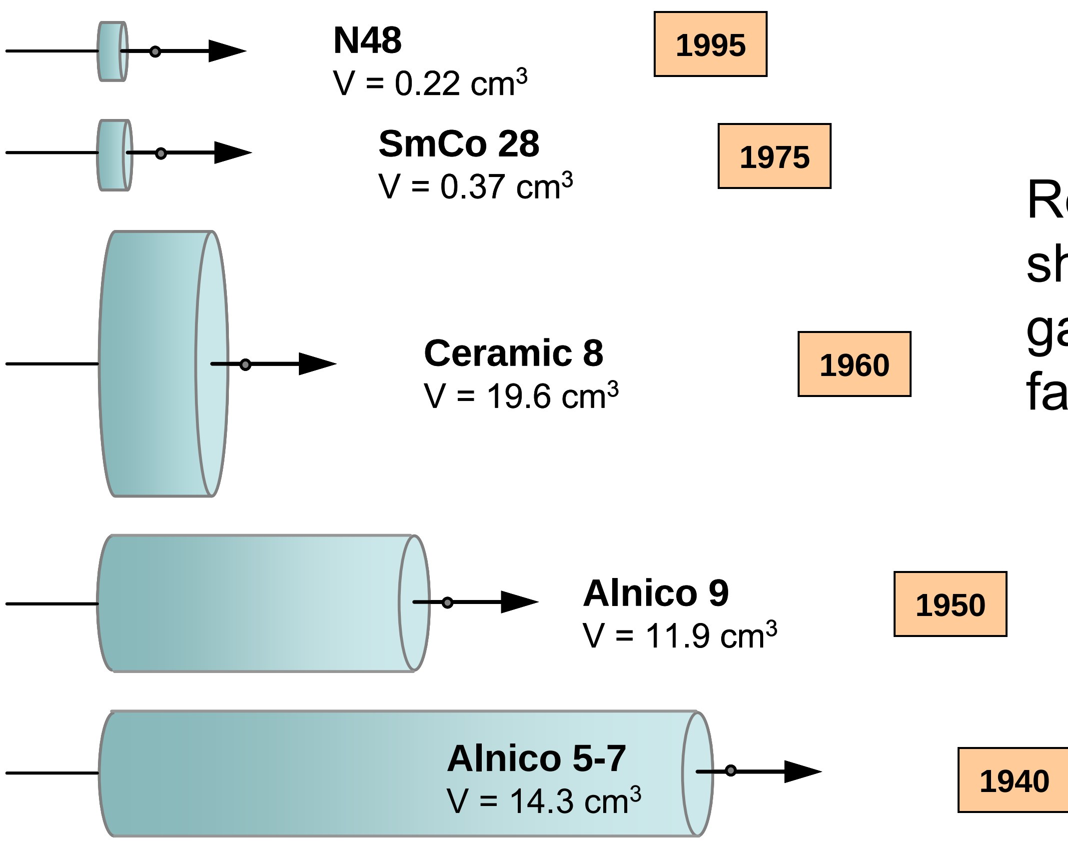
Material	**First Reported**	**BH(max)**	**Hci**
Remalloy	1931	1.1	230
Alnico	1931	1.4	490
PtCo	1936	7.5	4,300
Cunife	1937	1.8	590
Cunico	1938	1.0	450
Alnico, field treated	1938	5.5	640
Vicalloy	1940	3.0	450
Alnico, DG	1948	6.5	680
Ferrite, isotropic	1952	1.0	1,800
Ferrite, anisotropic	1954	3.6	2,200
Lodex®	1955	3.5	940
Alnico 9	1956	9.2	1,500
$RECo_5$	1966	16.0	20,000
$RECo_5$	1970	19.0	25,000
$RE_2(Co,Fe,Zr,Cu)_1$	1976	32.0	25,000
$RE_2TM_{14}B$	1984	26.0	**25,000**
		35.0	11,000
$RE_2TM_{14}B$	2010	30.0	**35,000**
		52.0	11,000

Table based on information in *Advances in Permanent Magnetism* by Rollin J. Parker, p.331-332

Improvement in Magnet Strength

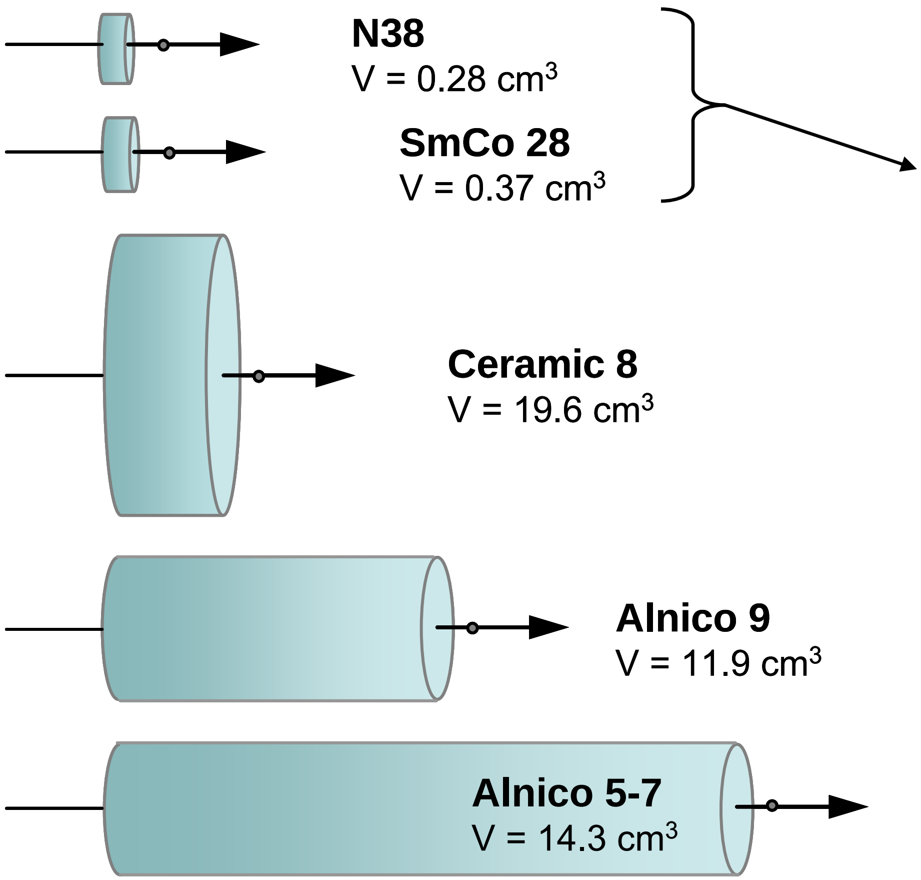


Relative Magnet Sizes

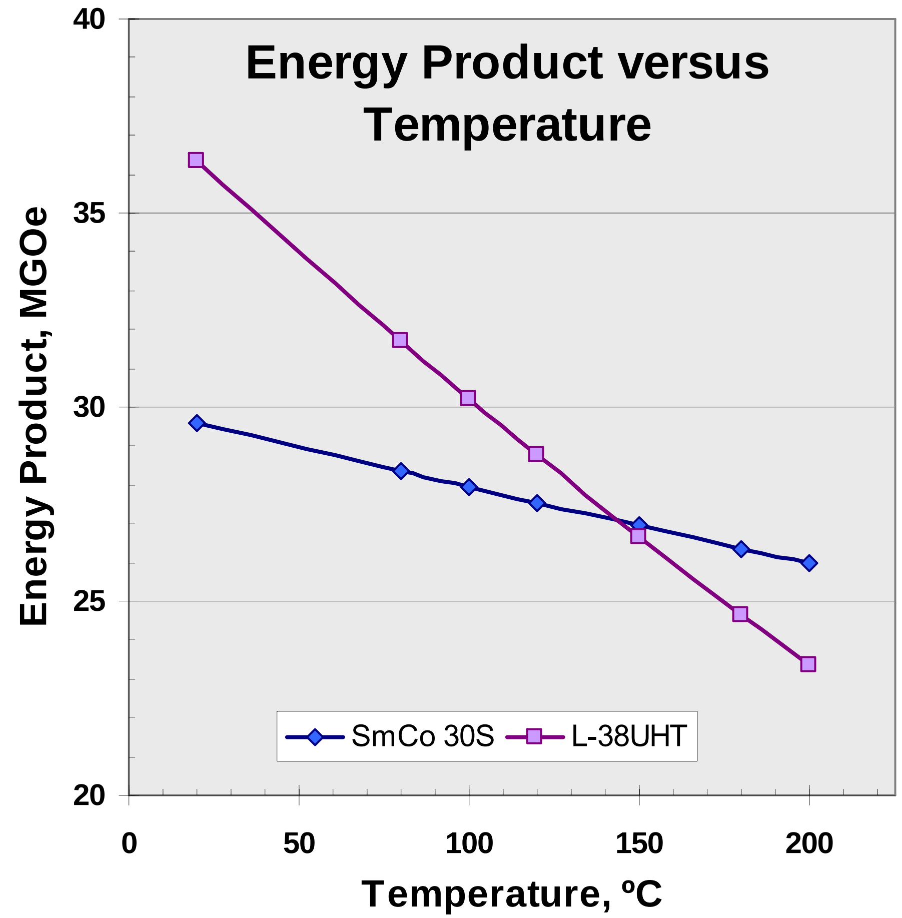


Relative magnet size and shape to generate 1000 gauss at 5 mm from the pole face of the magnet.

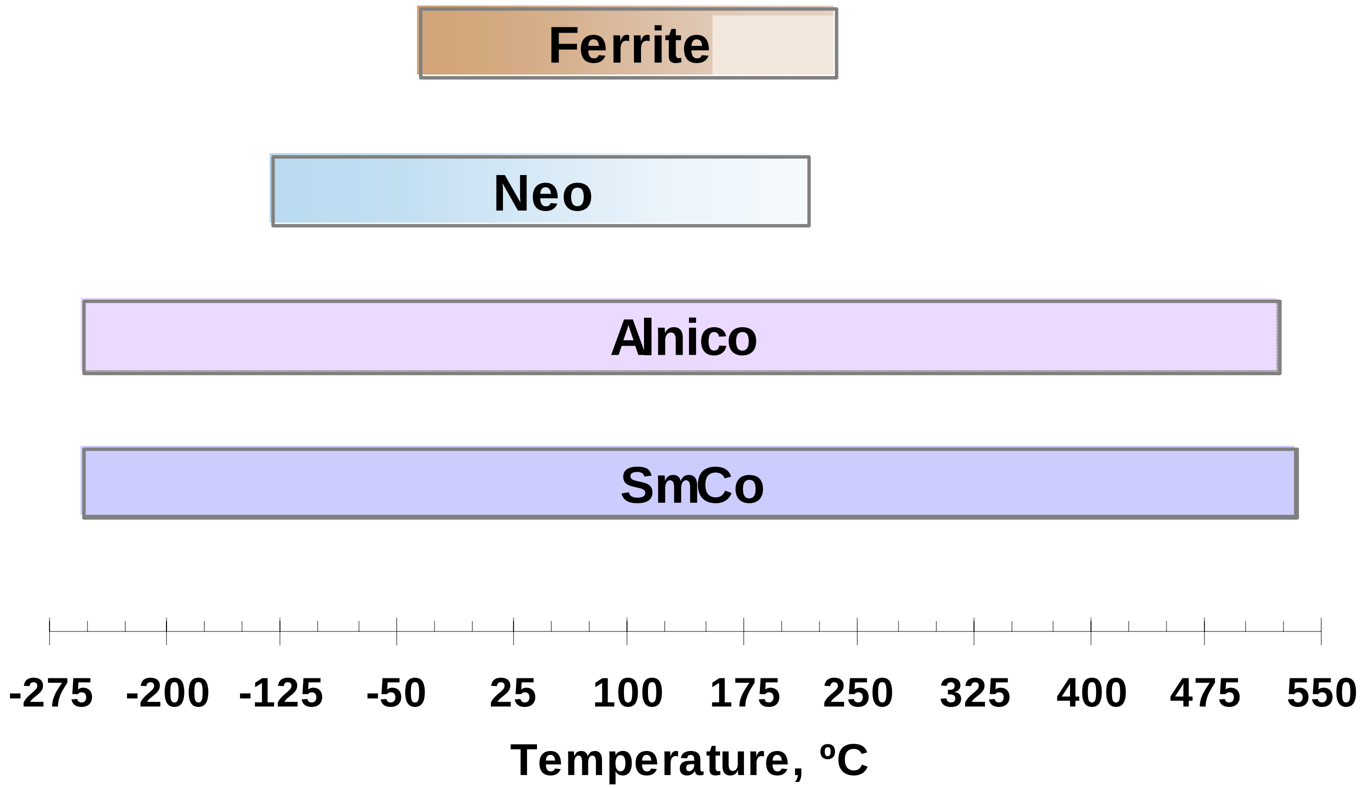
SmCo – Neo: Compared

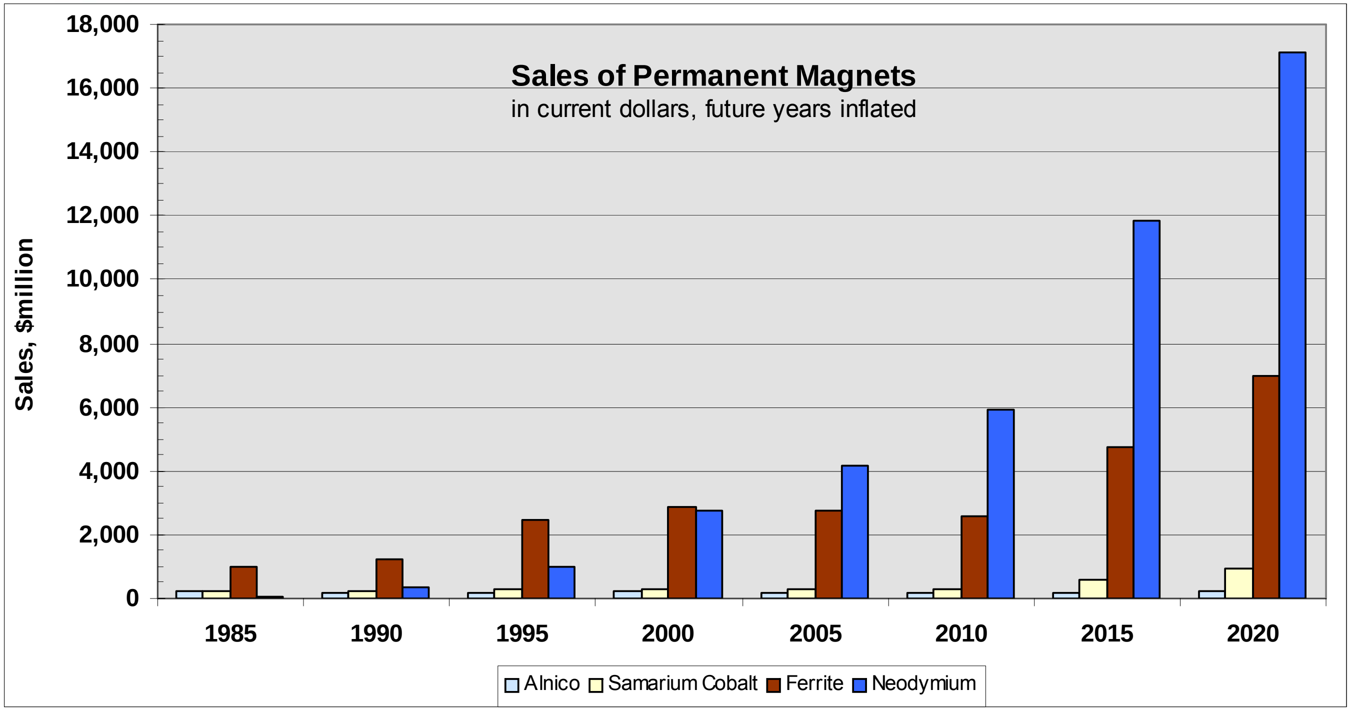


Comparison of magnetic performance only

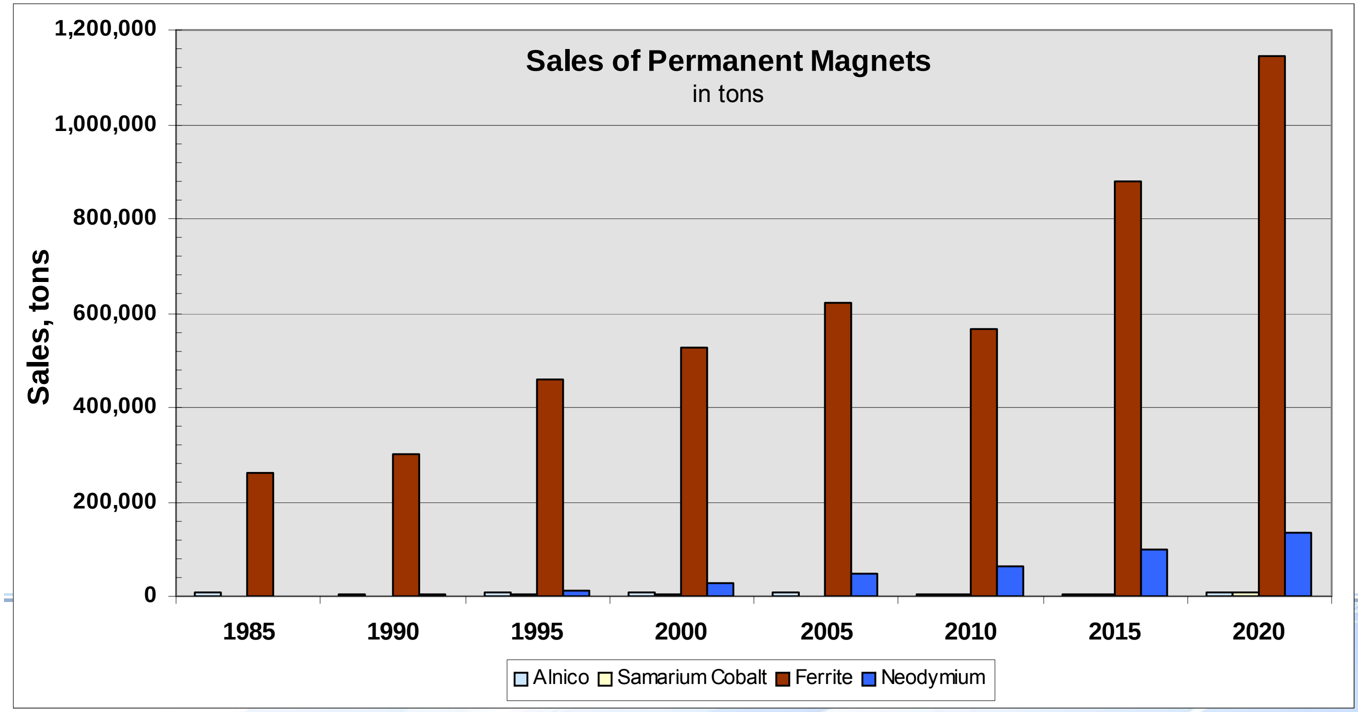


Usable Temperature Range for Common Permanent Magnets





US$

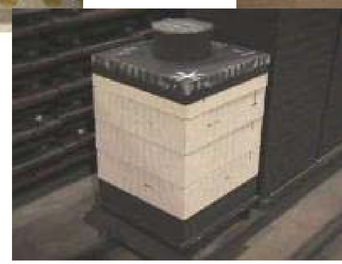


tons

Global Magnet Sales

Alnico Magnet Manufacturing

- Press Sand Molds
- Build Stacks
- Melt alloy
- Break-out
- Rough Grind
- Field Heat Treat
- Finish Grind
- Test
- Assemble

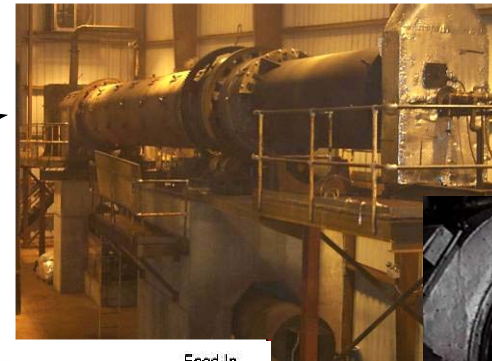


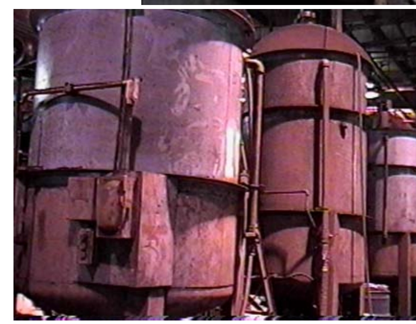


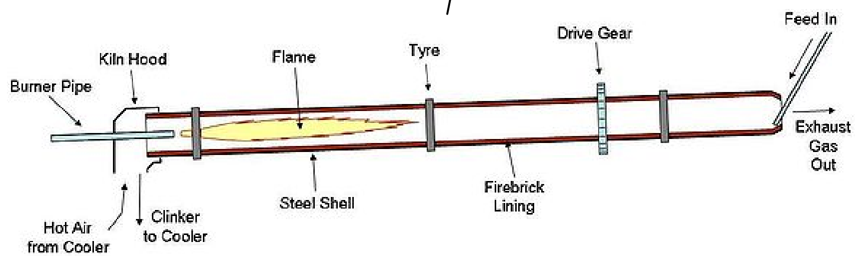


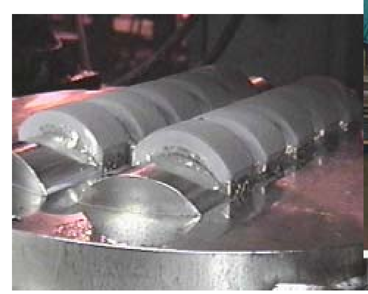

Ferrite Magnet Manufacturing

- Blend Powders
- Calcine
- Mill
- Storage: Dry or Slurry
- Press
- Sinter
- Grind / Slice
- Test







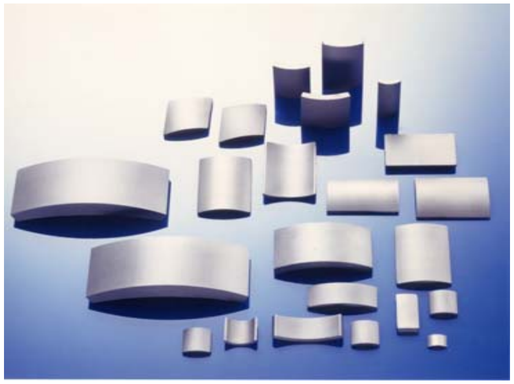


ARNOLD MAGNETIC TECHNOLOGIES

Rare Earth Magnet Supply Chain

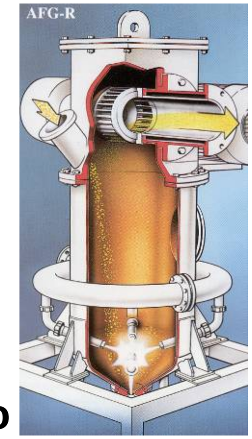
Mine to **Magnet**

- Mine / Mill
- Concentrate
- Separate RE's
- Metal Extraction
- Alloy Melt & Cast
- Hydride
- Fine Milling
- Align & Press
- Sinter
- Finish Machine
- Coat



Neo & SmCo Magnet Manufacturing

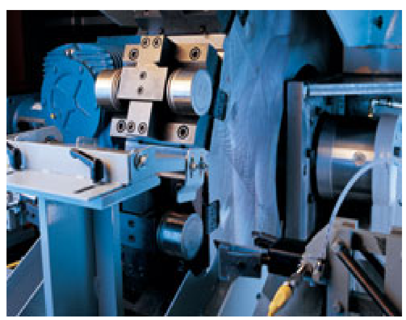
Cast Alloy → H_2 Decrepitate (NdFeB) → Mill to fine powder



→ Press powder

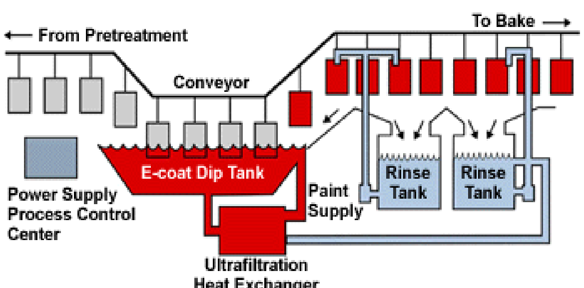
→ Sinter & Anneal

→ Finish Machine
Grind, Slice, EDM



→ Coat
- Nickel Plate
- E-coat
- Aluminum IVD
- …others

Typical Electrocoat System



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Rare Earth Magnet Applications
and RE Oxide Requirements

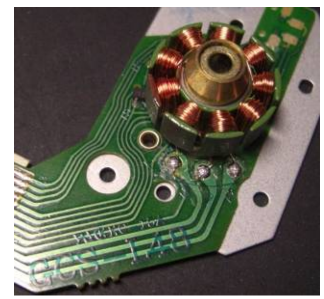
	2010				2015			
	yr 2010	**Magnet**	Oxide, tons		yr 2015	**Magnet**	Oxide, tons	
Applications	**% of mix**	tons	**Nd**	**Dy**	**% of mix**	tons	**Nd**	**Dy**
Motors, industrial, general auto, etc	25.5%	15,871	7,122	1,059	25.0%	24,316	10,912	1,622
HDD, CD, DVD	13.1%	**8,140**	4,196	0	14.4%	**14,040**	7,237	0
Electric Bicycles	9.1%	**5,680**	2,549	379	8.2%	**7,955**	3,570	531
Transducers, Loudspeakers	8.5%	5,290	2,727	0	6.5%	6,322	3,259	0
Unidentified and All Other	6.5%	4,046	1,995	90	6.0%	5,836	2,878	130
Magnetic Separation	5.0%	3,112	1,466	138	3.4%	3,307	1,558	147
MRI	4.0%	2,490	1,228	55	1.5%	1,459	720	32
Torque-coupled drives	4.0%	2,490	1,117	166	2.5%	2,432	1,091	162
Sensors	3.2%	1,992	982	44	1.5%	1,459	720	32
Hysteresis Clutch	3.0%	1,867	879	83	1.5%	1,459	687	65
Generators	3.0%	1,867	769	194	1.0%	973	400	101
Energy Storage Systems	2.4%	1,494	670	100	2.5%	2,432	1,091	162
Wind Power Generators	2.1%	**1,300**	583	87	10.1%	**9,810**	4,402	654
Air conditioning compressors and fans	2.0%	1,245	559	83	2.5%	2,432	1,091	162
Hybrid & Electric Traction Drive	0.9%	**570**	214	80	6.3%	**6,160**	2,308	867
Misc: gauges, brakes, relays & switches, pipe inspection, levitated transportation, reprographics, refrigeration, etc.	7.7%	4,792	2,186	285	7.1%	6,906	3,113	447
Total	100.0%	**62,246**	29,243	2,843	100.0%	**97,296**	45,037	5,115

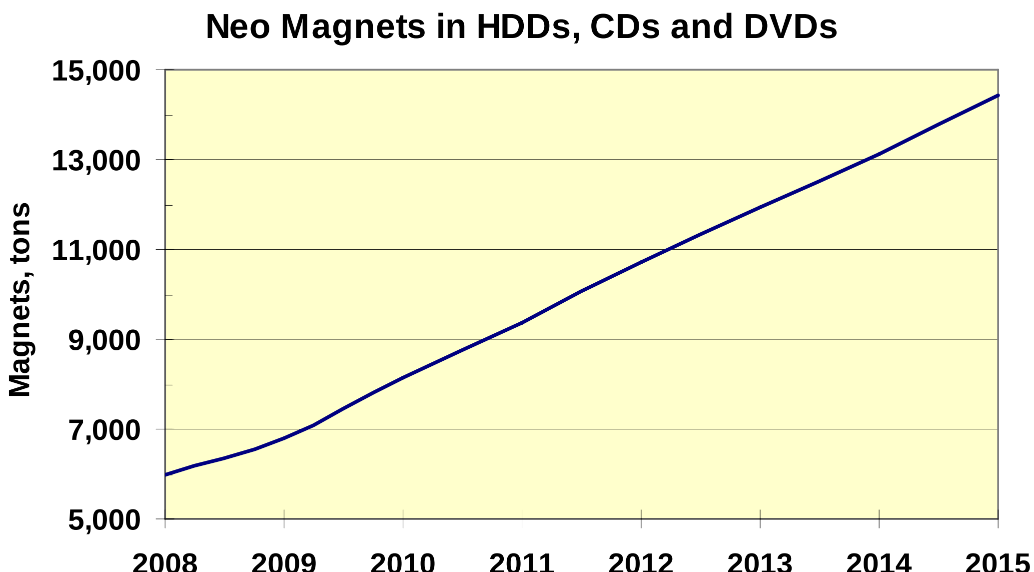
Nd: 54% increase
Dy: 80% increase

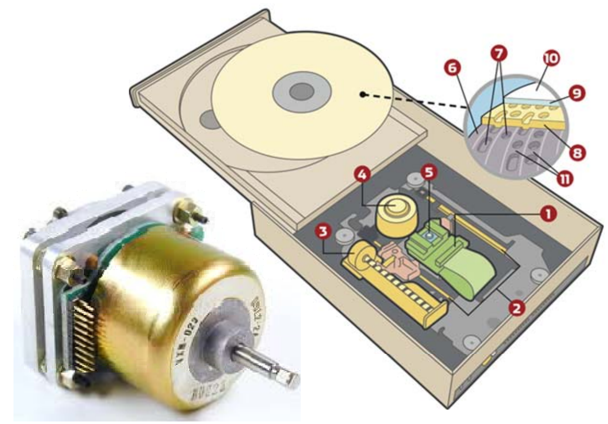
REO requirement includes 80% oxide to metal, 97% metal alloying, and 80% magnet manufacturing material yields.

Hard Disk Drives (HDD’s), CD’s, DVD’s

- Drives (Global): existing and growing market
  - Overall drive shipments for 2008 would total 593.2 million units, up 14.9% compared to… 2007 (iSuppliCorp: www.isuppli.com)
  - Shipments of HDDs alone in the first half of 2011 were 327.6 million, on track for 660 million by year’s end







Transportation

- **EB**’s (electric bicycles) (primarily in Asia): large and growing application especially in 3rd world nations
  - 20 million sold in China in 2009
  - Forecast to 35 million per year in 2015
  - Year 2015 neo magnet usage = **3,800 tons**

- **Hybrid** and **EV** vehicles (Global): in growth phase
  - Estimate of 1.73 million hybrid or EV’s to be manufactured in 2015
  - Total neo magnet usage in **2015** = **4,200 tons**

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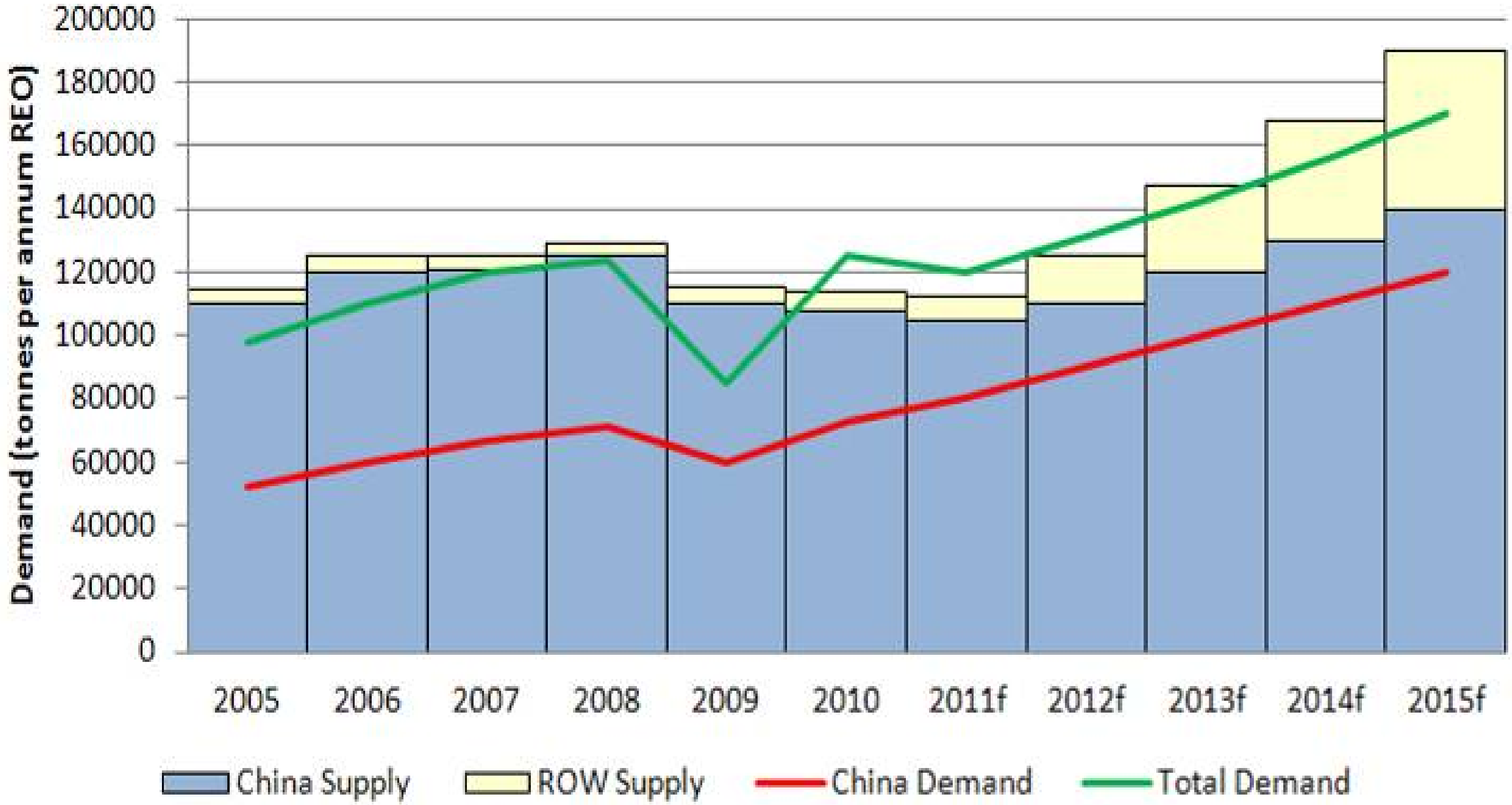
The "Dudley Chart"



Source: Dudley Kingsnorth, IMCOA, 2011

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Rare Earth China Export Quotas

Year		RARE EARTH OXIDE EXPORT QUOTAS							
		1st Allocation		2nd Allocation		Total		Grand Total	% Change
		Domestic Companies	Foreign Companies	Domestic Companies	Foreign Companies	Domestic Companies	Foreign Companies		
2005		n/a	n/a	n/a	n/a	48,040	17,569	65,609	
2006		n/a	n/a	n/a	n/a	45,752	16,069	61,821	-5.8%
2007		19,600	8,211	23,974	8,289	43,574	16,500	60,074	-2.8%
2008		22,780	8,211	11,376	5,082	34,156	13,293	47,449	
		Adjusted for 12-month basis				40,987	15,834	56,939	-6.6%
2009		15,043	6,685	18,257	10,160	33,300	16,845	50,145	-11.9%
2010		16,304	5,978	6,208	1,768	22,512	7,746	30,258	-39.7%
2011		10,762	3,746	12,221	3,517	14,508	15,738	30,246	0.0%
2012	LRE	15,999	6,097	4,000	1,524	19,999	7,621	27,620	
	HRE	2,202	852	551	213	2,753	1,065	3,818	
	Total	18,201	6,949	4,551	1,737	22,752	8,686	31,438	3.9%

Separating rare earth export quotas into LREs and HREs suggests that China understands they need to be separately managed

2012 quotas are divided into LRE and HRE; 1st half quotas were published and updated May 17; second half quotas are inferred to be 20% of annual total resulting in a 3.9% increase year over year.

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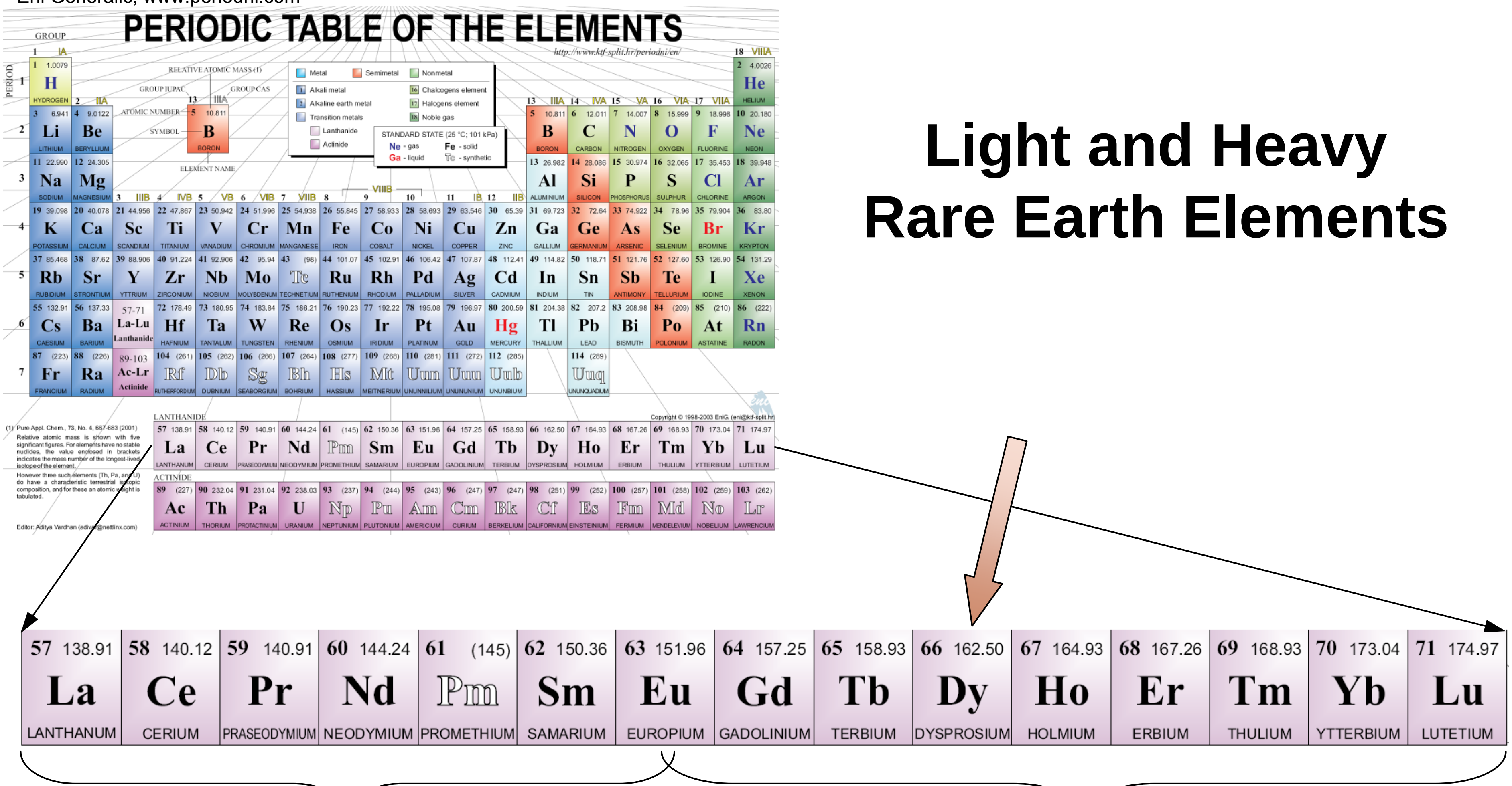
Light and Heavy Rare Earth Elements

Eni Generalic, www.periodni.com



LREEs
Light Rare Earth elements

HREEs
Heavy Rare Earth Elements

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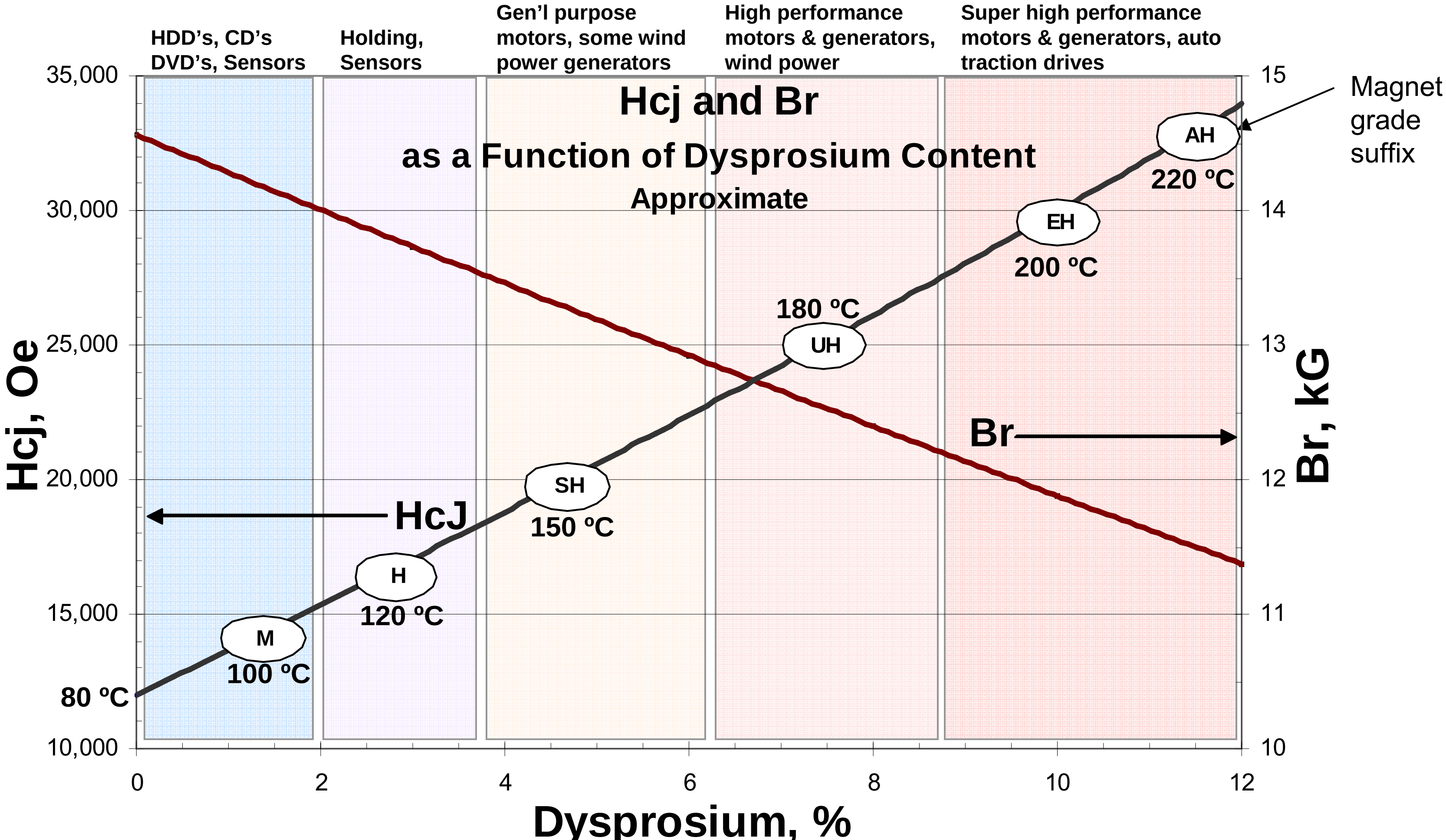
Dysprosium is a Short & Long Term Issue

	2010 Production[69]	Potential Sources of Additional Production between 2010 and 2015										Total 2015 Production Capacity	Supply Increase
		United States		Australia			Vietnam	South Africa				
		Mt. Pass Phase I[72]	Mt. Pass Phase II	Mt. Weld[73]	NolansBore[74]	Dubbo Zirconia[75]	Dong Pao[76]	Steenkamps-kraal[77]	Russia & Kazakhs-tan[70]	India[71]		
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	65% increase
Sm	2,800	130	160	510	240	56	27	125	5	68	4,000	43% increase
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	6% increase
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	

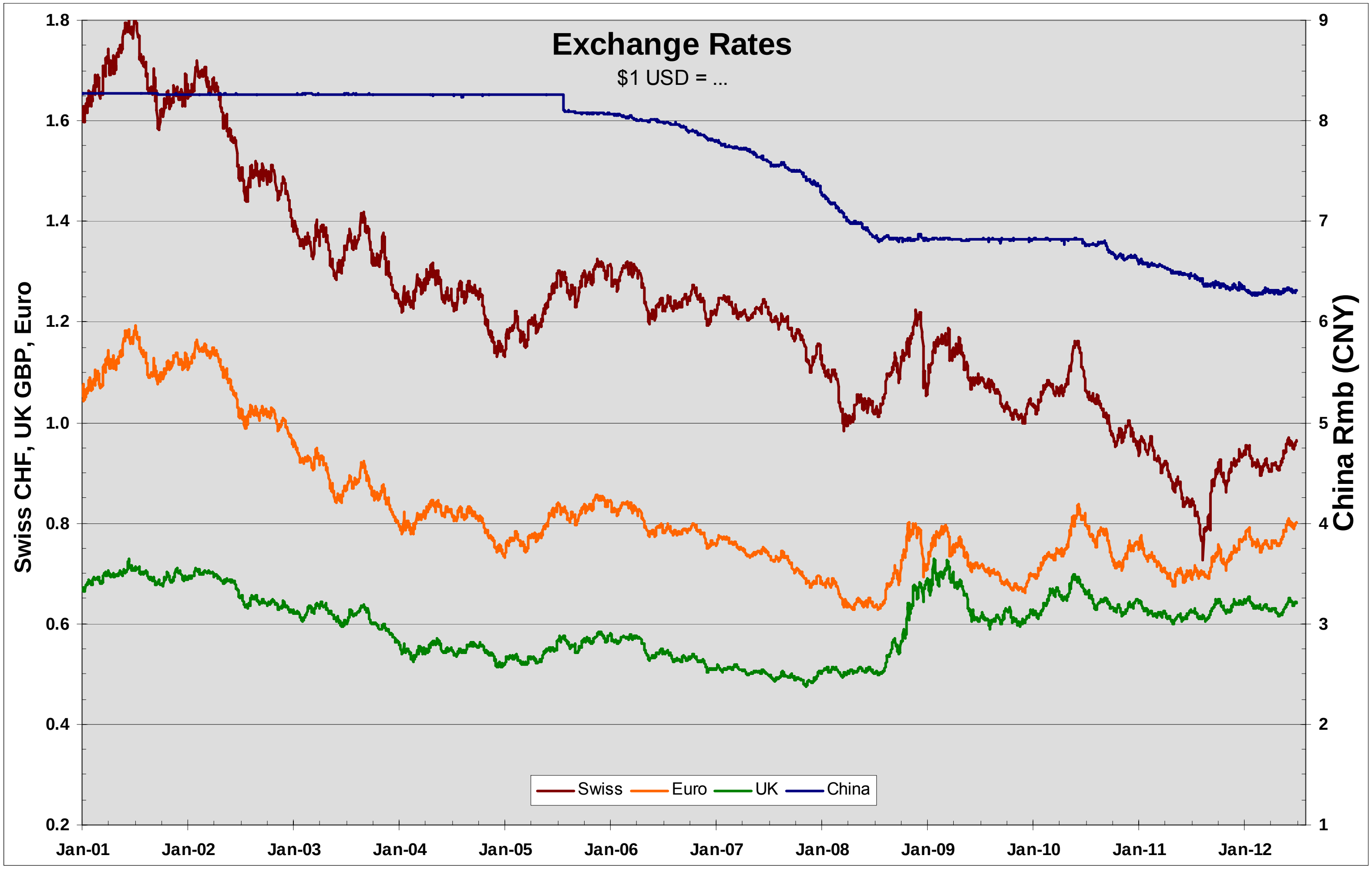
Quantities are metric tons of Rare Earth Oxides
DOE Critical Materials Strategy, final version January 10, 2012; Table 4.2, p.84

Neo Magnet Dysprosium Issue



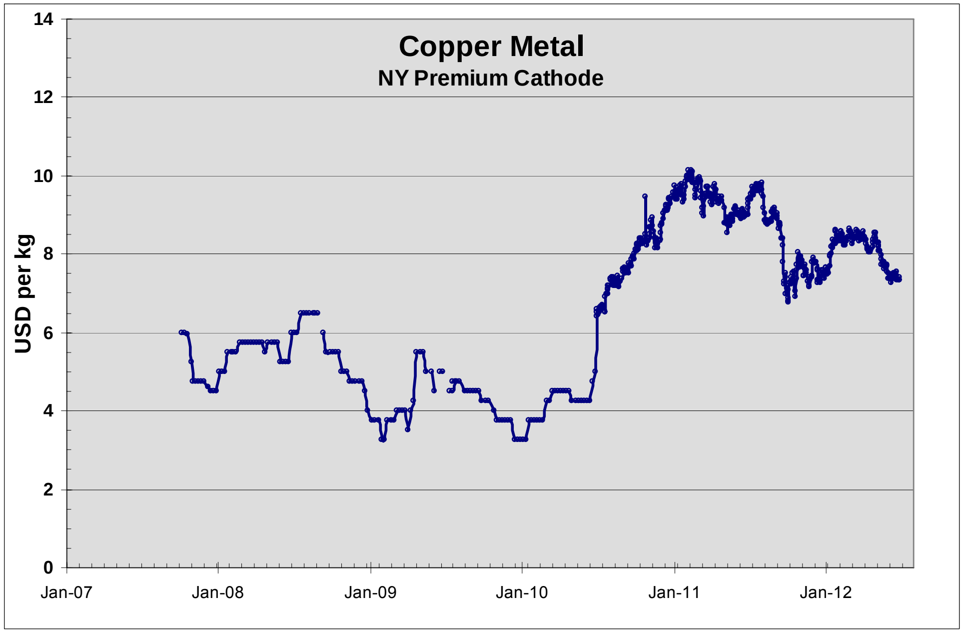
Temperature is manufacturer's maximum recommended use temperature

Selected Currency Exchange Rates



Copper and Aluminum Pricing

Through June 28, 2012



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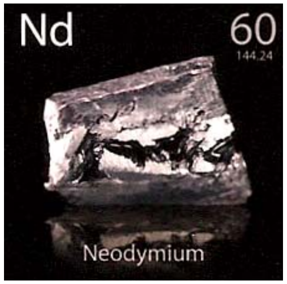
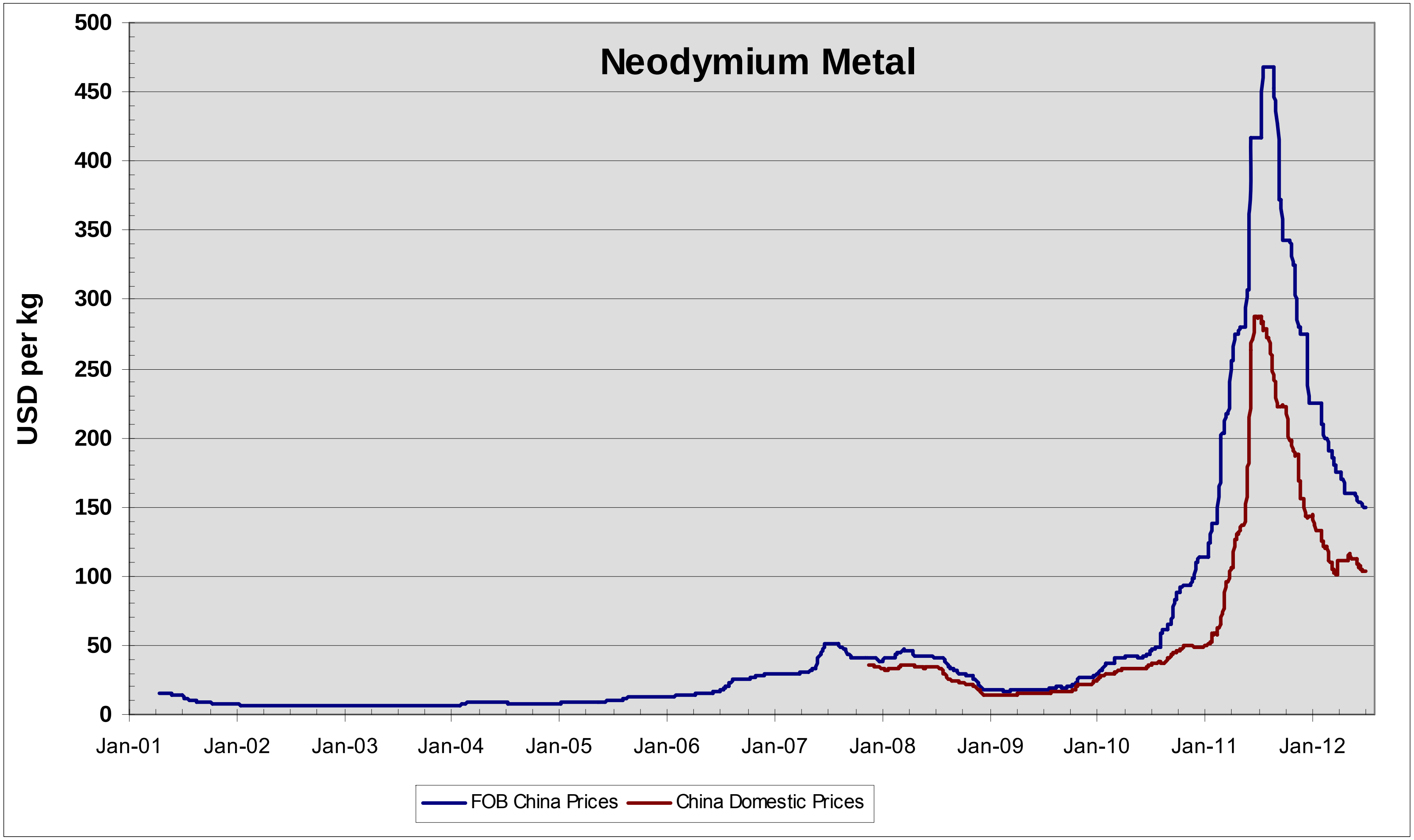
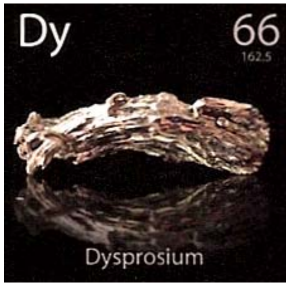
RE Metal Pricing

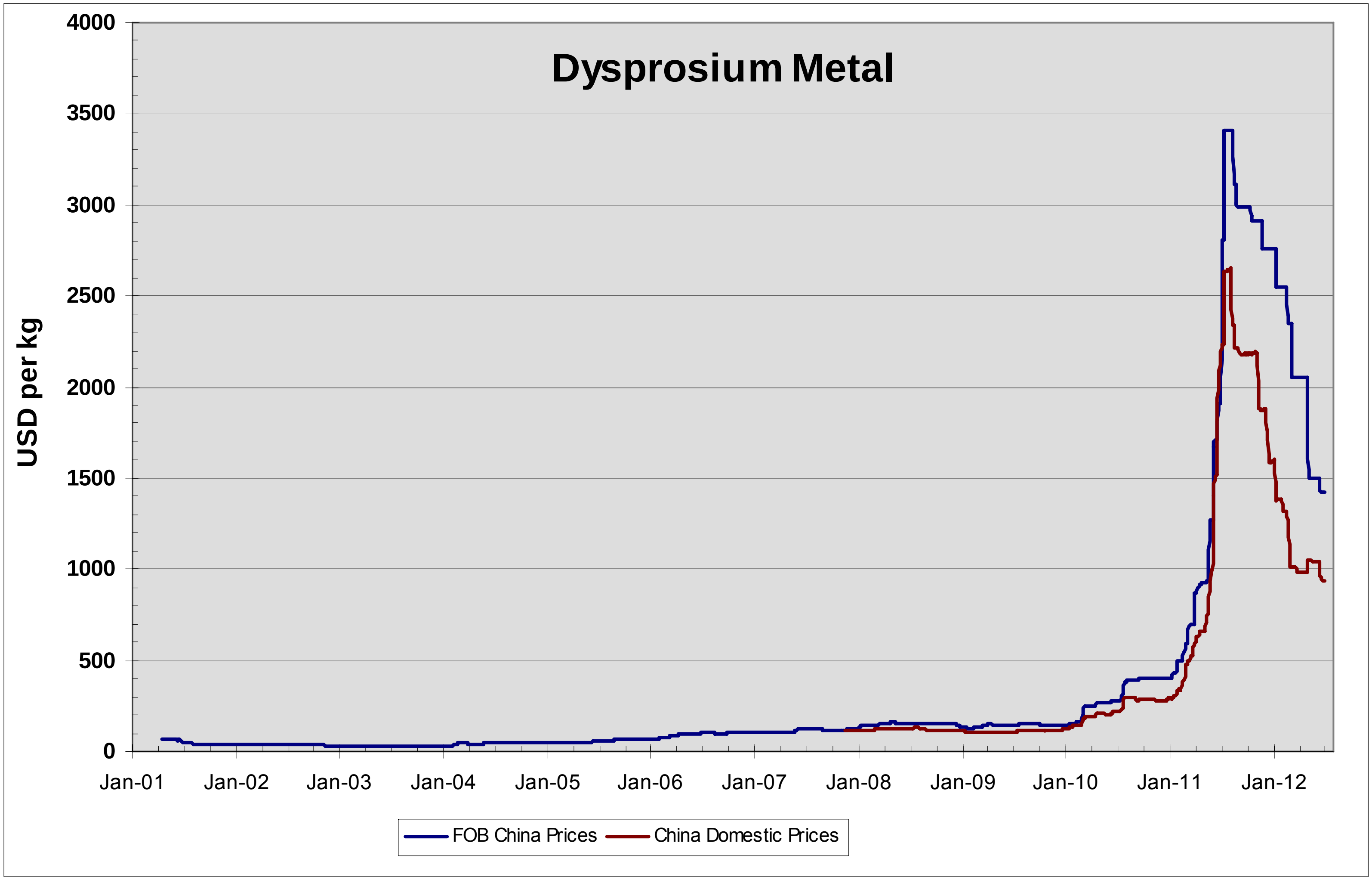
Through June 28, 2012





RE Metal Pricing
Through June 28, 2012





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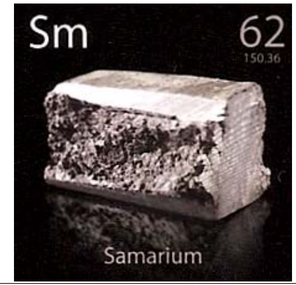
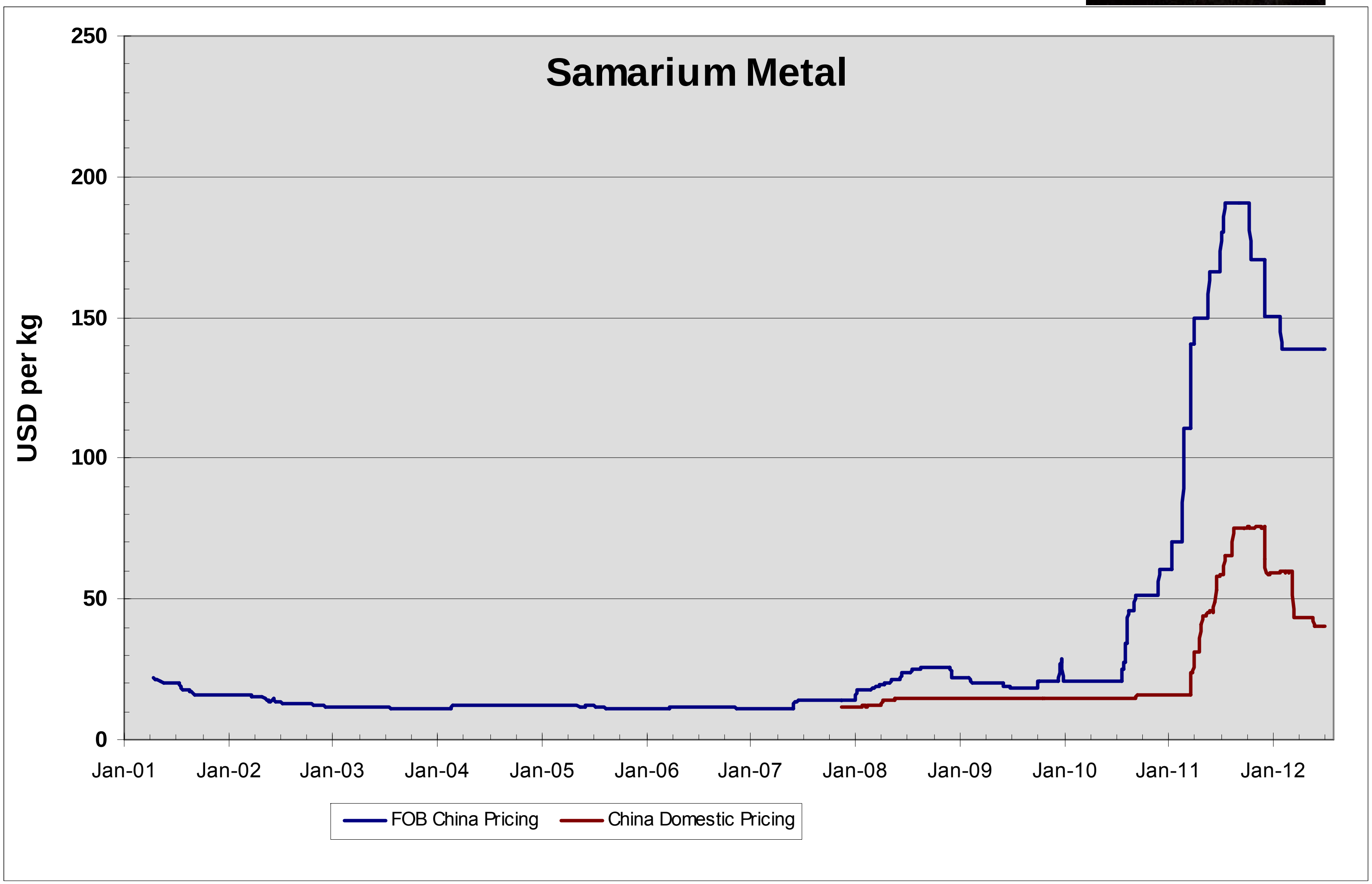


RE Metal Pricing

Through June 28, 2012



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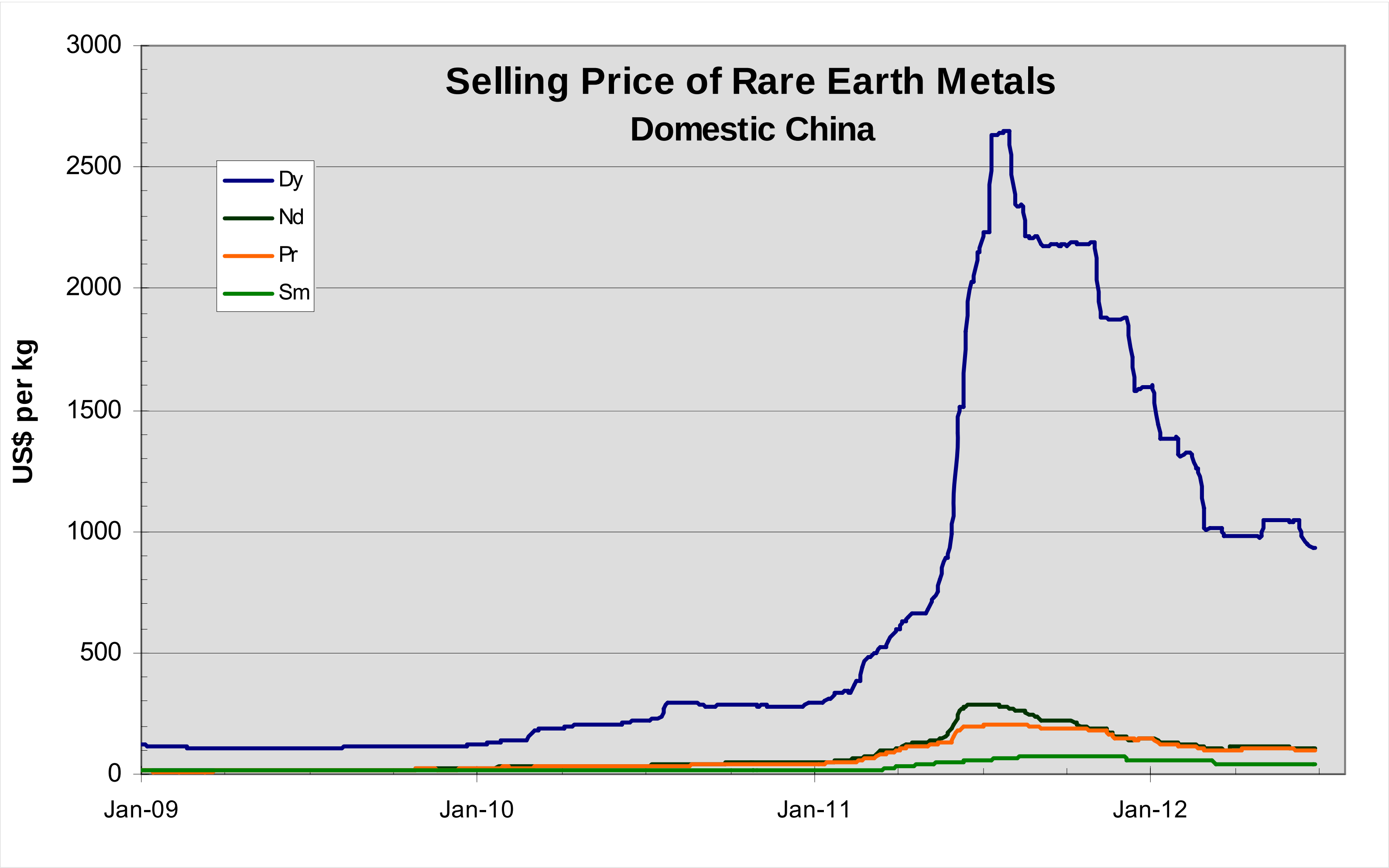
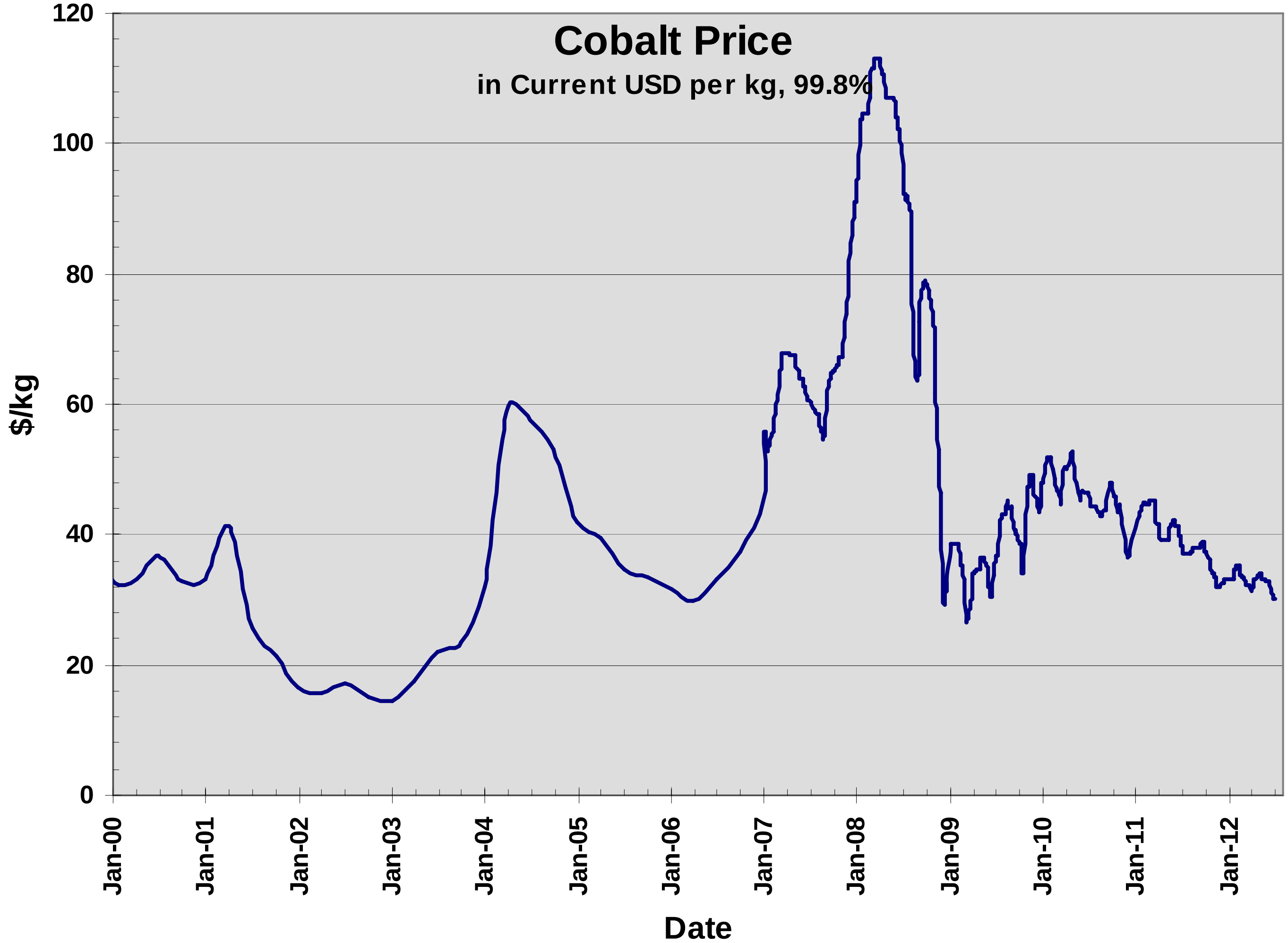
RE Metal Pricing

Through June 28, 2012



Material Pricing: Cobalt

Through June 28, 2012



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Magnet Material Costs

in US Dollars, June 28, 2012

Domestic China Raw Material Costs, USD

Element	SmCo 26HE	SmCo 30S	N30AH	N35EH	N40UH	N45SH
Nd	-	-	21.5	23.9	26.3	28.7
Dy	-	-	102.8	81.3	59.8	38.3
Sm	10.5	10.5	-	-	-	-
Co	15.1	15.1	0.2	0.2	0.2	0.2
Fe	0.2	0.2	0.8	0.8	0.8	0.8
Other	0.4	0.4	0.1	0.1	0.1	0.1
Total	**26**	**26**	**125**	**106**	**87**	**68**

- **While neodymium has become expensive it is the very expensive dysprosium that dominates Neo magnet material costs.**
  - Based on 1 kg block magnet
  - Material prices as published by Asian Metals and Metal Pages

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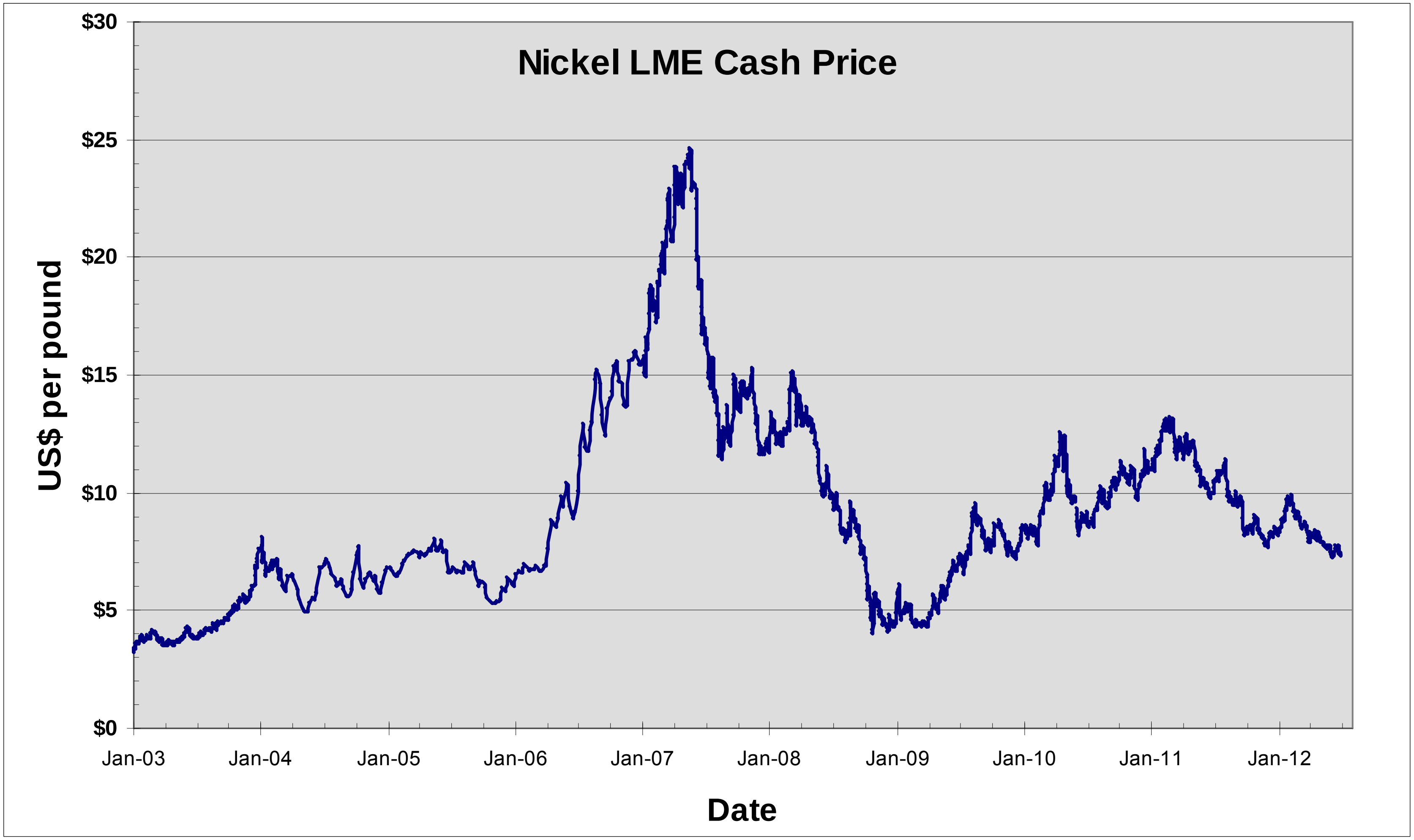
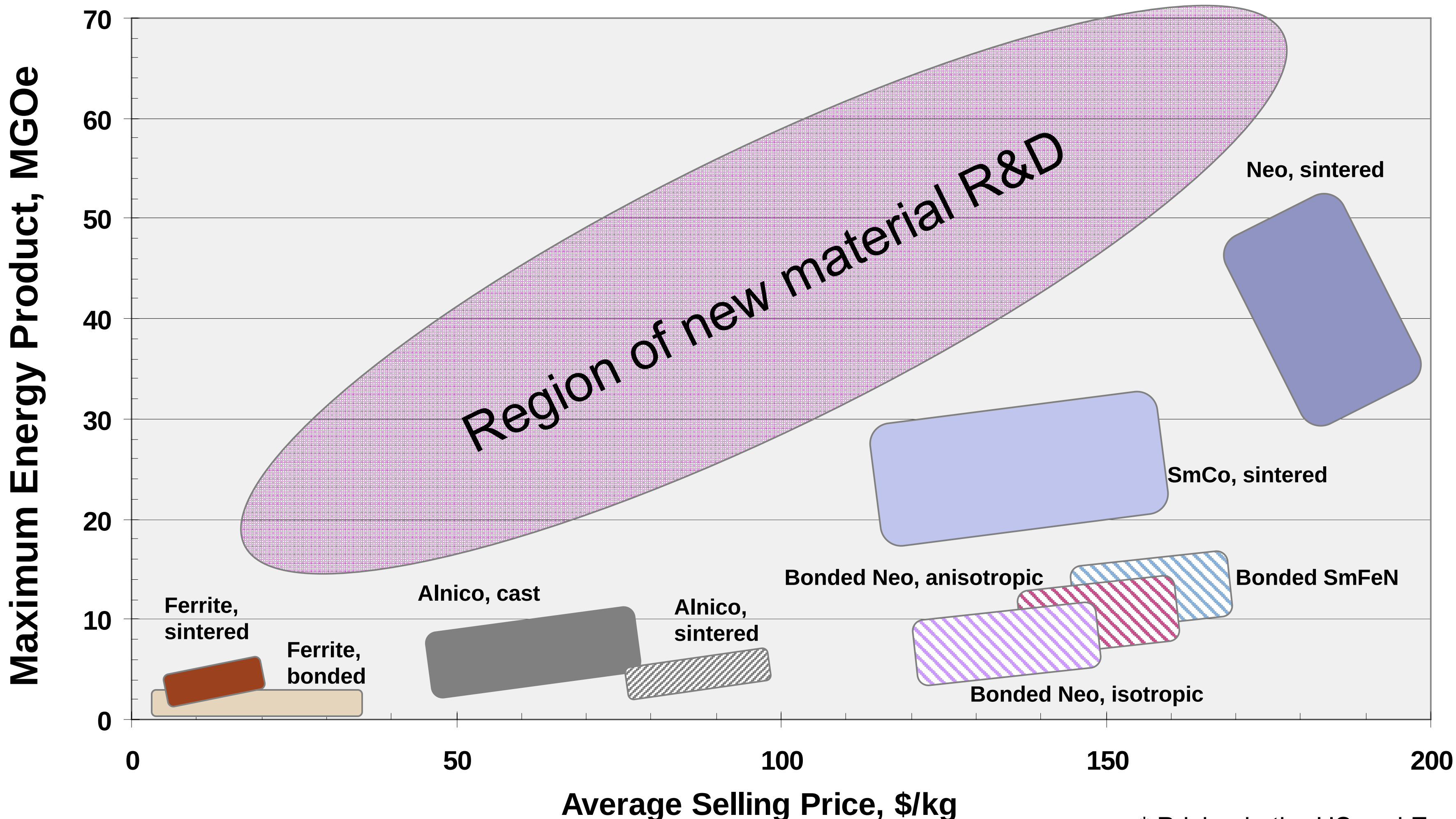
Material Pricing: Nickel
Through June 28, 2012



Magnet Price* versus Energy Product



* Pricing in the US and Europe

Widely Available Materials

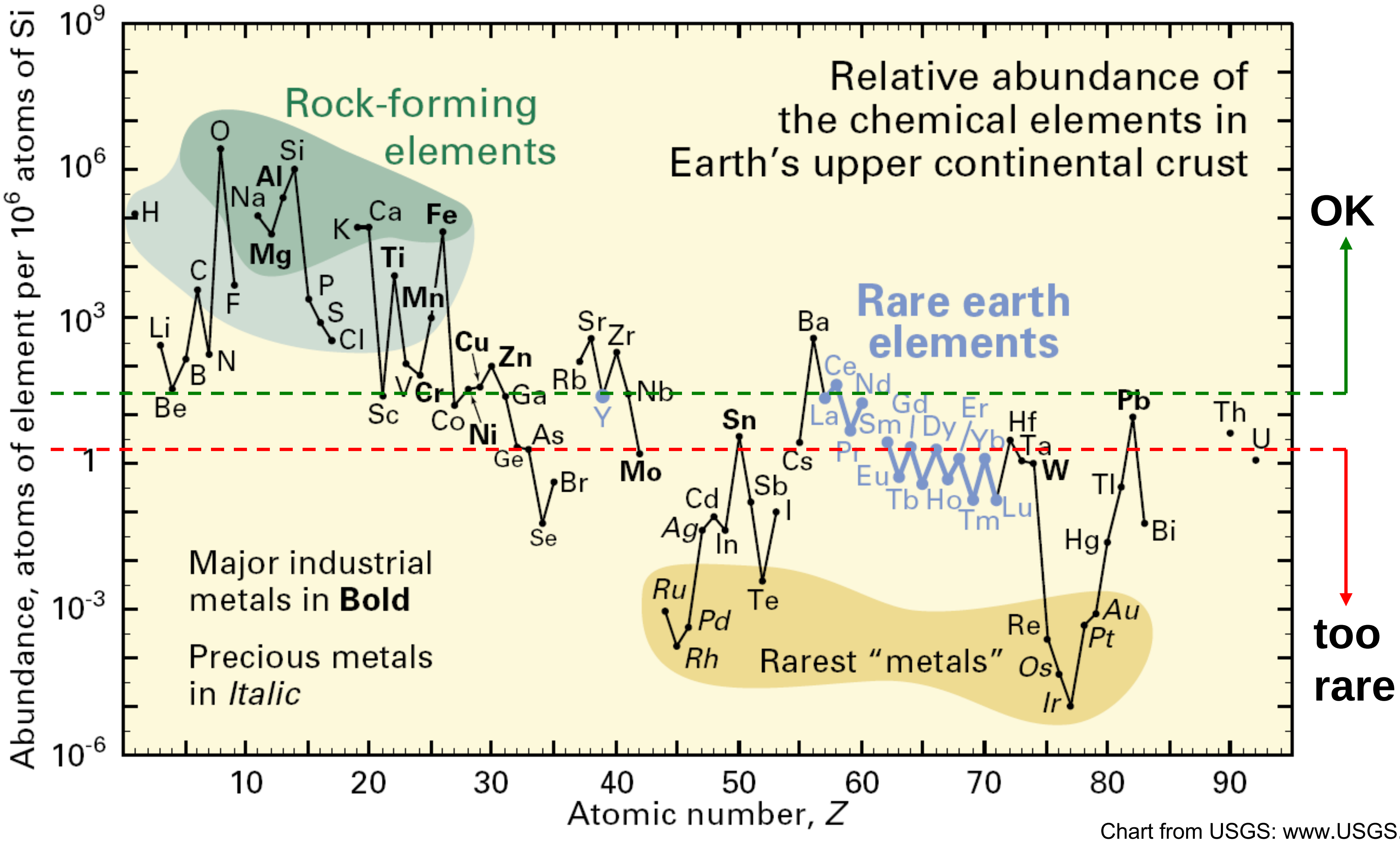


Chart from USGS: www.USGS.org

- Research -
Variations on a Theme
Revisiting & modifying prior materials

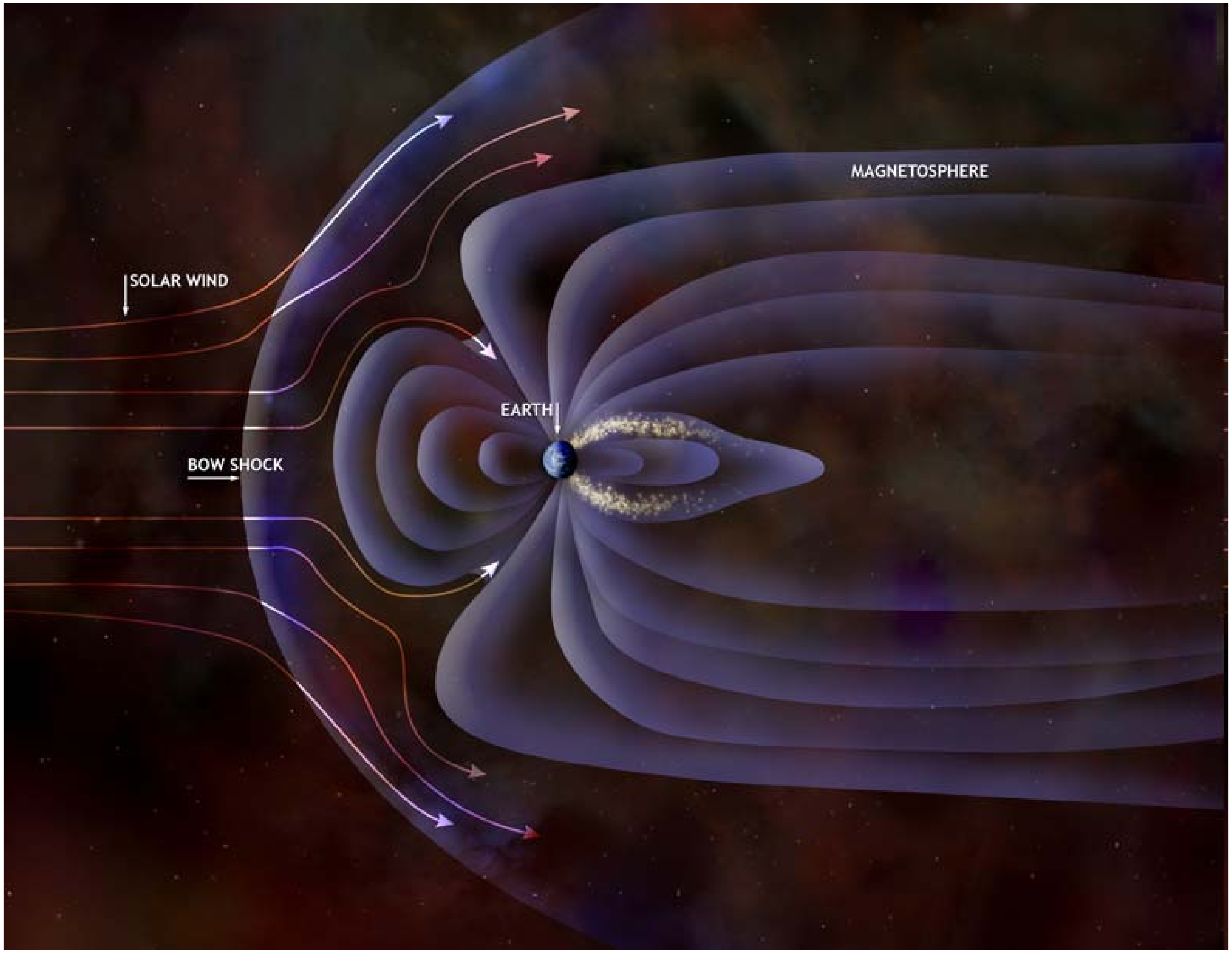
- SmCo plus exchange-coupled soft phase
- NdFeB plus exchange-coupled soft phase
- Fe-N (variation of SmFeN), interstitial N
- Mn alloys: MnBi, MnAlC
- Heusler alloys
- Alnico – modified to enhance coercivity
- Carbides: FeC, CoC
- Modified Ferrites (chemical or structural modifications): La-Co Ferrites, Core-Shell structure ferrites
- Ce-Co,Fe and Ce-Fe,Co-B,C

- Research -
"Greenfield" Magnets

- Computer calculations to arrive at alloy structure with net magnetic moment
- Promising alloys are then formed in the lab and evaluated
- 2 and 3-component alloys are practical
  - 4+ component alloys represent significant computational difficulty
- Finished magnet must be...
  - Fully dense to take advantage of undiluted properties
  - Domains must be oriented to that the magnetic field is in one preferred direction

Summary

- The selection and use of materials in production and utilization of electric energy requires consideration of many factors including
  - price and availability
  - appropriateness for the application
  - environmental impact
- Practical alternatives to rare earth magnets may not exist for some applications
  - this maintains the burden on adequate supply of rare earths
- Dysprosium is the single most important element in the RE magnet supply dynamic
- Alternative technologies and materials will be employed where cost and availability dictate and performance, size and weight permit
- Reduction or elimination of rare earth elements and other expensive ingredients in high performance permanent magnets is a focus of numerous R&D initiatives
  - R&D is a long process and not likely to relieve the rare earth criticality short to mid-term



http://chandra.harvard.edu/photo/2005/earth/index.html