ARNOLD
MAGNETIC TECHNOLOGIES

Electricity, Magnetism and… Survival

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March 1, 2015

APS physics MARCH MEETING 2015

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- First, a brief introduction to Arnold.
- Arnold started largely as a magnetic products manufacturer.
- Over the years we have evolved into an integrated producer as shown here – still manufacturing magnets, but increasingly producing assemblies and finished devices that use magnetic materials.

Agenda

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

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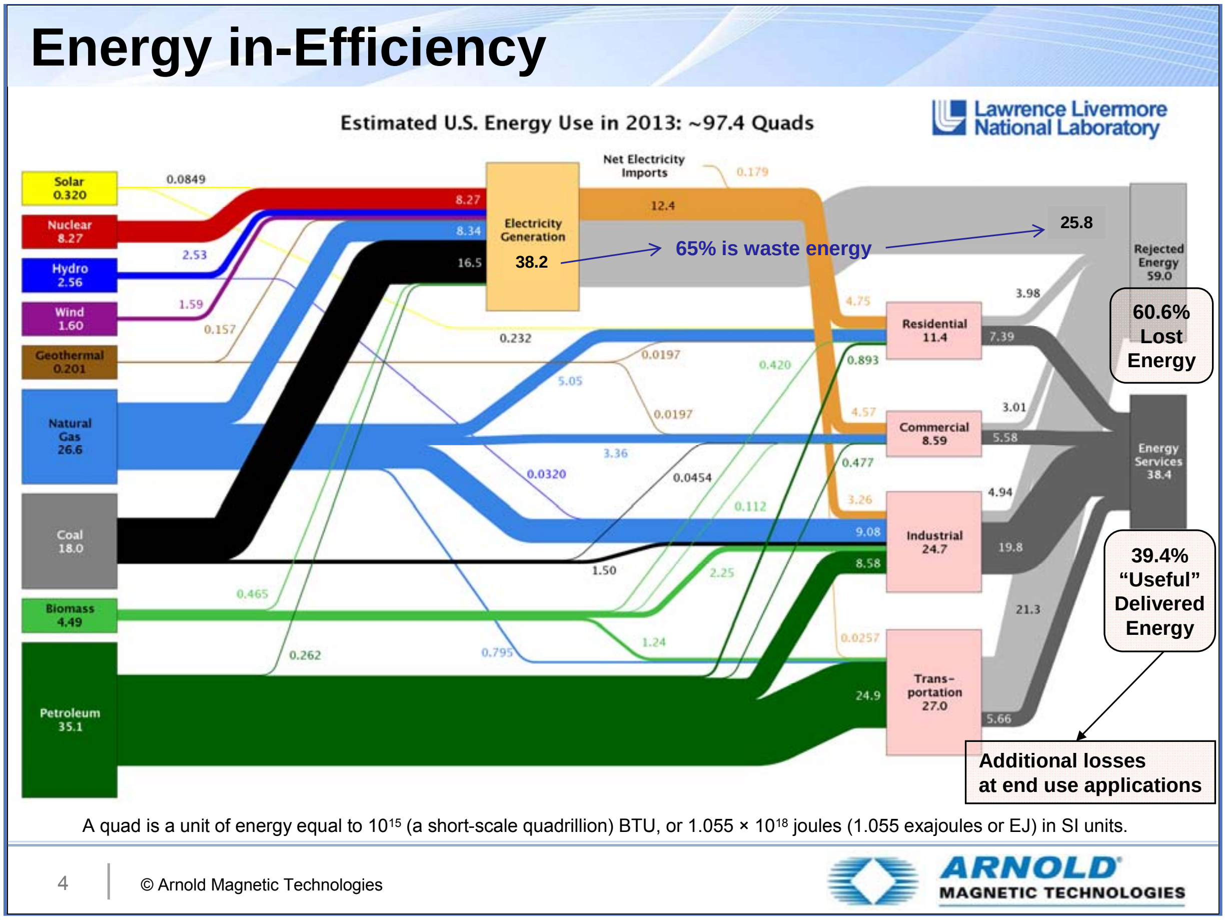
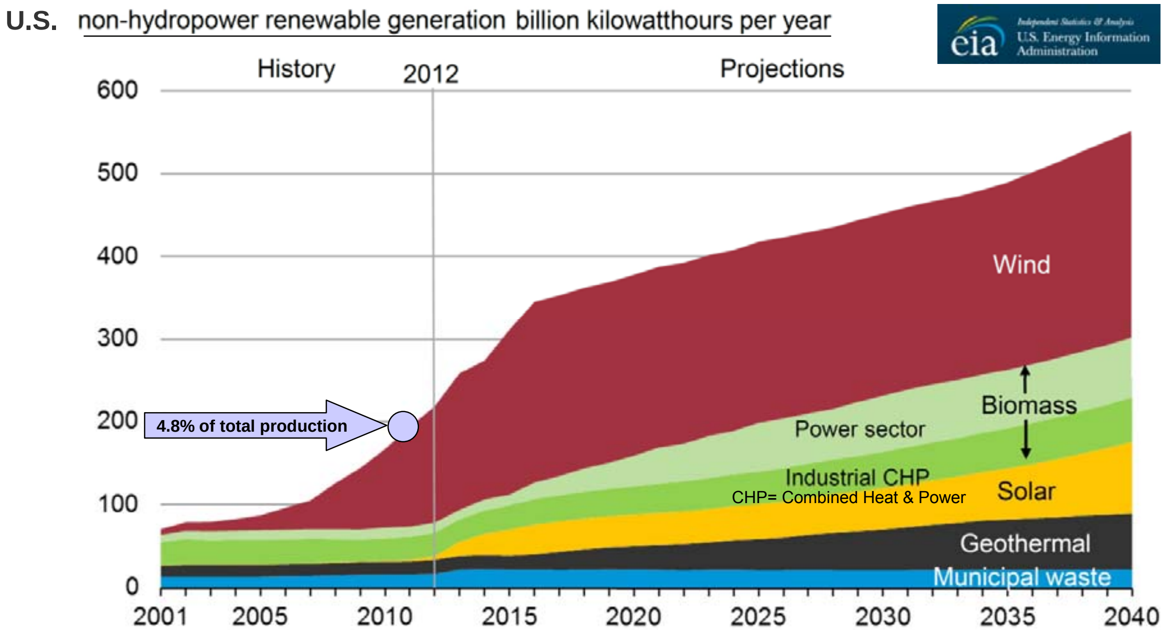
- Let's follow the professor through these topics starting with an introduction to what magnetism is and where it originates.



- Lawrence Livermore National Laboratories personnel have produced Sankey plots of energy production and use for over a hundred countries.
- This chart for the USA, for example, shows us that most petroleum is used primarily for transportation (gasoline, diesel, jet fuel).
- It also shows that electricity is produced by many methods from solar down to coal (left of chart) with coal and natural gas providing the greatest input.
- The efficiency of production and distribution is low.
- Efficiency of machines using electricity is variable, ranging from 30% to 98.5% with the majority of electric consumption due to motors (>50%).
- Magnetic materials (soft and permanent magnetic materials) are used in production, transmission and use of electrical energy and are, therefore, hugely important to our economies and standard of living.

Renewable Energy Electricity Generation (USA)



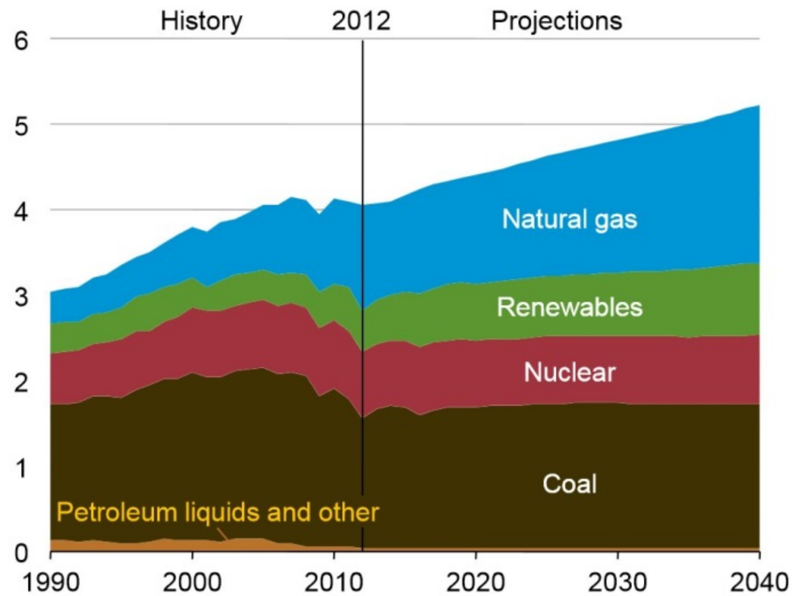
Annual Energy Outlook 2014 with projections to 2040, U.S. Energy Information Administration, www.eia.gov/forecasts/aeo

- Let's start the discussion with a brief examination of production and use of electricity.
- After all, the correct term for magnetism is "electro-magnetism".
- The electromagnetic force is one of four forces identified by physicists. The others are the weak and strong atomic forces and force due to gravity.

- This is a powerful graphic!
- In 2011, output from non-hydro renewable energy sources was 4.8% of total electricity production.
- This forecast chart suggests that output from renewable sources will more than double by 2035.

Overall Electric Generation - USA

Figure ES-5. Electricity generation by fuel in the Reference case, 1990-2040 (trillion kilowatthours)



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

- With hydro output remaining constant, total renewables (hydro plus non-hydro) will represent approximately 14.9% of electric production – which means that ~85% will still be produced by fossil fuels and nuclear.

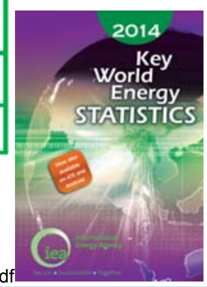
Fuel used for production of electricity - 2012

Coal*	TWh
People's Rep. of China	3 785
United States	1 643
India	801
Japan	303
Germany	287
Korea	239
South Africa	239
Australia	171
Russian Federation	169
United Kingdom	144
Rest of the world	1 387
World	**9 168**

Natural gas	TWh
United States	1 265
Russian Federation	525
Japan	397
Islamic Rep. of Iran	170
Mexico	151
Italy	129
Egypt	125
Saudi Arabia	121
Thailand	117
Korea	112
Rest of the world	1 988
World	**5 100**

Oil	TWh
Japan	181
Saudi Arabia	150
Islamic Rep. of Iran	69
Mexico	56
Kuwait	40
Pakistan	35
United States	33
Indonesia	33
Russian Federation	28
Egypt	25
Rest of the world	478
World	**1 128**

We use the fuels which are available to us



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

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- The fuel consumed to produce electricity depends on what is available.
- In the USA we have coal and natural gas.
- China is greatly dependent upon coal.
- Japan imports most all its fuel and so uses oil to produce electricity.
- Saudi Arabia, as one of the larger producers of oil, consumes oil to produce electricity. Natural gas is frequently associated with oil and represents the second largest fuel source for Saudi Arabia.

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

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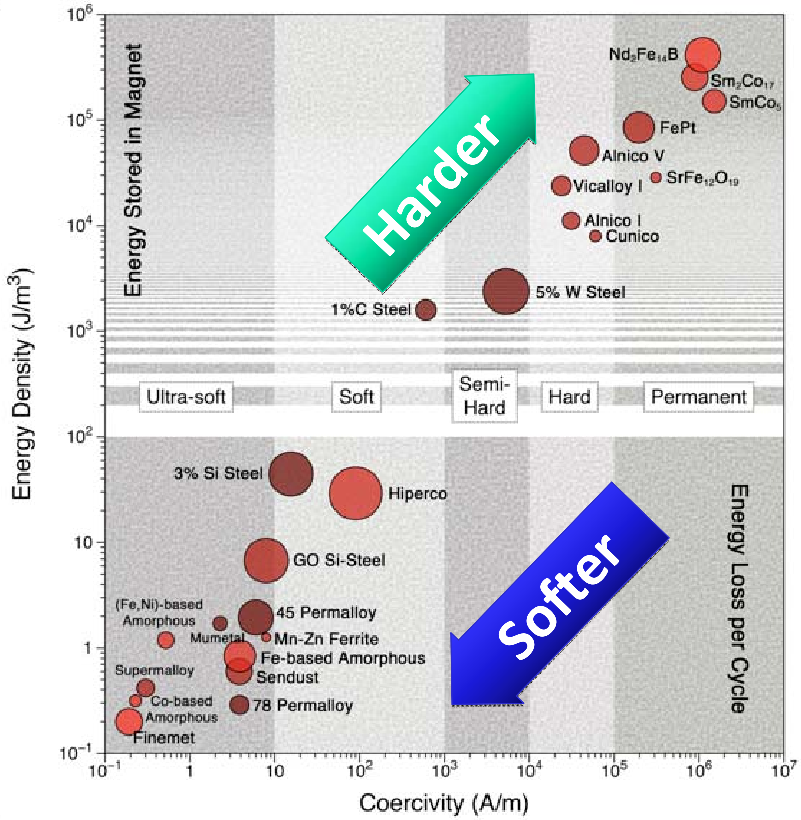
- Magnetic materials are important elements in the production, transmission and consumption of electrical energy.
- The magnetics industry is pursuing improvements in manufacture of magnetic products and in the devices that use them.

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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- This chart from Matt Willard of Case Western Reserve University, shows many important details.
- First, there is a continuum from the very "soft" magnetic materials to the very "hard" permanent magnet materials - with an intermediate region we call "semi-hard".
- Soft magnetic materials are better performers when the energy consumed (lost) per cycle is very low. Thus the best performing soft magnetic materials may be seen near the bottom left of the chart.
- Conversely, permanent magnets are expected to retain their properties and are useful for their "stored" energy with the best performers found near the upper right of the chart.

Agenda

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

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- Let’s follow the professor through these topics now looking at magnets and motors.

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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- Ferrite magnets, commercialized in the late 1950s, still represent the largest portion of permanent magnet products – on a weight basis.
- The total fraction of ferrite used in motor-type devices is about 70%.
- Acoustic transducers, which include loudspeakers, headphones, cell phone speakers, and ear buds are actually linear motors and are included in the motor total.

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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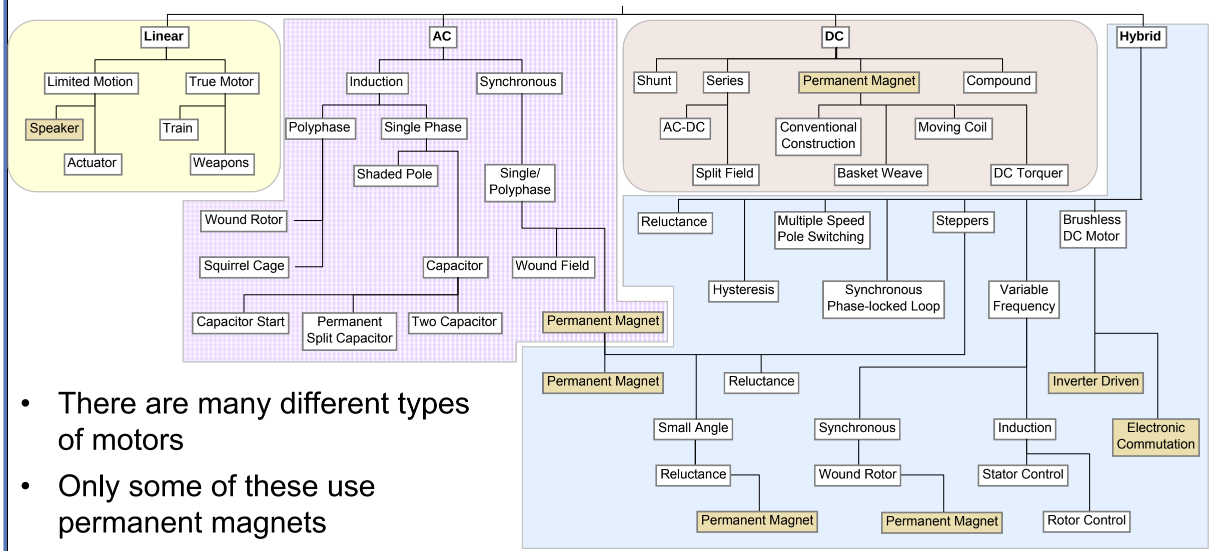
- Rare earth magnets enjoy a more diverse set of applications.
- Nevertheless, adding-up the motor-type applications (indicated by blue dots) yields 67% - very similar to the fraction for ferrite.
- Since ferrite and rare earth magnets represent about 97% of permanent magnet production (weight basis), this tells us that motors (and generators) consume the great majority of permanent magnets.

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

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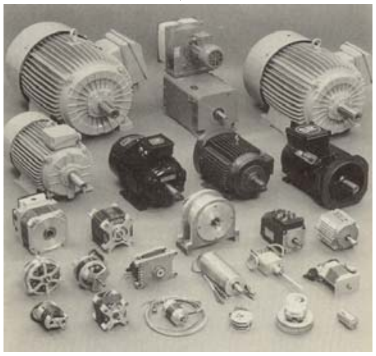
- The single largest use for permanent magnets is in motors.
- However, only a fraction of all motors use permanent magnets.
- PM motors are becoming more common due in part to government efficiency regulations – PM motors being more efficient than induction, wound field and similar types.
- Improvements in electronics and the reduced cost of electrical controls is allowing permanent magnet BLDC and ECM drives to penetrate the market to an extent not possible 25 years ago.

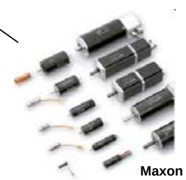
Electric Motors

to very big



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

From very small



Maxon

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)

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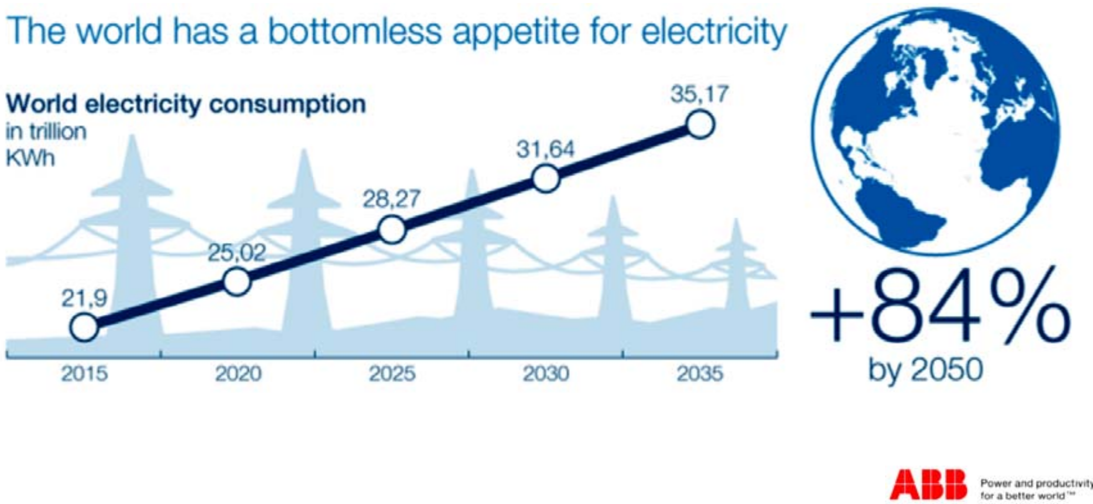
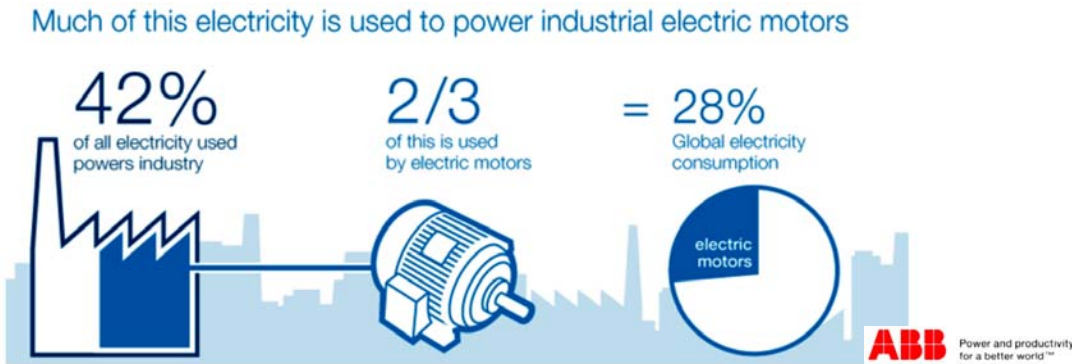
- Motor size ranges from the very small to the extremely large.

World electricity consumption



Electricity consumption by motors



"…~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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- Soft magnetic materials
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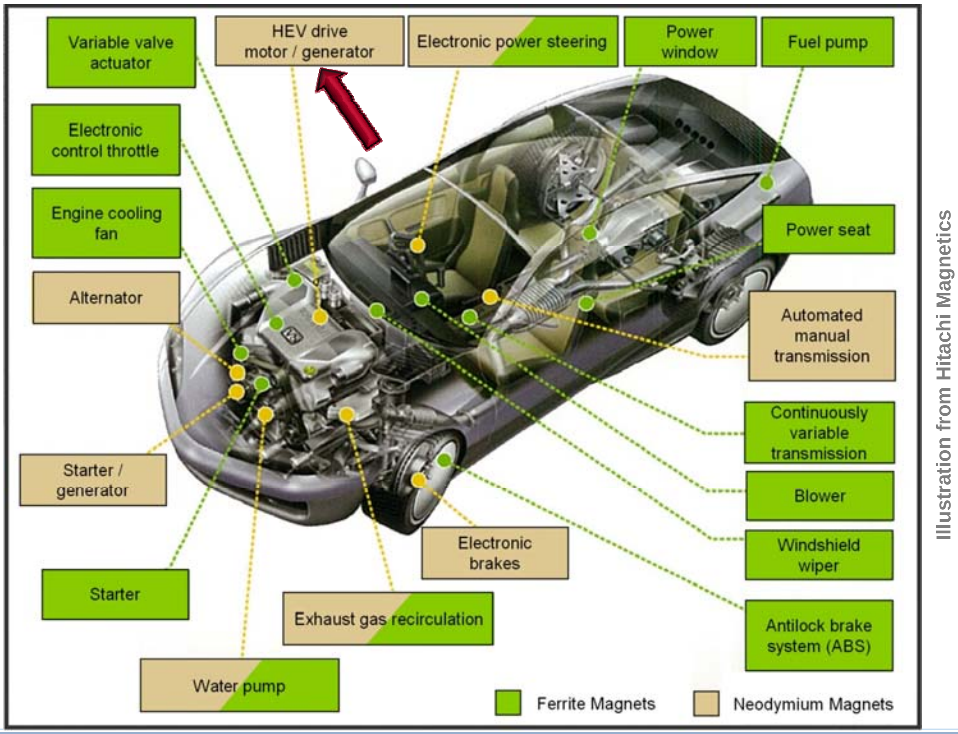
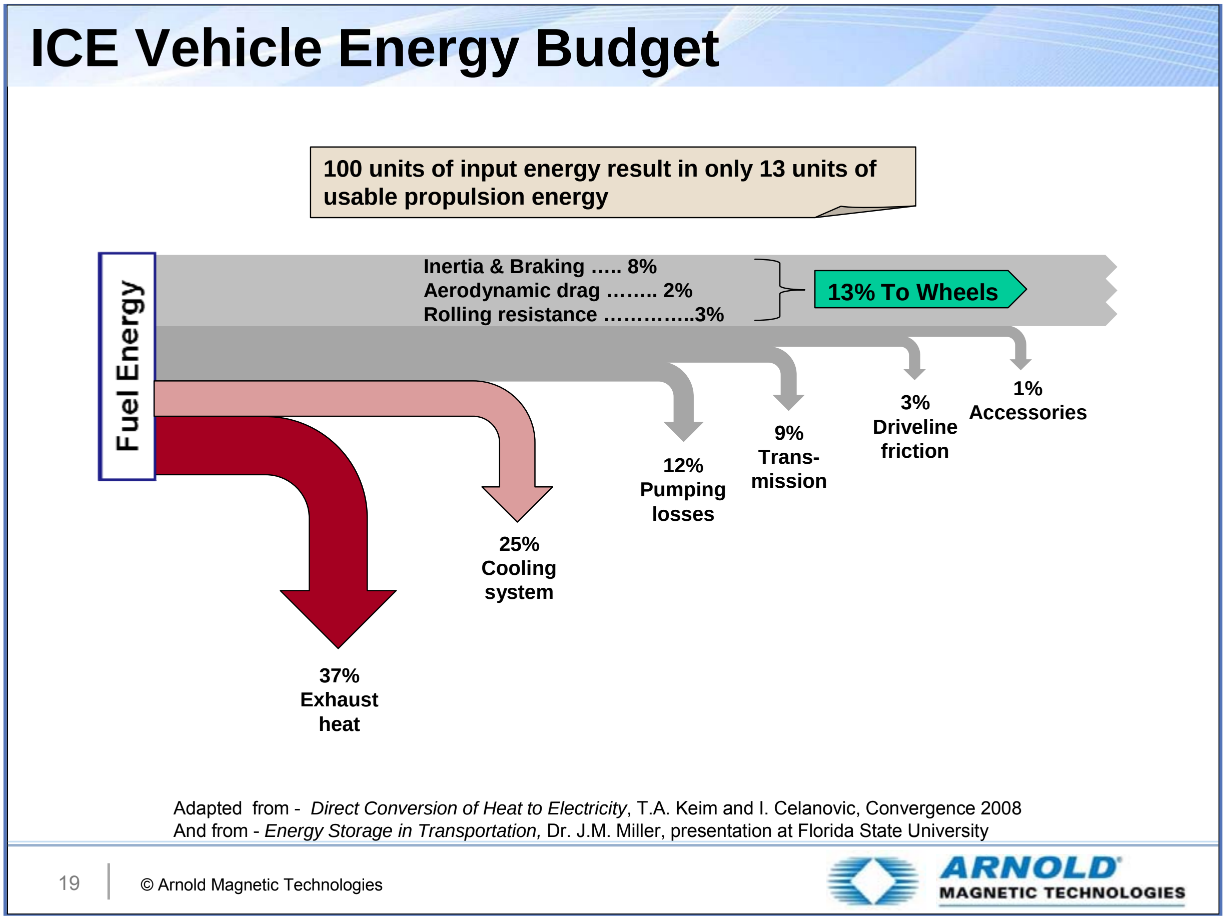
- The professor next wishes us to discuss applications for permanent magnets.

Automotive Motors & Actuators



- One of the largest markets for permanent magnets is the transportation industry.
- It is tempting to focus on rare earth magnets such as NdFeB for use in automotive motors.
- However, many vehicular systems still rely on ferrite magnets as they are less expensive, adequately strong, and naturally corrosion resistant, including to road salt.
- This illustration from Hitachi shows several applications and likely magnet type(s) with green representing ferrite and tan representing rare earth magnets, most of which are neodymium iron boron, although a few SmCo magnets are used (primarily in sensors).
- When a motor is mentioned, most of us will immediately think of a device that drives a spinning shaft, but there are linear motors such as door lock actuators and entertainment system speakers.
- Note the red arrow pointing to the traction drive motor…



- The traditional internal combustion engine (ICE) wastes a great deal of energy.
- Electric traction drives have the potential to dramatically improve efficiency by reducing heat generation, cooling requirements, and cooling fluid pumping energy.
- Depending on the motor-to-wheel connection, friction losses may also be considerably less.

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

- Although other topologies are used, permanent magnet motors offer the optimal combination of performance versus cost.
- But due to the recent high cost of powerful rare earth magnets and instability of raw material supply, some car manufacturers, such as Tesla, are using induction drive motors (with no magnets).

Alternative Powertrain Types

		Examples
HEV	**Hybrid Electric Vehicle** Uses both an electric motor and an internal combustion engine to propel the vehicle.	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.	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.	Volt
BEV	**Battery Electric Vehicle BEV)** Powered exclusively by electricity from it's on-board battery, charged by plugging into the grid	Leaf; Tesla Model S
FCEV	**Fuel Cell (Electric) Vehicle (FCEV)** Converts the chemical energy from a fuel, such as hydrogen, into electricity.	Honda FCX Clarity; Hyundai Tuscon

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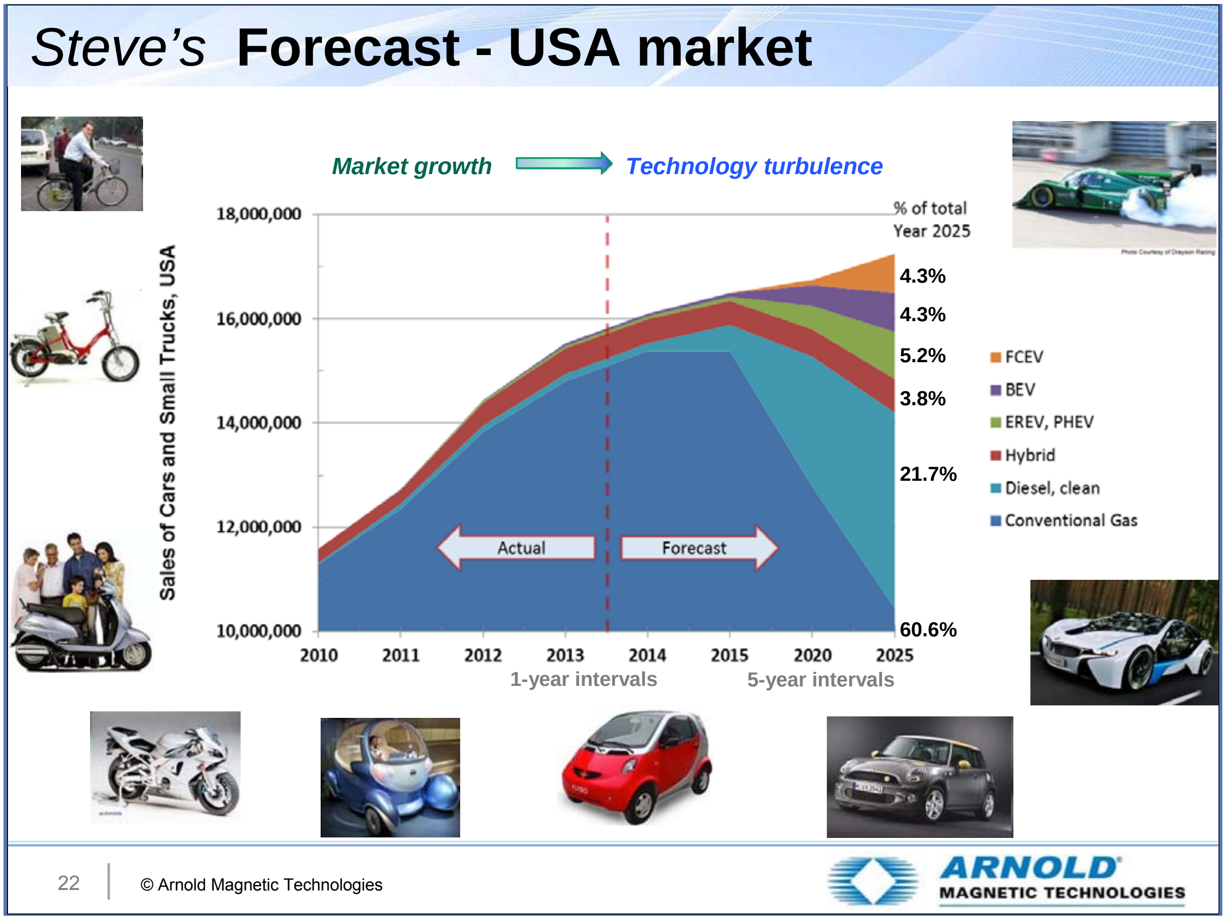
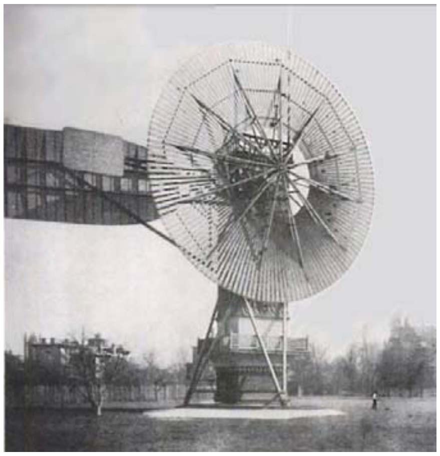
- There are many “alternative drive” types.
- This list shows most of them including one or more examples of each that are in production.
- Some use permanent magnet motors such as the Prius and Nissan Leaf, while some use induction motors such as the Tesla Model S.



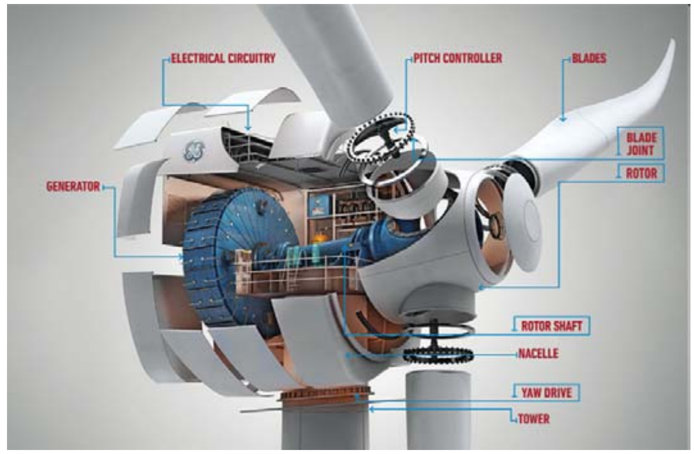
- In response to other overly optimistic forecasts, over the last few months data and opinions have been sought regarding the development of the transportation industry.
- This chart is my humble attempt to show a consensus of the development of alternate drive systems by type.
- One reason why ICE (including clean diesel) will remain the primary source of tractive power, at least through 2025, is the technological advances being made to provide ever more efficient drive systems at modest price increases and using existing fuel distribution infrastructure with simultaneous "light-weighting" of the vehicles.
- Expansion in use of any type drive depends upon a range of factors including economic, political, and technical.

- N.B.: the scale at the bottom is by year to 2015 and then by 5-year increments.

Wind Energy



Charles Francis Brush wind mill from 1888



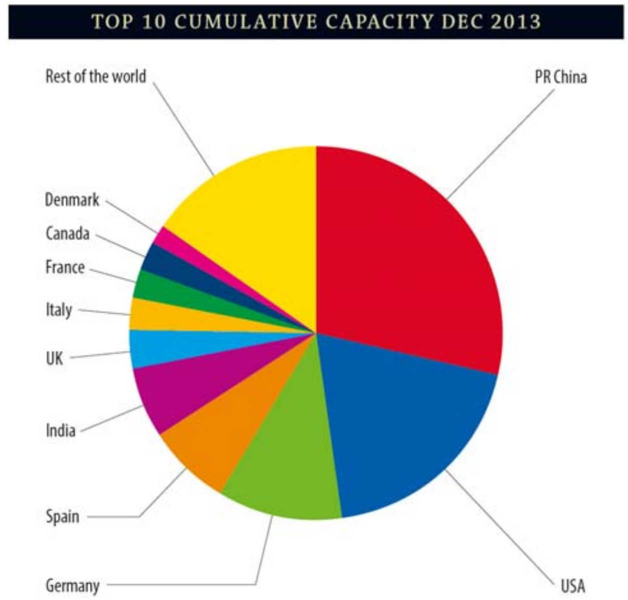
GE Gen-4 Permanent magnet generator

- Wind energy is not new.
- But Utility-scale wind is a more recent development having grown slowly until: 1) government subsidies were offered starting a few years ago (e.g. USA) and 2) need for a more environmentally friendly power generation alternative was recognized (e.g. Germany and China).

Cumulative installed utility-scale wind power

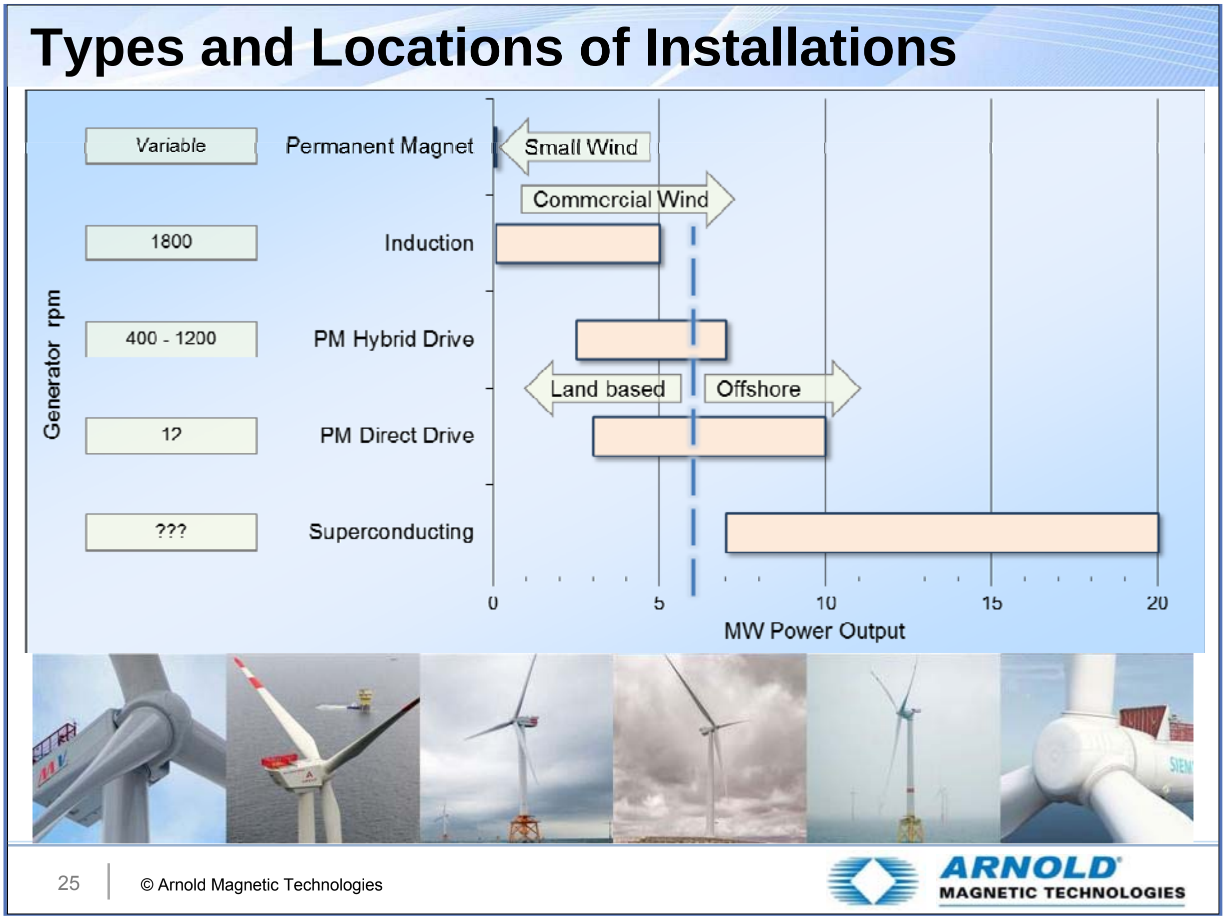
Through December 2013

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

- If all 318,137 MW of wind power indicated here for global installations were produced using direct drive PM generators, at 600 kg per MW, this would have consumed 191,000 tons of NdFeB magnets which requires about 500,000 tons (all RE elements) REO production.
- That equates to about 4 years output of RE mines globally (2010 published data, USGS).



- Although direct drive (permanent magnet) generators have been in development and trials for several years, installation has been limited.
- In the USA, one estimate is less than 250 direct drive units versus 33,000+ installed generators (as of 2014).
- The situation is similar in the UK with less than 1% of generators using PM direct drive technology (as of 2014).
- China has reputedly installed more direct drive units, perhaps up to 25% of new systems installed in 2010, prior to the neo material shortages and price spikes.

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

Source: http://www.windpowermonthly.com/10-biggest-turbines

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- The largest generators are designed for use off-shore.
- Of the current top ten generators identified by Wind Power Monthly, 8 are PM type.
- The largest to-date is the MHI-Vestas 8.0 MW generator.

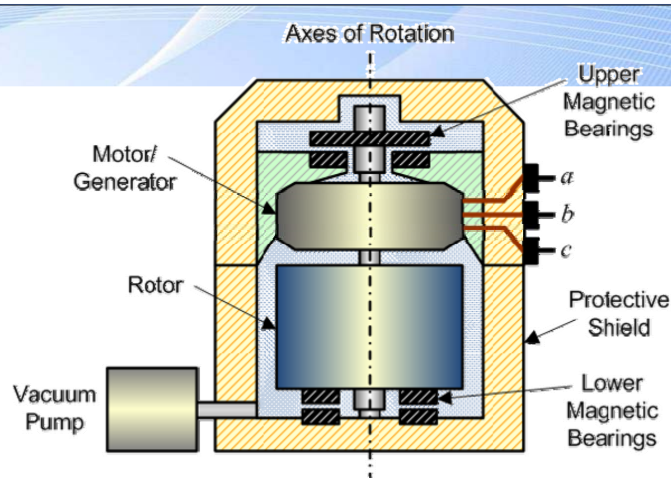
Energy Storage

- 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
- Reduces the need for major new transmission grid upgrades; augments 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

- Introduction of alternative electric generation coupled with an aging grid structure provides advantages to installation of energy storage systems.

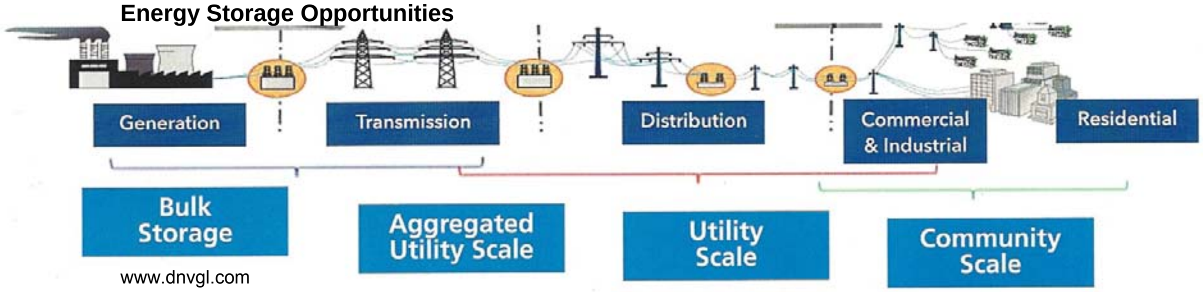
Energy Storage

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



www.intechopen.com

Energy Storage Opportunities



www.dnvgl.com

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- There are several technologies being explored for energy storage and each has advantages.
- The method most related to the magnet industry is flywheel storage which could be implemented at any of several points within the electric distribution system.
- Magnets are likely to be used in the “frictionless” magnetic bearing system and quite probably in the generator.

Agenda

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- Motors
- Applications
- <u>Soft magnetic materials</u>
- Future of magnetic materials

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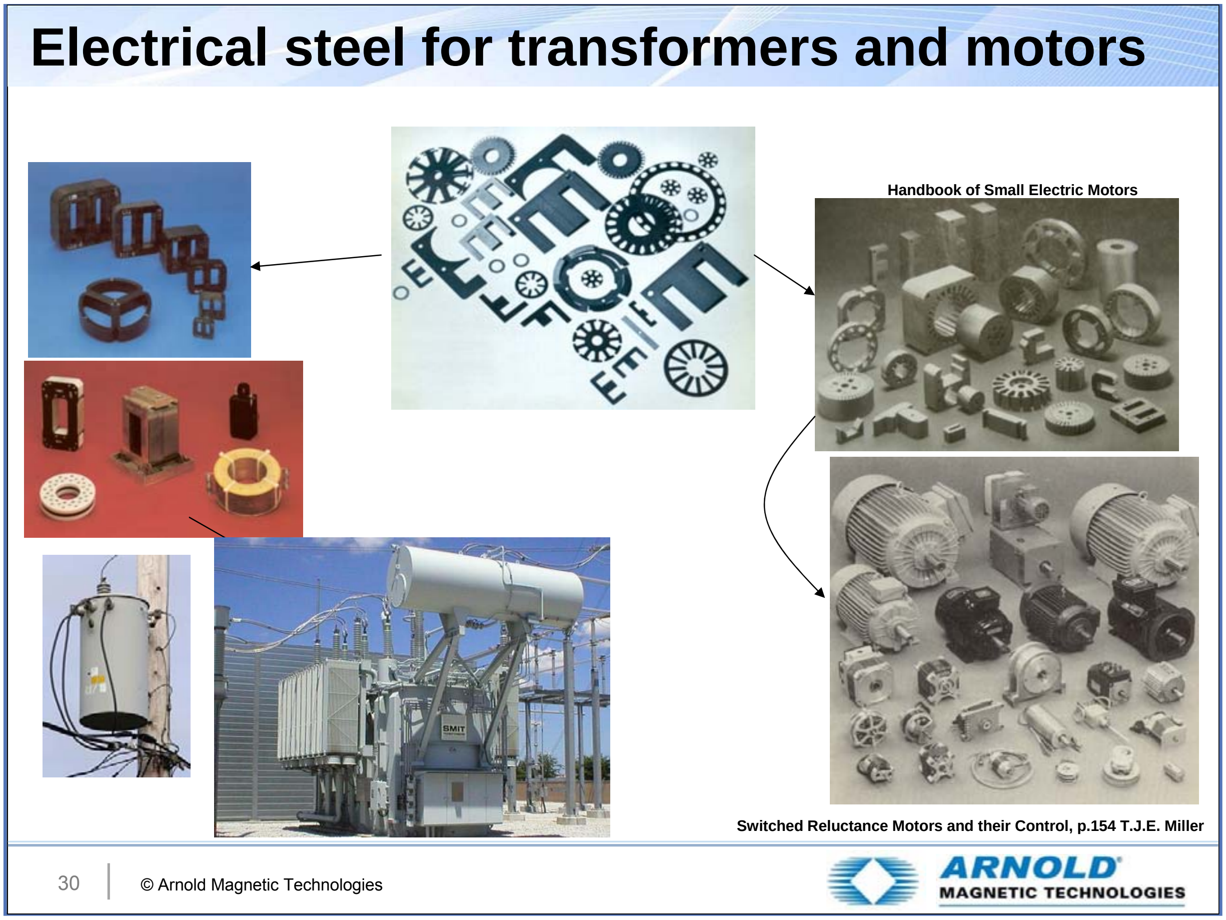
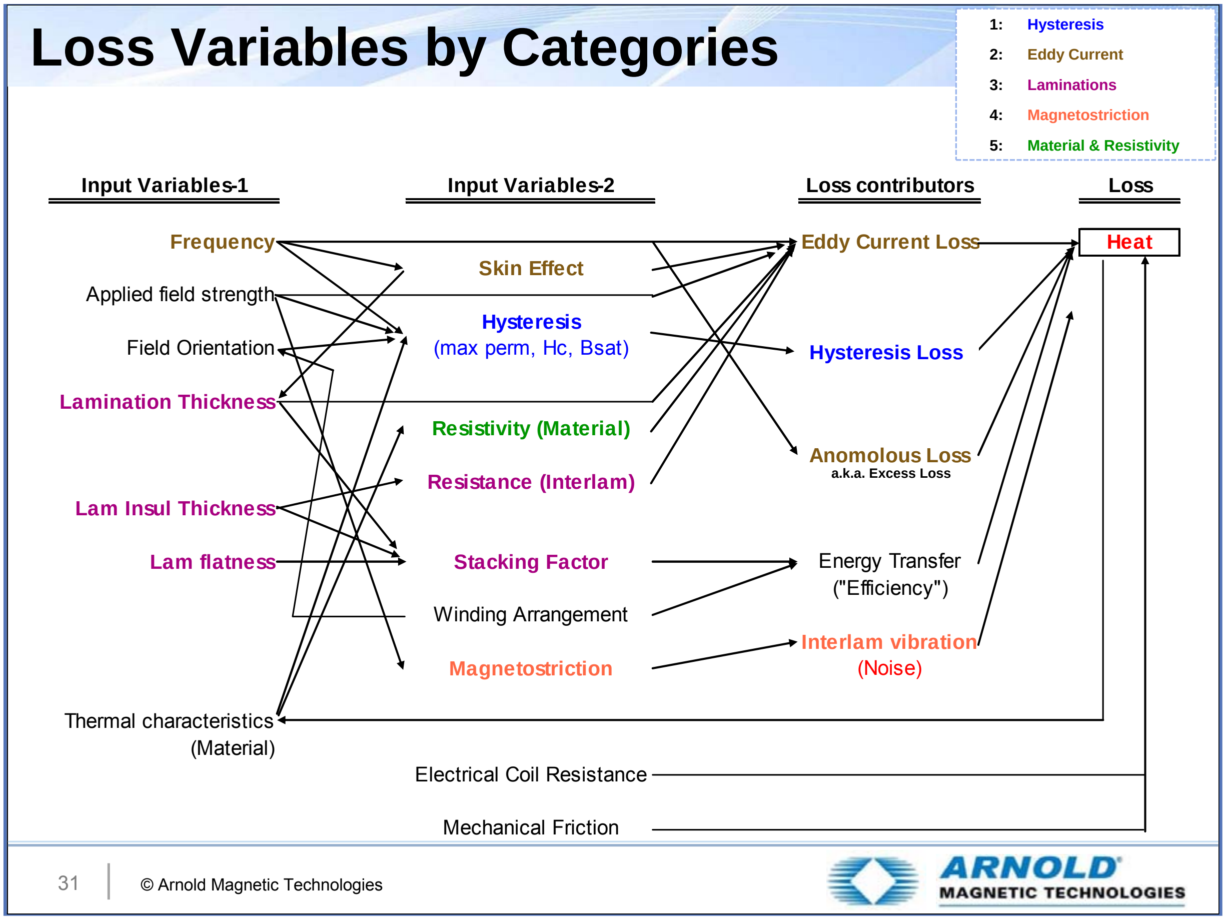
- The professor now leads us to examining soft magnetic materials.

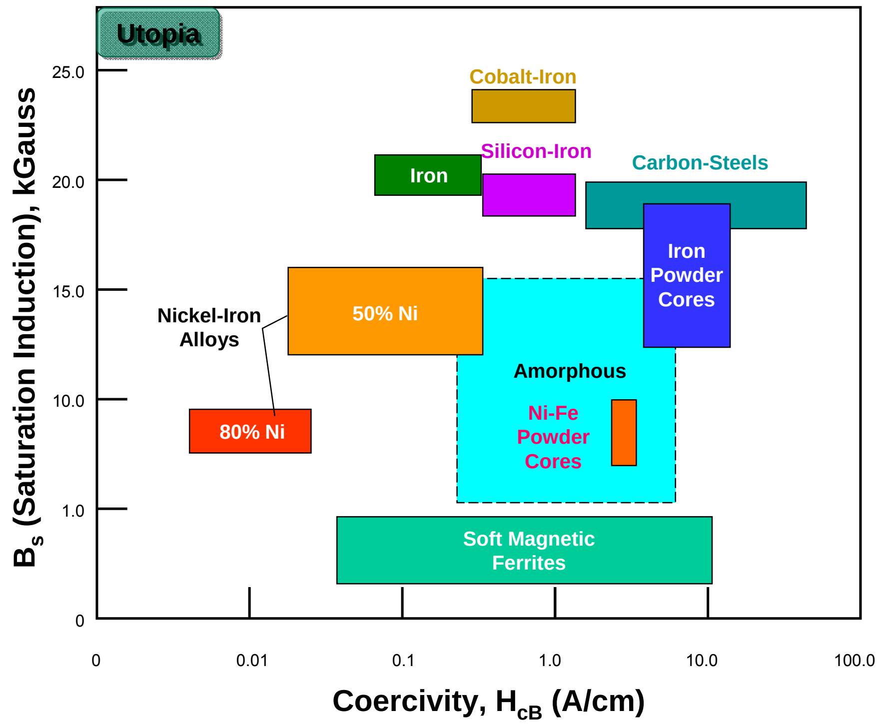


- The greatest uses for soft magnetic materials are laminations, thin layers of metal alloy, used in transformers and motors/generators.
- Transformers, motors and generators range from the very small to devices as large as a house.
- In addition to laminations, the lowest cost alternative is rolled and stamped-to-shape low carbon steel.
- Most devices use a combination of laminations and steel components.

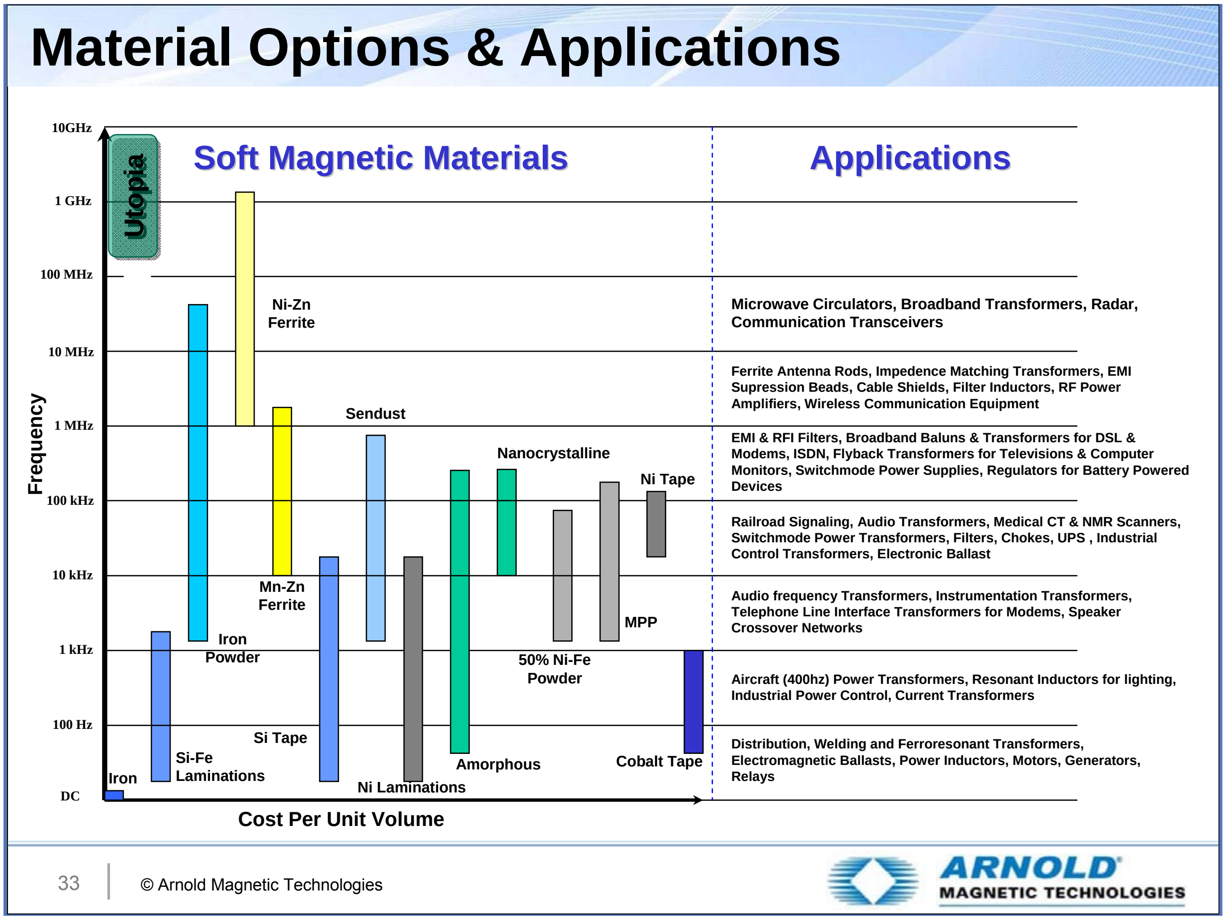


- This slide shows a complex set of variables involved with selecting the proper material grade and thickness of lamination material, typically, but not necessarily Si-Fe. Other materials include Fe-Co and Fe-Ni.
- Lower efficiency is mostly the result of energy being converted to heat.
- Note that many of the variables are interactive. One variable can affect another variable. For example, switching frequency affects how deep the field will penetrate a lamination which affects desirable lamination thickness which affects stacking factor, etc.
- That is, the use of thin gauge alloy (e.g. Arnon® 5 and Arnon ® 7 Si-Fe) can minimize the losses associated with most of these variables.
- These variables can be grouped into similar categories for further discussion as desired and the 5 groups have been created here as shown in the upper right of the chart.

Comparing Material Properties



- There is a trade-off between maximum (saturation) induction and coercivity.
- Plotting the coercivity, Hcb, against the saturation induction, Bs for a number of commercially important materials results in this chart.
- A high Hcb indicates that the material will have high (hysteresis) core loss.
- From this loss standpoint, the 80% Nickel alloys, with low Hcb, are desirable.
- Where high saturation (flux carrying capability) is required, silicon iron and cobalt iron are desirable.
- Cobalt iron is used less often than silicon iron as it is far more expensive – it is only used where absolutely necessary, such as ultra-high power density, sealed motors/generators.



- It is also important to examine frequency of the application and cost.
- Some applications are cost-forgiving, but most are not.
- Ability to perform at high frequency is an additional figure of merit.

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:

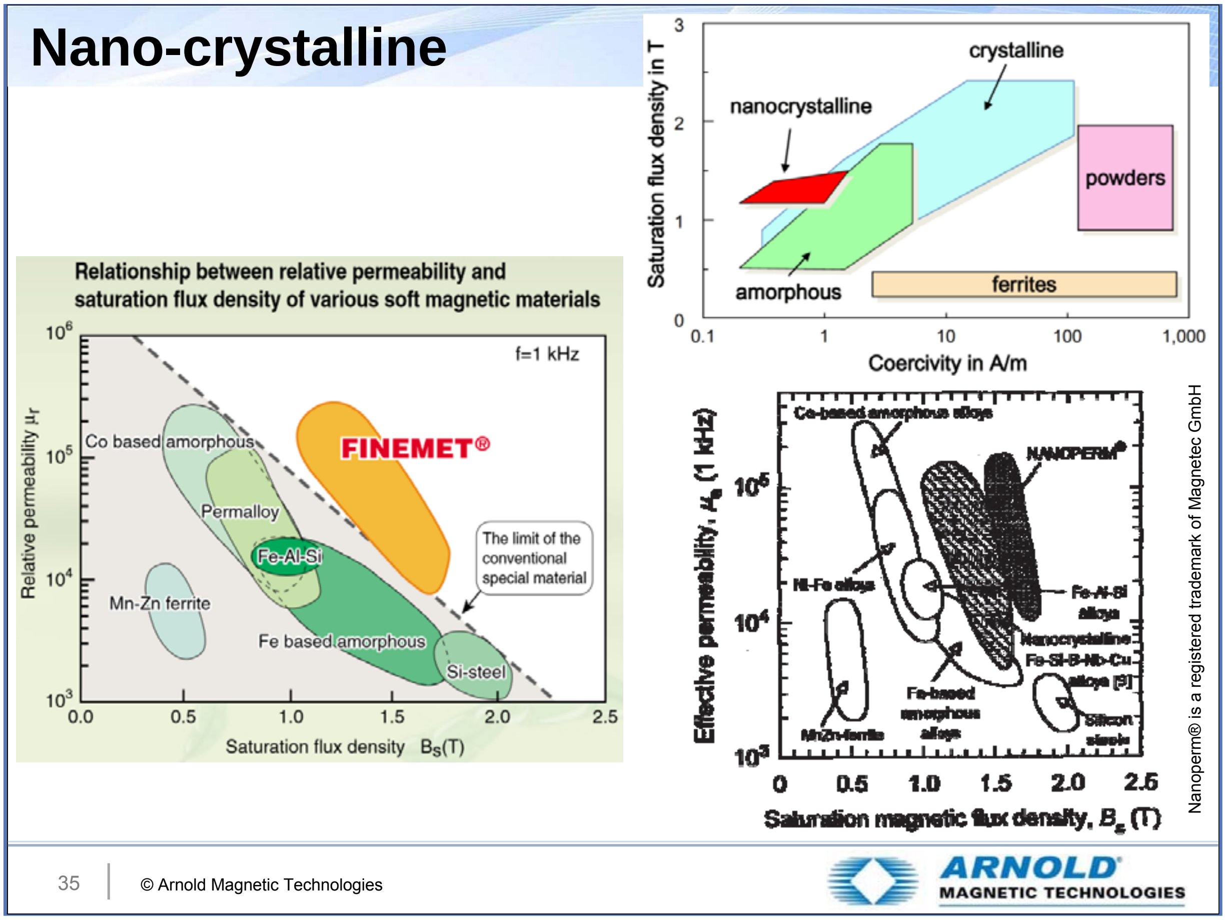
Electrical Distribution Transformers
Industrial Power Distribution Transformers
Material for Anti -Theft tags
High Efficiency Inverters and Inductors
Solar Inverters, Wind Inverters
Harmonic Filters
Pulse Power Cores for Lasers
High Power Magnetic Forms for Medical Use
High Purity Brazing Filler Metals

		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	$\%\bullet10^{-6}$	27	27	20	<0.5	12
Curie Temperature	°C	395	364	358	225	353

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

ARNOLD MAGNETIC TECHNOLOGIES

- A few decades ago, melt-spun soft magnetic alloys were developed having remarkable properties.
- The company that spearheaded the development of this family of materials (Metglas®) was a division of Allied Signal.
- Allied Signal purchased Honeywell and then took the Honeywell name. Shortly thereafter, the Metglas® business unit was sold to Hitachi who remains the owner.
- The name Metglas® is apropos as the material is non-crystalline – just as glass is a non-crystalline solid.
- Some grades of Metglas have extraordinarily high maximum permeability (ease of magnetization) such as grade 2714 with μ_{max} of 1,000,000.
- However, there are trade-offs among maximum permeability, saturation magnetization, and magnetic hardening due to mechanical stress.



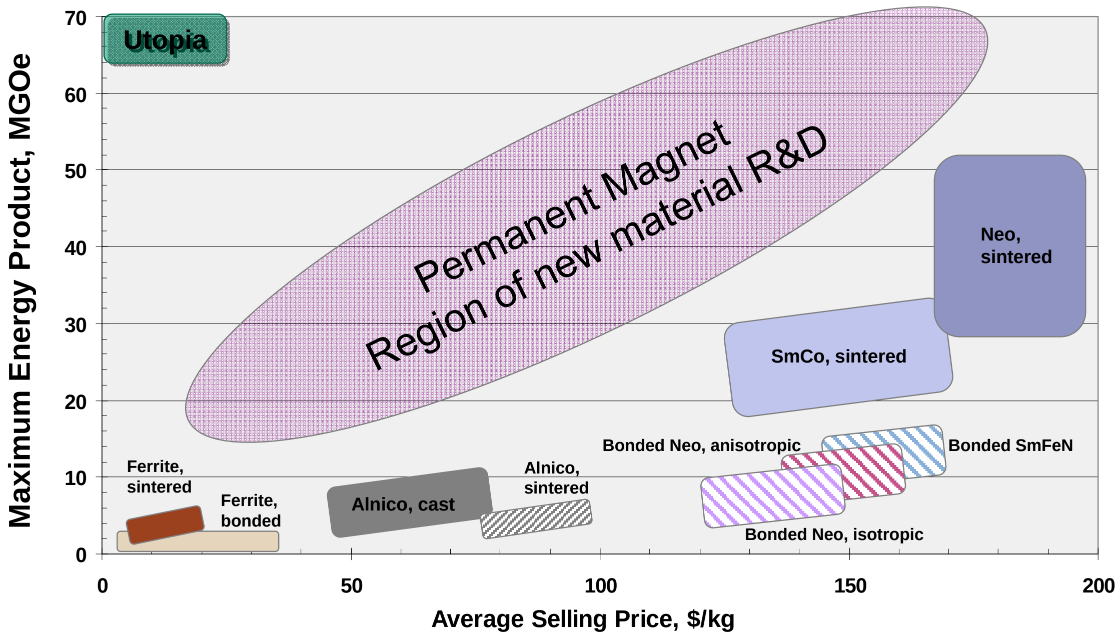
- Another recently developed family of materials are nano-crystalline soft magnetic alloys.
- These go by the trade names such as:
  - o Finemet® - Hitachi
  - o Nanoperm – Magnetec GmbH
  - o Vacoperm – Vacuumschmelze
- Each material offers benefits with trade-offs in properties, handling, manufacturability, cost, etc.

Agenda

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

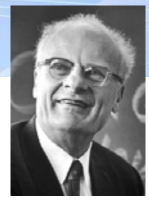
- What does the future hold for magnetic materials?

Magnet Price versus Energy Product



- Many factors such as shape, complexity and size contribute to a magnet's selling price.
- The values shown here are fair estimates of standard shapes and sizes.
- Selling noted price is for western markets (USA and Europe) and is approximate. More important are the relative prices for comparing one product to another.

Origin of the Field



Hans Bethe

John C. Slater

- Heisenberg: quantum theory explanation for ferromagnetism

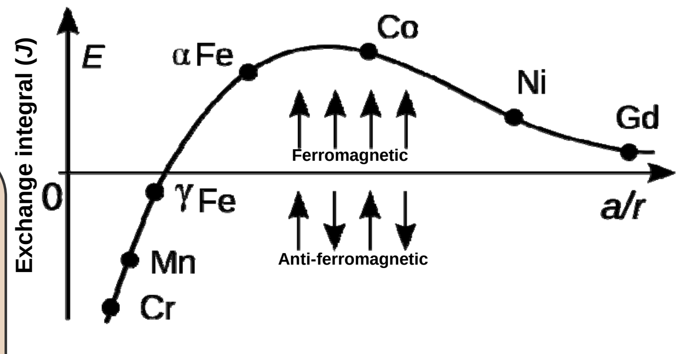
Keywords:

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

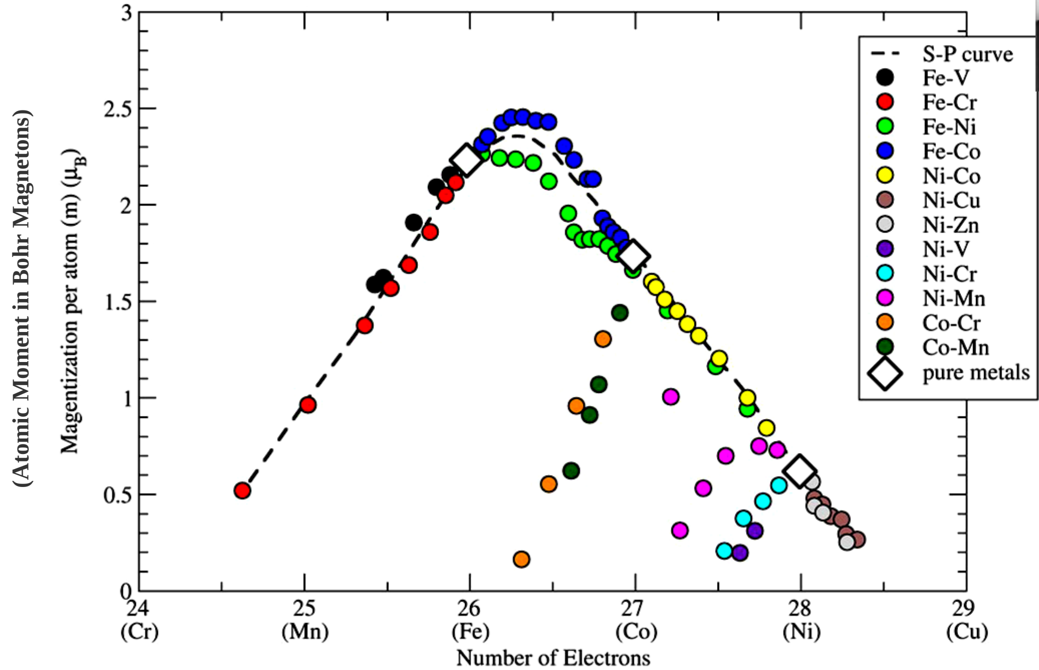
Bethe-Slater Curve



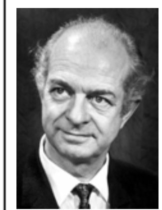
ARNOLD MAGNETIC TECHNOLOGIES

- Heisenberg, using the quantum theory, in 1928 explained that as atoms with partially filled electronic shells at large distances from each other move closer to one another their shells begin to overlap and quantum mechanical exchange forces arise between the incomplete shells. The corresponding energy appears in the mathematical formulation as an "exchange integral".
- When the exchange energy is positive, as it is for Fe, Co, Ni, and Gd, ferromagnetic properties are exhibited. This occurs when the atomic spacing (a) is about 3-4 times the radius of the incomplete shell (r).
- Additionally, some combinations of otherwise weak magnetic materials have strong magnetic characteristics. Examples are MnAlC and MnBi. Alloying modifies the atomic spacing between adjacent manganese atoms changing the exchange interaction for manganese, moving it from a negative value to positive and causing the material to exhibit ferromagnetism.
- On the other hand, when alpha iron transforms in the presence of carbon to form gamma phase, it loses its ferromagnetic properties.

Slater-Pauling Curve



John C. Slater



Linus Pauling

R.M. Bozorth, Ferromagnetism, IEEE, 1993, p.438-441

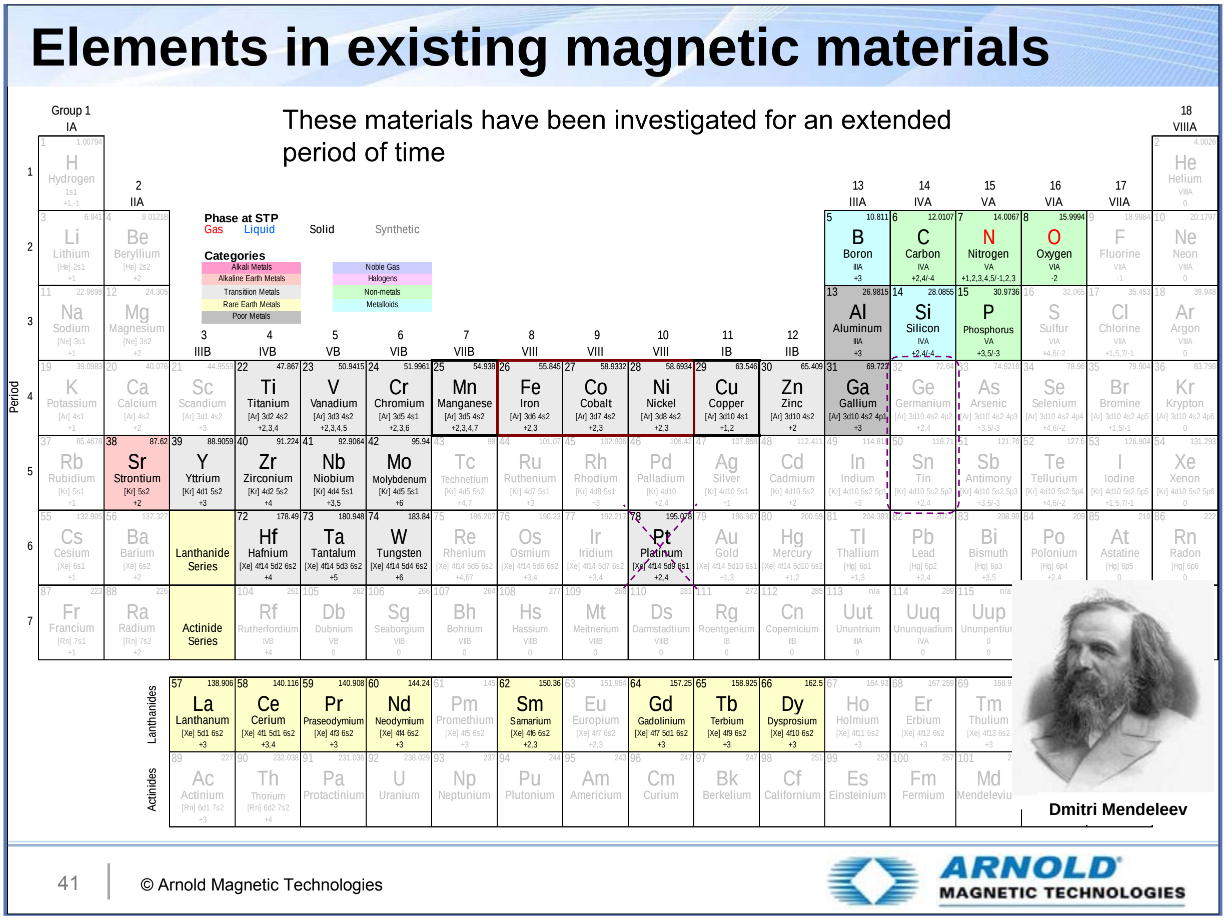
Color-edited by Dr. Bill McCallum, Ames Lab

- The Slater-Pauling curve shows the calculated magnetization for several transition elements and binary combinations.
- The highest magnetization is exhibited by a mix of iron and cobalt at approximately 2.4 Bohr magnetons.
- The calculated value is very close to that achieved in products such as Supermendur and vanadium Permendur.

Elements in Existing Magnetic Materials

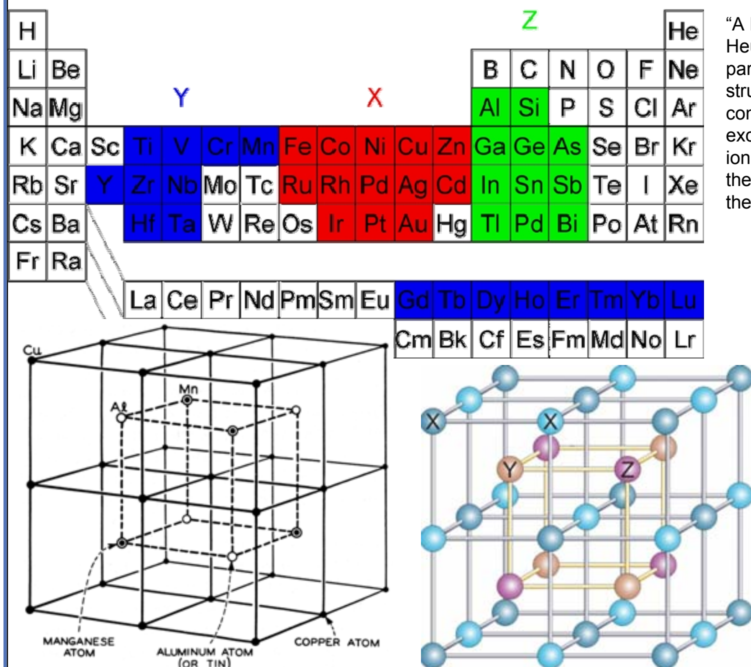
	Major constituents						Minor constituents				Comments
Soft Magnetic Materials											
Iron	Fe										Low carbon mild steel
Silicon Steel	Fe						Si				Si at 2.5 to 6%
Nickel-Iron	Fe	Ni									Ni at 35 to 85%
Moly Permalloy	Ni	Fe					Mo				Ni at 79%, Mo at 4%, bal. Fe
Iron-Cobalt	Fe	Co					V				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

- These are the majority of magnetic materials and are listed with their constituent elements.



- Many elements, listed in the periodic table, are not useful for commercial magnetic products.
- These include: artificially created elements, toxic elements, truly rare elements, those elements that do not contribute to the magnetic moment, inert elements, and elements that will react to form salts (rock-forming elements).
- When we eliminate the magnetically non-useful elements from the periodic table, we are left with those shown highlighted.
- These have been the elements researched individually and in combination for over 150 years.
- Most current research is therefore focused on: 1) creating modified atomic structures via nano-technology with exchange coupling of high saturation magnetization and high anisotropy field (coercivity) materials 2) combined with esoteric manufacturing techniques resulting in modified structures.

Heusler Alloys



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

"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."

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

- I've included this slide on Heusler alloys due to the interesting crystalline structure.
- They were first identified as a family of materials in 1905 and have found recent revival in spintronics.

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 [need not be]—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.

(Wikipedia)

Sensitivity to Thermal Treatment

Affect of Thermal Treatment on SmCo 2:17 Magnetic Properties

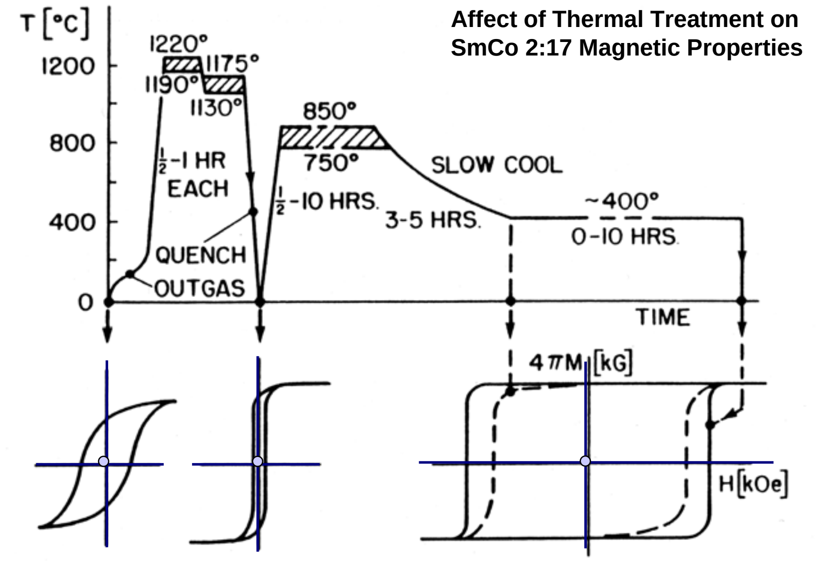


Fig. 32. Typical temperature profile for the sintering and heat-treating of "2–17"-type $Sm(Co, Fe, Cu, Zr)_{7.2-8.5}$ magnets.

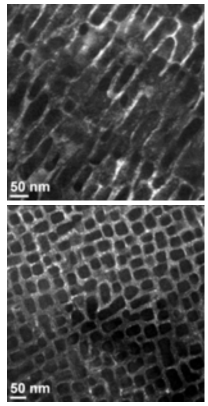
Source: Rare earth-Cobalt Permanent Magnets, K.J. Strnat, 1988

- In addition to the importance in current research of crystal structure is the importance of thermal processing to develop optimal microstructure.
- With the exception of ceramic (hard ferrite) magnets, magnetic alloys are just that – alloys of metals.
- Therefore, thermal treatments to form the stable and desirable phase structure are necessary.
- For example, in this chart Strnat shows the development of the hysteresis loop of Sm2Co17 during its thermal treatment.

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

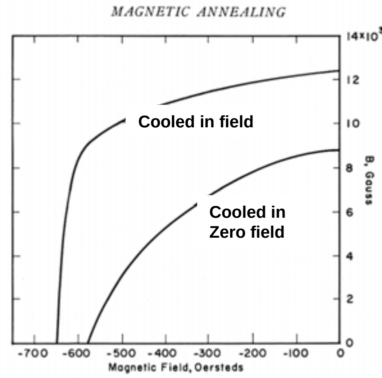


Fig. 8—Effect of Magnetic Annealing of Alnico 5 (142).

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

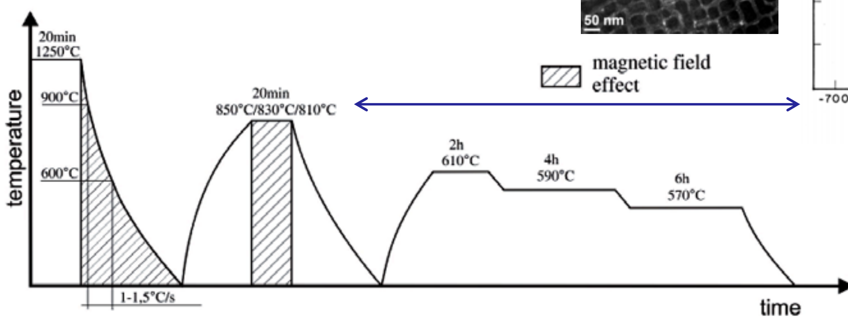


Fig. 3. Scheme of thermo-magnetic treatment of Alnico 8 alloy

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

- In another example, alnico is solution treated at high temperature (about 1230 °C) followed by a conditioning treatment effected by controlled cooling from the solution treatment temperature (e.g. alnico 5) or by isothermal treatment of the magnets – anisotropic magnets (alnico 5-7 and 9) are treated in a field during spinodal decomposition at ~820 °C, slightly below the Curie temperature.
- The third and final treatment is called a “draw” or coercive aging treatment to obtain maximum coercivity and optimal loop shape.
- We might say that the right composition provides the opportunity and the correct thermal treatment creates the best phase structure.

Wrapping it up

- We require energy to survive and thrive. Demand for energy will continue to 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 more than 20x 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 both a challenge and an opportunity.

ARNOLD® MAGNETIC TECHNOLOGIES