ARNOLD
MAGNETIC TECHNOLOGIES

Electricity, Magnetism and… Survival

Steve Constantinides, Director of Technology
Arnold Magnetic Technologies Corporation
March 1, 2015

APS physics MARCH MEETING 2015

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What we do…

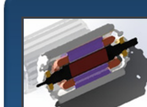
Performance materials enabling energy efficiency

Magnet Production & Fabrication

- Rare Earth Samarium Cobalt (RECOMA®)
- Alnico
- Injection molded
- Flexible Rubber

Permanent Magnet Assemblies

- Precision Component Assembly
- Tooling, Machining, Cutting, Grinding
- Balancing
- Sleeving



High Performance Motors

- Smaller, Faster, Hotter motors
- Power dense package
- High RPM magnet containment
- >200°C Operation

Precision Thin Metals

- Specialty Alloys from 0.000069” (~1.75 microns)
- Sheets, Strips, & Coils
- Milling, Annealing, Coating, Slitting
- ARNON® Motor Lamination Material
- Light-weighting

Engineering | Consulting | Testing
Stabilization & Calibration | Distribution

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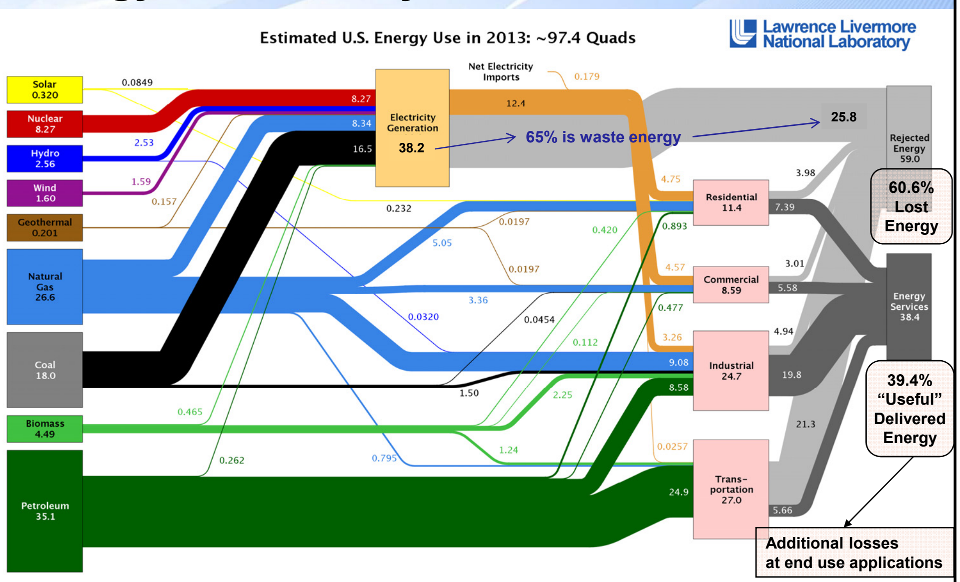
Agenda

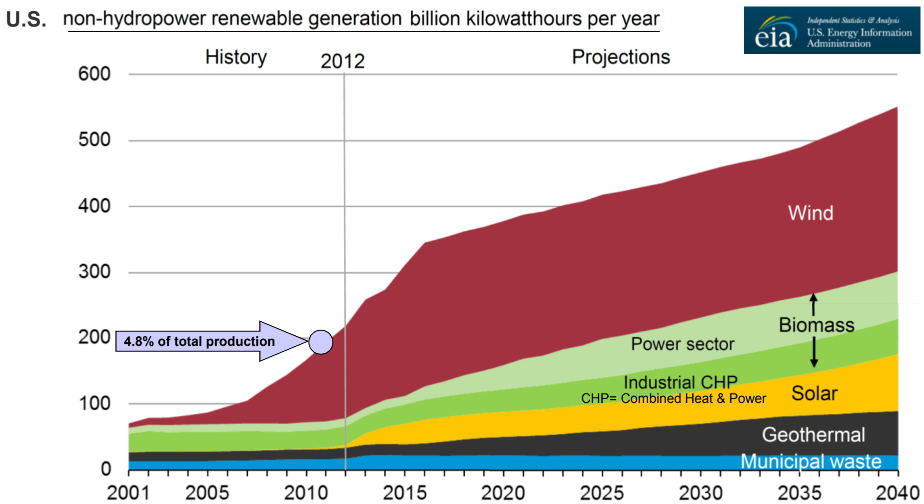
- **Energy and Magnetism**
- Permanent Magnets and Motors
- Applications
- Soft magnetic materials
- Future of magnetic materials

Energy in-Efficiency



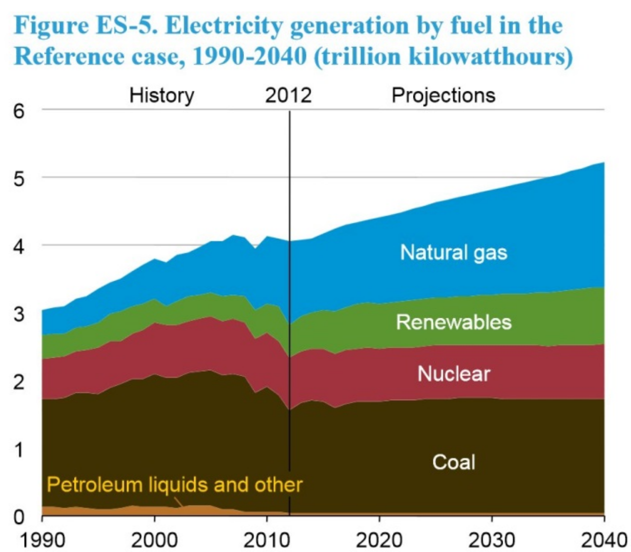
A quad is a unit of energy equal to 10^{15} (a short-scale quadrillion) BTU, or 1.055×10^{18} joules (1.055 exajoules or EJ) in SI units.

Renewable Energy Electricity Generation (USA)



Annual Energy Outlook 2014 with projections to 2040, U.S. Energy Information Administration, www.eia.gov/forecasts/aeo

Overall Electric Generation - USA

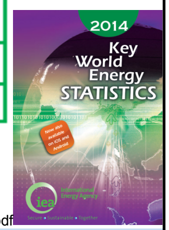


Annual Energy Outlook 2014 with projections to 2040, p.MT-16, U.S. Energy Information Administration, www.eia.gov/forecasts/aeo

Fuel used for production of electricity - 2012

Coal*	TWh	Natural gas	TWh	Oil	TWh
People's Rep. of China	3 785	United States	1 265	Japan	181
United States	1 643	Russian Federation	525	Saudi Arabia	150
India	801	Japan	397	Islamic Rep. of Iran	69
Japan	303	Islamic Rep. of Iran	170	Mexico	56
Germany	287	Mexico	151	Kuwait	40
Korea	239	Italy	129	Pakistan	35
South Africa	239	Egypt	125	United States	33
Australia	171	Saudi Arabia	121	Indonesia	33
Russian Federation	169	Thailand	117	Russian Federation	28
United Kingdom	144	Korea	112	Egypt	25
Rest of the world	1 387	Rest of the world	1 988	Rest of the world	478
World	**9 168**	**World**	**5 100**	**World**	**1 128**

We use the fuels which are available to us



International Energy Agency: http://www.iea.org/publications/freepublications/publication/keyworld2014.pdf

Electricity and magnetic materials

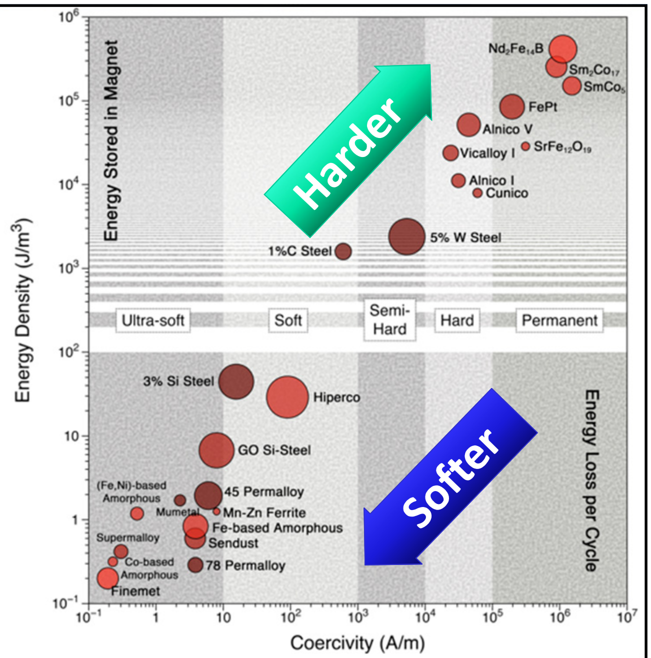
What is the role of magnetic materials?

They facilitate the efficient…

- **Conversion of mechanical into electrical energy**
  Both soft and permanent magnetic materials
- **Transmission of electrical energy**
  Primarily soft magnetic materials
- **Conversion of electrical into mechanical energy**
  Both soft and permanent magnetic materials

Spectrum of magnetic materials

M. A. Willard, "Stronger, Lighter, and More Energy Efficient: Challenges of Magnetic Material Development for Vehicle Electrification" Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2012 Symposium, National Academies Press: Washington, DC (2013) pp. 57-63.



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Ferrite magnet use

Greater than 88% of all permanent magnets on a weight basis.

Motors - Automotive	18%	70% in motors
Motors - Appliances	13%	
Motors - HVAC	13%	
Motors - Industrial & Commercial	12%	
Motors - All Other	5%	
Loudspeakers	9%	
Separation Equipment	5%	
Advertising & Promotional Products	5%	
Holding & Lifting	5%	
MRI	3%	
Relays & Switches	1%	
All Other - Miscellaneous	11%	

Source: Numerous including Benecki, Clagett and Trout, personal communications with industrial partners, conferences, suppliers, etc.

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Rare Earth magnet use (2010)

Greater than 65% of all permanent magnets on a $$ basis.

Motors, industrial, general auto, etc	24.0%	●
HDD, CD, DVD	16.3%	●
Electric Bicycles	8.4%	●
Transducers, Loudspeakers	8.1%	●
Magnetic Separation	4.6%	
MRI	3.9%	
Torque-coupled drives	3.3%	
Sensors	3.1%	
Generators	3.0%	●
Hysteresis Clutch	2.8%	
Air conditioning compressors and fans	2.4%	●
Energy Storage Systems	2.3%	●
Wind Power Generators	1.9%	●
Gauges	1.5%	
Magnetic Braking	1.5%	
Relays and Switches	1.3%	
Pipe Inspection Systems	0.9%	
Hybrid & Electric Traction Drive	0.8%	●
Reprographics	0.6%	
Wave Guides: TWT, Undulators, Wigglers	0.3%	
Unidentified and All Other	6.6%	

● Motor-type applications = 67%

Updated June 2014

Source: Numerous including Benecki, Clagett and Trout, personal communications with industrial partners, conferences, suppliers, etc.

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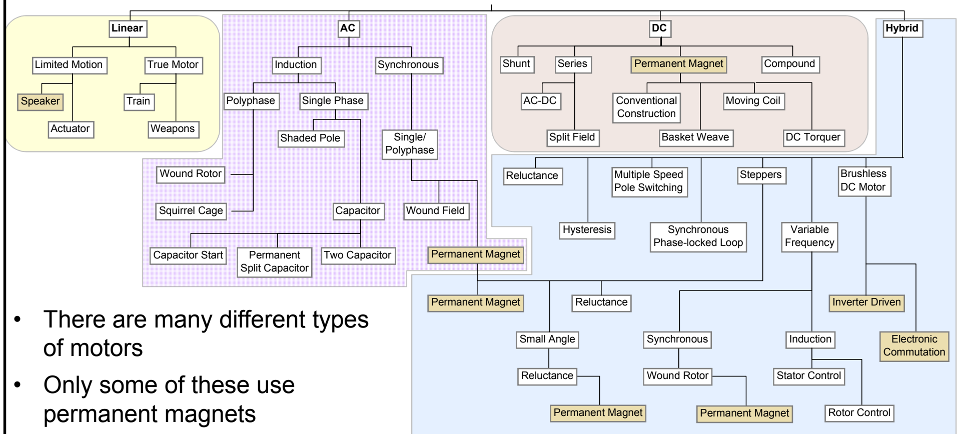
Motors and Generators

The Electric Motor Family

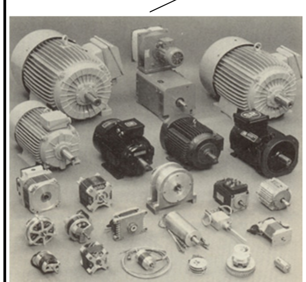


- There are many different types of motors
- Only some of these use permanent magnets
- Virtually all use soft magnetic alloys
- Sophisticated electronics now power many motors

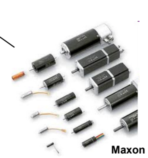
Based on: Rollin J. Parker, Advances in Permanent Magnetism, Figure 7.26, Motor family tree

Electric Motors

to very big



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



Maxon

From very small

Electric Ship Propulsion Motors

Specifications: 36.5 MW PM Machine for Electric Ship Propulsion

Performance	
Output	50,000 HP (36.5 MW)
Speed	1-127 RPM
Torque	>2 M ft. lbs. (2.7M Nm)
Motor Efficiency	97.5%
Mechanical	
Motor Length	202 inches (5.1 meters)
Motor Width	214 inches (5.4 meters)
Motor Height	209 inches (5.3 meters)
Motor Weight	280,000 lbs. (127 tonnes, 127,000 kg)
Cooling Method	Fresh water
Electrical	
Voltage	1450 VAC
Phases	Doubly-fed, 3-phase
Insulation Class	R (220° C)
Temperature Rise	H (180° C)

World electricity consumption

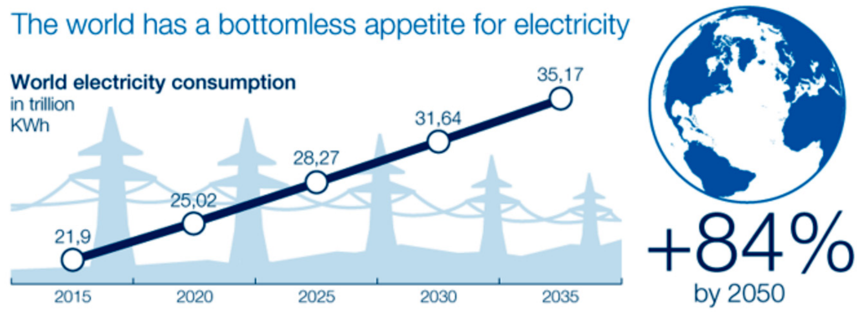


ABB Power and productivity for a better world™

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Electricity consumption by motors

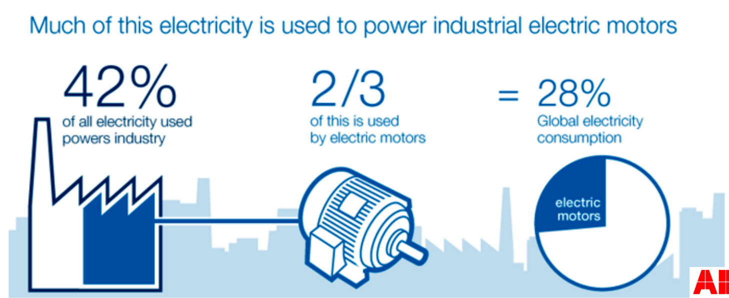

ABB Power and productivity for a better world™

"…~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

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Automotive Motors & Actuators

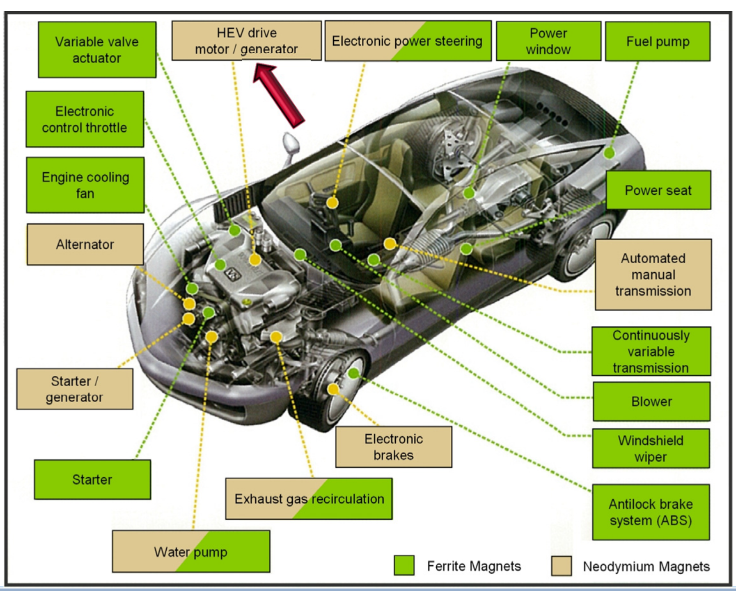

Illustration from Hitachi Magnetics

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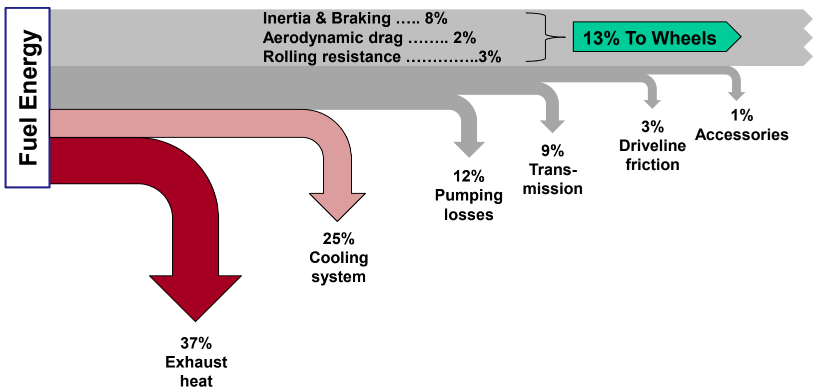
ICE Vehicle Energy Budget

100 units of input energy result in only 13 units of usable propulsion energy



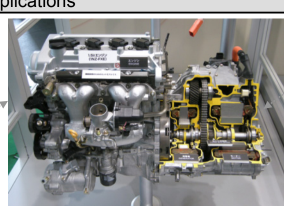
Adapted from - *Direct Conversion of Heat to Electricity*, T.A. Keim and I. Celanovic, Convergence 2008
And from - *Energy Storage in Transportation,* Dr. J.M. Miller, presentation at Florida State University

Comparison of Traction Drive Motor Technologies

	Permanent Magnet Motor	Induction Motor	Reluctance Motor
Cost ($/kW)	$$$	$$	**$**
Power density (kW/L)	**Highest**	Moderate	Moderate
Specific power (kW/kg)	**Highest**	Moderate	Moderate
Efficiency (%)	**Best**	Good	Better
Noise and vibration	Good	Good	Unacceptable
Manufacturability	Difficult	Mature	**Easy**
Potential for technical improvement for automotive applications	Significant	Minimal	Significant

Comparison of traction drive motor topologies – L. Marlino, ORNL

4-cylinder ICE



Electric traction drive motor

Wikipedia:
English Toyota 1NZ-FXE 1.5L Straight-4 Engine and Electric-Drive Motor
Date 22 August 2008
Source Own work
Author Hatsukari715

Alternative Powertrain Types

Examples

HEV **Hybrid Electric Vehicle**
Uses both an electric motor and an internal combustion engine to propel the vehicle.
Example: Prius

PHEV **Plug-In Hybrid Electric Vehicle (PHEV)**
Plugs into the electric grid to charge battery - is similar to a pure hybrid and also utilizes an internal combustion engine.
Example: Plug-in Prius

EREV **Extended Range Electric Vehicle (EREV)**
Operates as a battery electric vehicle for a certain number of miles and switches to an internal combustion engine when the battery is depleted.
Example: Volt

BEV **Battery Electric Vehicle BEV)**
Powered exclusively by electricity from it's on-board battery, charged by plugging into the grid
Example: Leaf; Tesla Model S

FCEV **Fuel Cell (Electric) Vehicle (FCEV)**
Converts the chemical energy from a fuel, such as hydrogen, into electricity.
Example: Honda FCX Clarity; Hyundai Tuscon

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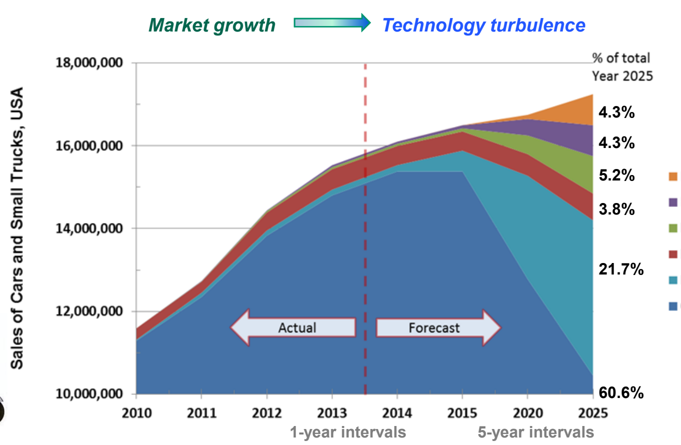
Steve's Forecast - USA market











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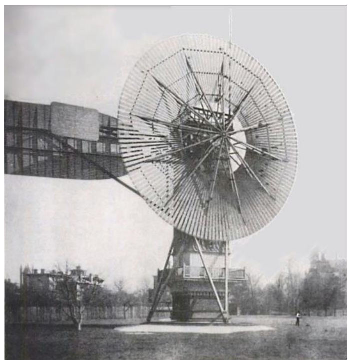
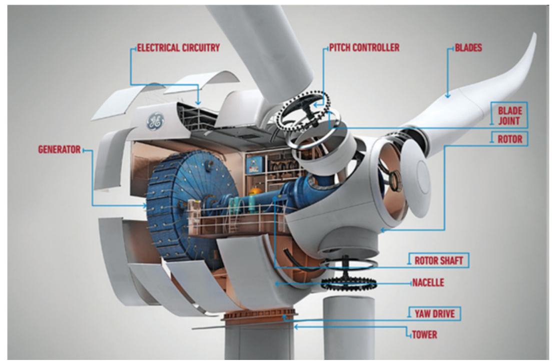
Wind Energy



Charles Francis Brush wind mill from 1888



GE Gen-4 Permanent magnet generator

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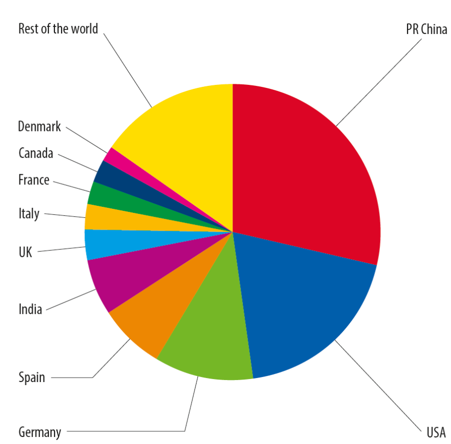
Cumulative installed utility-scale wind power

Through December 2013

Country	MW	% SHARE
PR China	91,424	28.7
USA	61,091	19.2
Germany	34,250	10.8
Spain	22,959	7.2
India	20,150	6.3
UK	10,531	3.3
Italy	8,552	2.7
France	8,254	2.6
Canada	7,803	2.5
Denmark	4,772	1.5
Rest of the world	48,352	15.2
Total TOP 10	**269,785**	**84.8**
World Total	**318,137**	**100.0**



Sources: http://www.gwec.net/wp-content/uploads/2014/04/GWEC-Global-Wind-Report_9-April-2014.pdf and http://www.gwec.net/wp-content/uploads/2014/02/GWEC-PRstats-2013_EN.pdf

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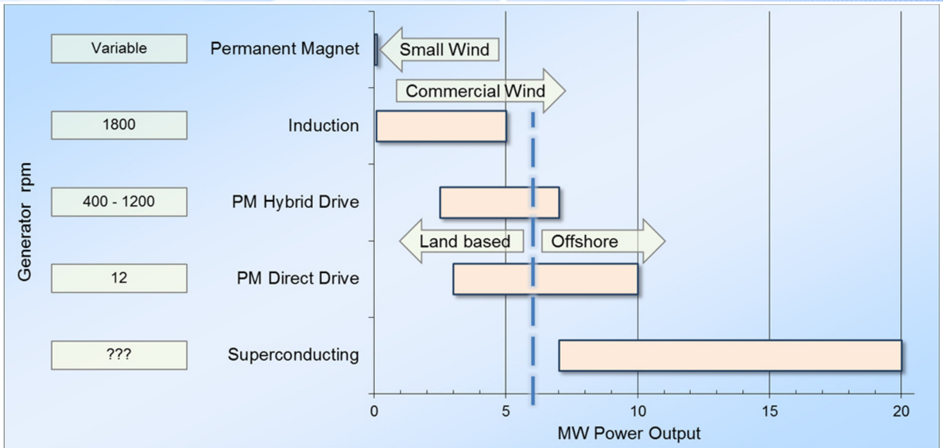
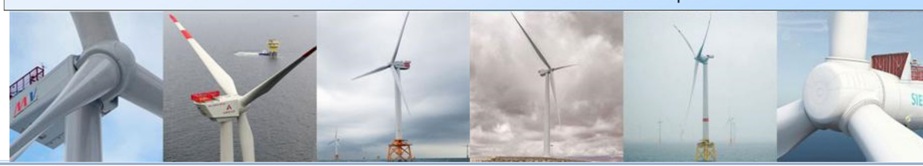
Types and Locations of Installations





Offshore Turbine development

TOP TEN OFFSHORE TURBINES *The wind industry's biggest, heaviest and most expensive products compared and contrasted*

Model	IEC class	Power rating	Rotor diameter	Drive system	Noteworthy
MHI-Vestas V164-8.0MW (Denmark)	S	8MW	164m	MSG, PMG	Clever combination of evolutionary and innovative design features; flanged tube-shaped drivetrain, favourable 500-tonne head mass
Ming Yang SCD 6.0 (China)	IIB	6MW	140m	MSG, PMG	Innovative two-blade downwind turbine with compact semi-integrated drivetrain and single rotor bearing, focused at typhoon-prone markets
Siemens SWT-6.0-154 (Germany)	I	6MW	154m	DD, PMG	Single rotor bearing; largest rotor diameter in 6MW class, converter and transformer in nacelle; favourable head mass
Alstom Haliade 150-6MW (France)	I	6MW	150.8m	DD, PMG	Stationary main shaft (pin); "pure torque" principle decouples rotor-bending moments and generator drive torque
Siemens SWT-4.0-130 (Germany)	I	4MW	130m	HSG, IG	Evolutionary development and optimisation of SWT-3.6-120 model, which has been the offshore market leader for several years
Senvion 6.2M152 (Germany)	S	6.15MW	152m	HSG, DFIG	Developed from pioneering 5MW turbine introduced in 2004; prototype of more powerful model with longer blades installed in 2014
Areva M5000-135 (France)	S	5MW	135m	MSG, PMG	Extensive upgrade of M5000-116 introduced in 2004; features clever pioneering low-speed hybrid-drive design
Gamesa G128-5.0MW (Spain)	IB	5MW	128m	MSG, PMG	Pioneer tube-type drivetrain; builds on 2009's G128-4.5MW platform; new variant with 132m rotor diameter has been announced
Hyundai HQ5500/140 (South Korea)	I	5.5MW	140m	HSG, PMG	Sister product of Dongfang 5.5MW, co-developed with AMSC; Sinovel SL5000/SL6000 uses same AMSC product platform
Goldwind GW 6MW (China)	I	6MW	150m	DD, PMG	Specification not verified; initial design basis 5MW power rating

BDFIG Brushless doubly-fed induction generator
CGFRE Carbon & glass-fibre reinforced epoxy
DD Direct drive
DFIG Doubly-fed induction generator
EESG Electrically excited synchronous generator
GFRE Glass-fibre reinforced epoxy
HH Hub height
HSG/LSG High-speed geared/Low-speed geared
IG Induction generator
MSG medium-speed geared
PMG permanent magnet generator
PCVS Pitch-controlled variable-speed

Energy Storage

- Complements renewable sources of energy
  - Storage of wind power output when demand is low
  - Storage of solar energy produced during the day for use in the evening and at night
- Provides for rapid-on peak shaving
- Provides a more distributed power input to the grid
- Reduce the need for major new transmission grid upgrades; augment existing transmission and distribution assets.
  - 70% of transmission lines are 25 years or older,
  - 70% of power transformers are 25 years or older,
  - 60% of circuit breakers are more than 30 years old
- Energy storage for EVs

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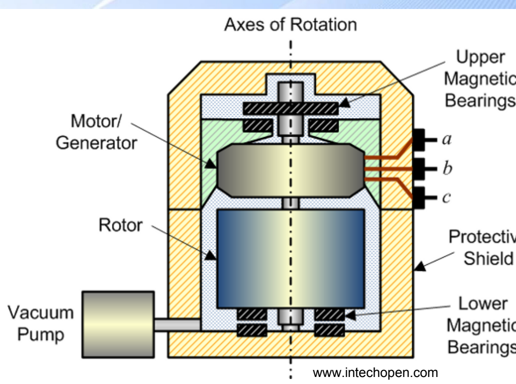
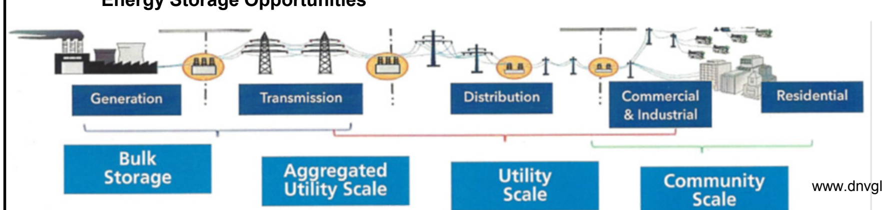
Energy Storage

- **Batteries**
- **Super-capacitors**
- **Pumped storage**
- **Flywheel energy storage** →



www.intechopen.com

Energy Storage Opportunities



www.dnvgl.com

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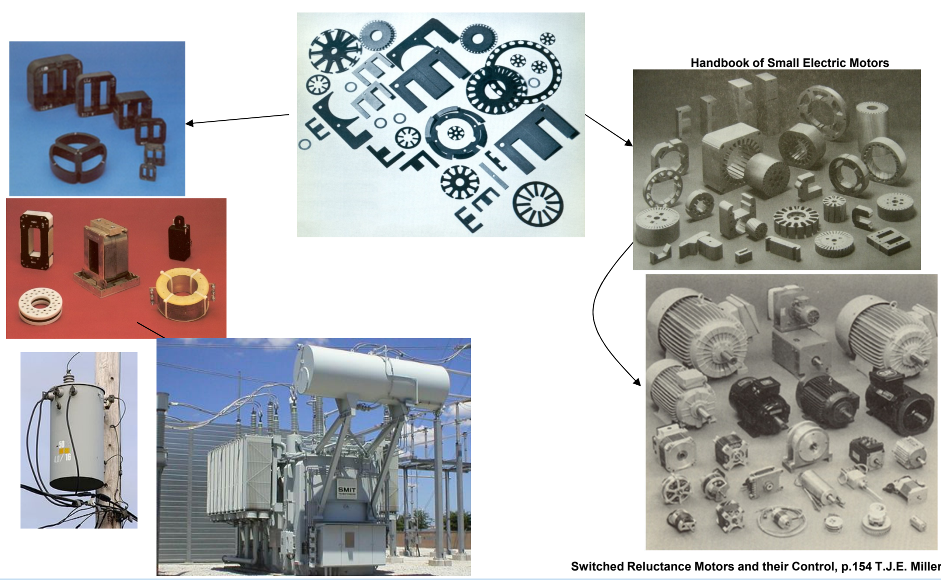
Electrical steel for transformers and motors

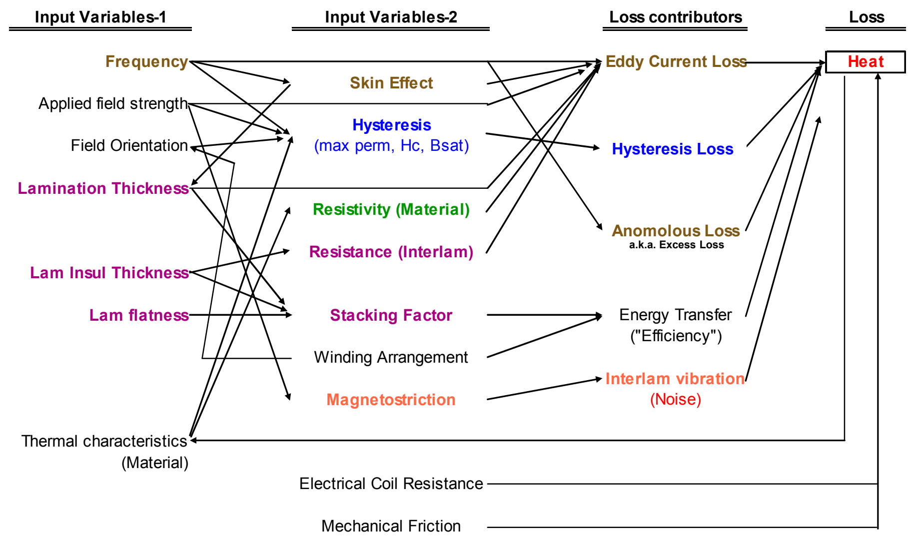


Handbook of Small Electric Motors

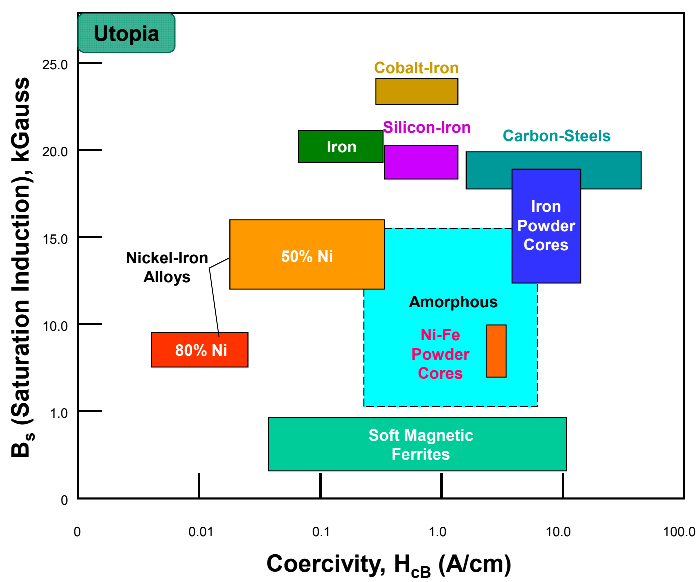
Switched Reluctance Motors and their Control, p.154 T.J.E. Miller

Loss Variables by Categories

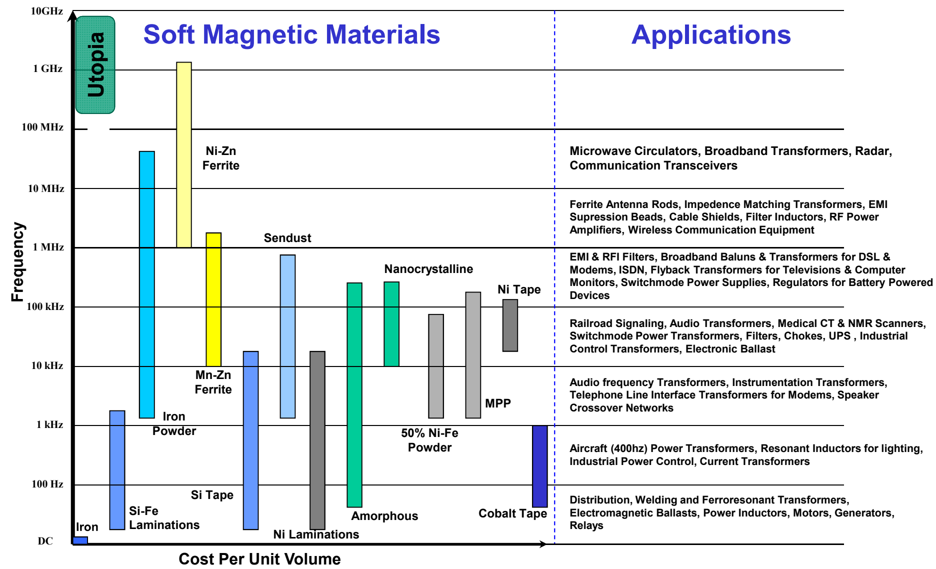
1: Hysteresis
2: Eddy Current
3: Laminations
4: Magnetostriction
5: Material & Resistivity



Comparing Material Properties



Material Options & Applications



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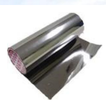
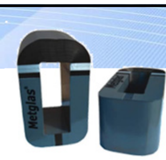
Metglas®





Key Products:

- Metglas®
- Amorphous Metals
- Glassy Metals
- **Transformer Core Alloys**
- Metglas Brazing Filler Metal
- **Distribution Transformer Core Ribbon**
- **Industrial Transformer Core Ribbon**
- Pulse Power Cores

Key End Applications:

- **Electrical Distribution Transformers**
- **Industrial Power Distribution Transformers**
- Material for Anti -Theft tags
- High Efficiency Inverters and Inductors
- Solar Inverters, Wind Inverters
- Harmonic Filters
- Pulse Power Cores for Lasers
- High Power Magnetic Forms for Medical Use
- High Purity Brazing Filler Metals

		2605SA1	2605HB1M	2605SA3	2714A	2826MB
Characteristic	**Unit**	Iron-based	Iron-based	Iron-based	Cobalt-based	Nickel-based
Bsat	Tesla	1.56	1.63	1.41	0.57	0.88
Max. Permeability, μ_{max}	n/a	300,000	300,000	35,000	1,000,000	800,000
Electrical Resistivity	μΩ·cm	130	120	138	142	138
Magnetostriction	%•10^{-6}	27	27	20	<0.5	12
Curie Temperature	°C	395	364	358	225	353

http://www.metglas.com/metglas_company_history/overview/

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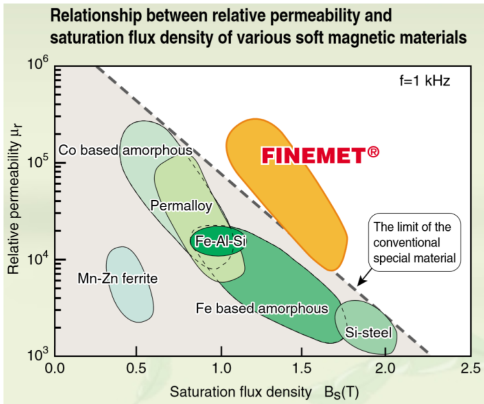
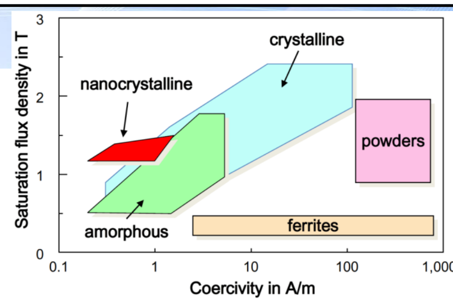
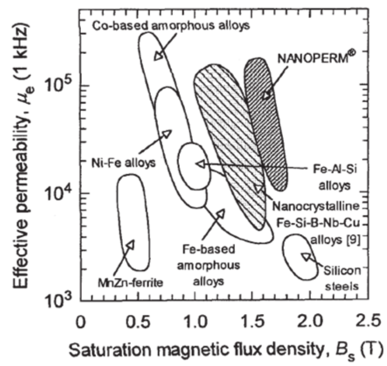
Nano-crystalline







Nanoperm® is a registered trademark of Magnetec GmbH

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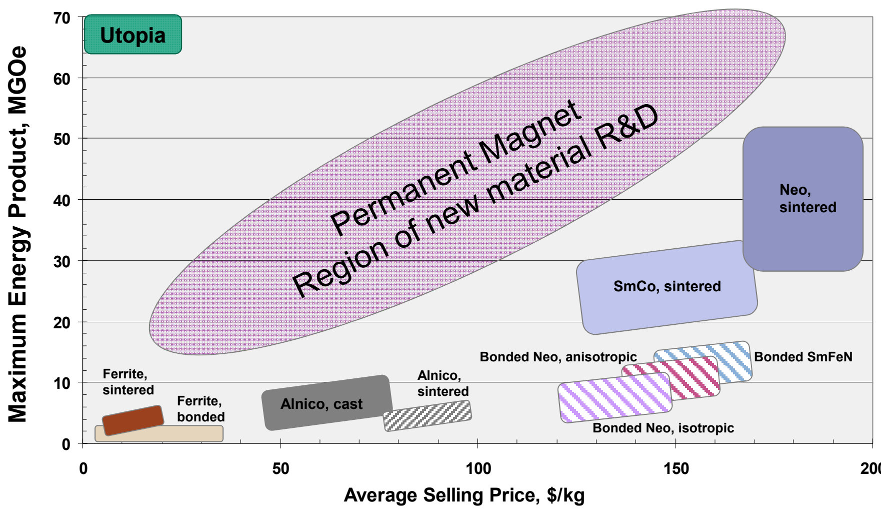
Magnet Price versus Energy Product



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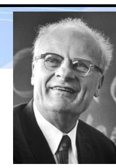
Origin of the Field

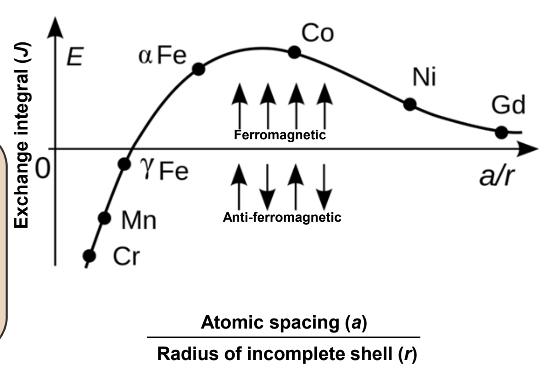


Hans Bethe

John C. Slater

- Heisenberg: quantum theory explanation for ferromagnetism

Bethe-Slater Curve



Keywords:

Exchange Interaction

In physics, the exchange interaction is a quantum mechanical effect which increases or decreases the expectation value of the energy or distance between two or more identical particles when their wave functions overlap.

Heavy Math - - Use with Caution

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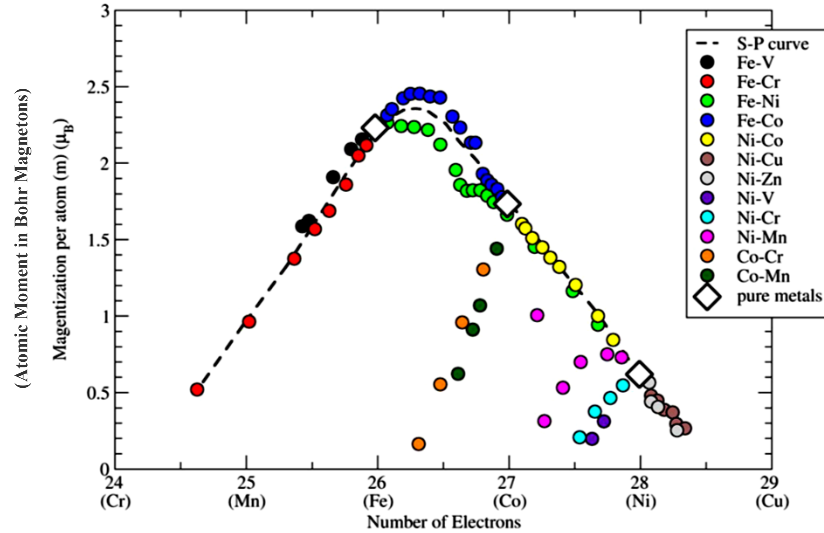
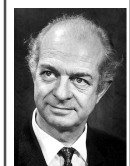
Slater-Pauling Curve



John C. Slater



Linus Pauling

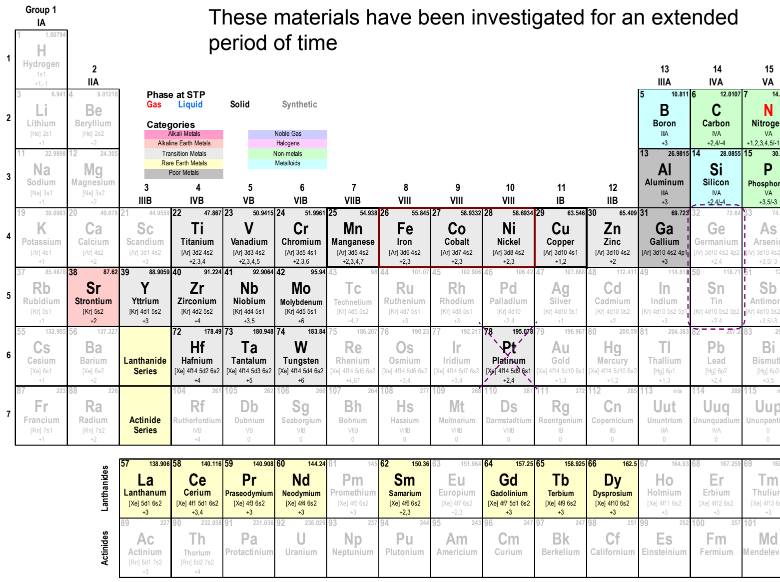
R.M. Bozorth, Ferromagnetism, IEEE, 1993, p.438-441   Color-edited by Dr. Bill McCallum, Ames Lab

Elements in Existing Magnetic Materials

	Major constituents						Minor constituents				Comments
Soft Magnetic Materials											
Iron	Fe										Low carbon mild steel
Silicon Steel	Fe						Si				Si at 2.5 to 6%
Nickel-Iron	Fe	Ni									Ni at 35 to 85%
Moly Permalloy	Ni	Fe					Mo				Ni at 79%, Mo at 4%, bal. Fe
Iron-Cobalt	Fe	Co					V				23 to 52% Co
Soft Ferrite	Fe	Mn	Ni	Zn			O				
Metallic Glasses	Fe	Co	Ni				B	Si	P		Amorphous and nanocrystalline
Permanent Magnets											
Co-Steels	Fe	Co									
Alnico	Fe	Ni	Co	Al	Cu		Ti	Si			
Platinum Cobalt	Pt	Co									
Hard Ferrites	Fe	Sr									Oxygen dilutes; Ba no longer used
SmCo	Co	Sm	(Gd)	Fe	Cu	Zr					
Neodymium-iron-boron	Fe	Nd	Dy	(Y)	B	Co	Cu	Ga	Al	Nb	
Cerium-iron-boron	Fe	Nd	Ce	B							Limited use in bonded magnets
SmFeN	Fe	Sm	N								Nitrogen is interstitial; stability issue
MnBi	Mn	Bi									Never commercialized
MnAl(C)	Mn	Al					C				Not successfully commercialized

Elements in existing magnetic materials

These materials have been investigated for an extended period of time



Dmitri Mendeleev

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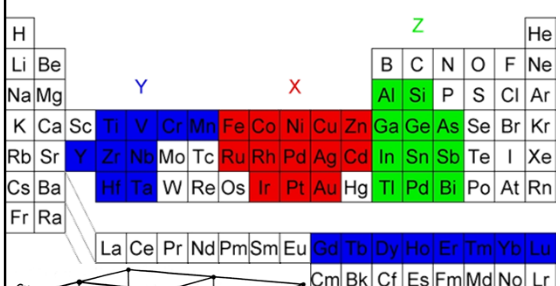
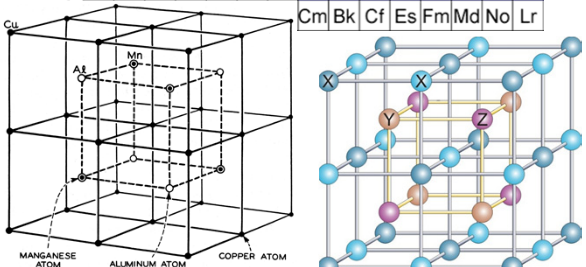
Heusler Alloys



"A Heusler alloy is a ferromagnetic metal alloy based on a Heusler phase. Heusler phases are intermetallics with particular composition and face-centered cubic crystal structure. They are ferromagnetic—even though the constituting elements are not—as a result of the double-exchange mechanism between neighboring magnetic ions. The latter are usually manganese ions, which sit at the body centers of the cubic structure and carry most of the magnetic moment of the alloy."



Sources: Ferromagnetism, Richard M. Bozorth, IEEE Press, p.328; Wikipedia

Magnetism and Magnetic Materials, J.M.D. Coey, p.394

Table 11.9. Heusler and half-Heusler alloys

	a_0 (pm)	T_C (K)	σ_0 (A m^2 kg^{-1})	m (μ_B)
Cu_2MnIn	621	500	75	4.0
Co_2MnGa	577	694	93	4.1
Co_2MnSi[a]	565	985	141	5.0
Co_2MnGe[a]	574	905	116	5.1
Co_2MnSn	600	829	97	5.1
Ni_2MnGa	583	380	96	4.2
Ni_2MnSn	605	360	81	4.2
Pd_2MnSb	642	247	63	4.4
NiMnSb[a]	592	730	93	4.0
PtMnSb[a]	620	572	60	4.0
Mn_2VAl[a]	760	730	59	2.0

[a] Half-metal

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Sensitivity to Thermal Treatment

Affect of Thermal Treatment on SmCo 2:17 Magnetic Properties

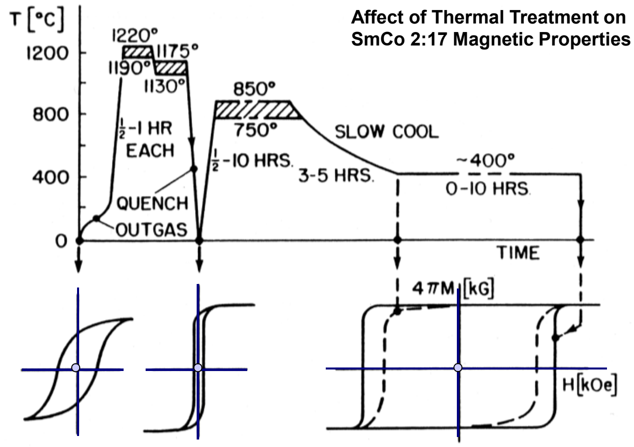


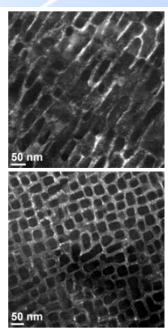
Fig. 32. Typical temperature profile for the sintering and heat-treating of "2–17"-type Sm(Co, Fe, Cu, Zr)$_{7.2-8.5}$ magnets.

Source: Rare earth-Cobalt Permanent Magnets, K.J. Strnat, 1988

Alnico Thermal Treatment, with field

Three treatments

- Solution treatment above 1200 °C
- Isothermal treatment for spinodal decomposition and magnetic alignment
- Draw (precipitation hardening) cycle



Affect of Thermal Treatment in an aligning magnetic field on magnetic properties of alnico 5

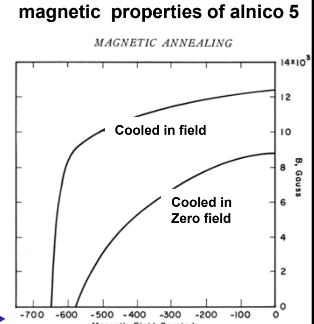


Fig. 8—Effect of Magnetic Annealing of Alnico 5 (142).

Source: Magnetic Properties of Metals and Alloys, published by the American Society for Metals, 1958, Chapter 13, C.D. Graham, Jr., p.307

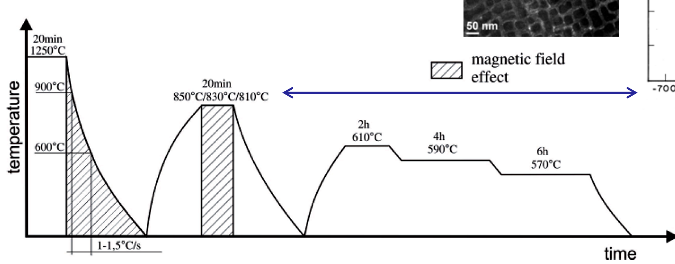


Fig. 3. Scheme of thermo-magnetic treatment of Alnico 8 alloy

Source: Investigations of Thermo-Magnetic Treatment of Alnico 8 Alloy, Stanek et al, Archives of Metallurgy and Materials, Vol 55, 2010 Issue 2

Wrapping it up

- We require energy to survive and thrive. Demand for energy will continue grow.
- Magnetism and magnetic materials are important in the production, distribution and use of (electrical) energy.
- Several markets are dramatically changing and benefit from the use of magnetic materials. Examples include wind energy and transportation
- While recent focus has been on permanent magnets and sensitivity to rare earth material supply, soft magnetic materials are used at a rate of 20 to 25x that of permanent magnets (weight basis) and are every bit as important to motor efficiency and performance.
- Developing improved permanent and soft magnetic materials presents a great challenge.

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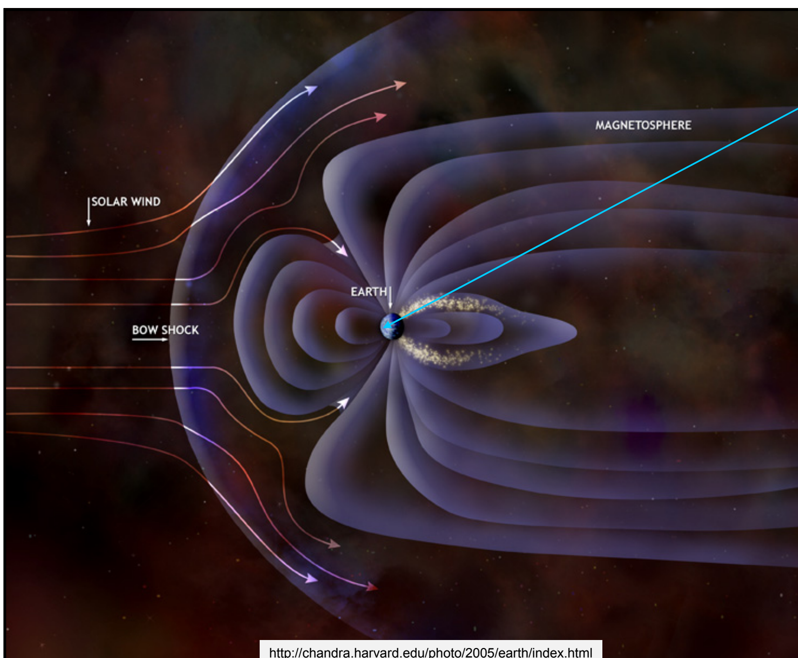

http://chandra.harvard.edu/photo/2005/earth/index.html

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