

The Big Picture

Putting the Magnet Market Trends Together

Steve Constantinides



Orlando, Florida, February 8, 2018

Preface

World Population by Region

Region	Population 2017	World Share	Forecast 2030	World Share	Net Change
Asia	4,504,428,373	59.7%	5,039,637,399	58.2%	535,209,026
Africa	1,256,268,025	16.6%	1,699,457,399	19.6%	443,189,374
Europe	742,073,853	9.8%	749,229,191	8.7%	7,155,338
Latin America and the Caribbean	645,593,253	8.6%	729,201,164	8.4%	83,607,911
North America	361,207,811	4.8%	394,151,461	4.6%	32,943,650
Oceania	40,690,786	0.5%	48,249,541	0.6%	7,558,755
World	7,550,262,101		8,659,926,155		

<http://www.worldometers.info/world-population/population-by-country/>



Magnet Production & Material Supply

Applications

Hard Disk Drives

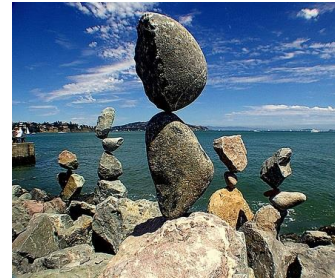
Transportation

Wind Power

Magnetic Refrigeration

Summary Comments

Balancing Supply and Demand



Commercially available magnets

Permanent magnets

- Alnico
- Ferrite (strontium ferrite, ceramic)
- Neodymium iron boron (“Neo”)
- Samarium cobalt
- Samarium iron nitride
- Bonded magnets
 - Include all of the materials listed above singly or in combination
 - Are produced in four forms / methods
Compression bonded, Injection molded, Extruded, Calendered

Semi-hard magnets

- FeCrCo
- Vicalloy

Global Sales of Permanent Magnets

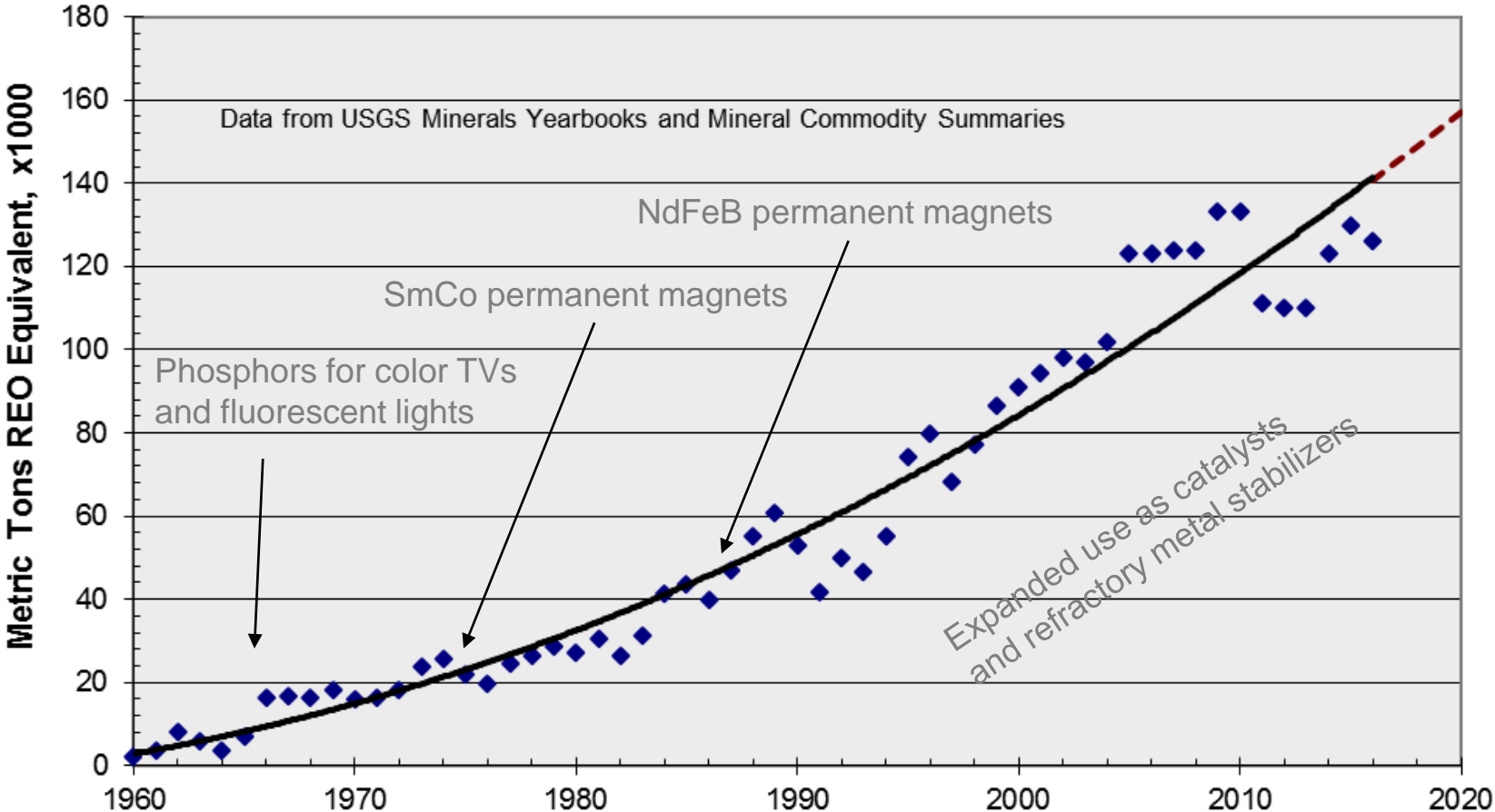
	2010 Actual					2016 Estimate				
	<u>tons</u>	<u>%</u>	<u>\$million</u>	<u>%</u>	<u>\$/kg</u>	<u>tons</u>	<u>%</u>	<u>\$million</u>	<u>%</u>	<u>\$/kg</u>
NdFeB	80,900	12.3%	6,850	65.2%	84.67	105,000	13.1%	7,250	52.7%	69.05
SmCo	2,310	0.4%	270	2.6%	116.88	3,864	0.5%	345	2.5%	89.29
Ferrite	567,000	86.4%	2,950	28.1%	5.20	685,000	85.5%	5,625	40.9%	8.21
Alnico	5,555	0.8%	375	3.6%	67.51	5,950	0.7%	375	2.7%	63.03
Other	540	0.1%	65	0.6%	120.37	1,450	0.2%	170	1.2%	117.24
Totals	656,305	100.0%	10,510	100.0%	16.01	801,264	100.0%	13,765	100.0%	17.18

Data updated as of 2/1/17.

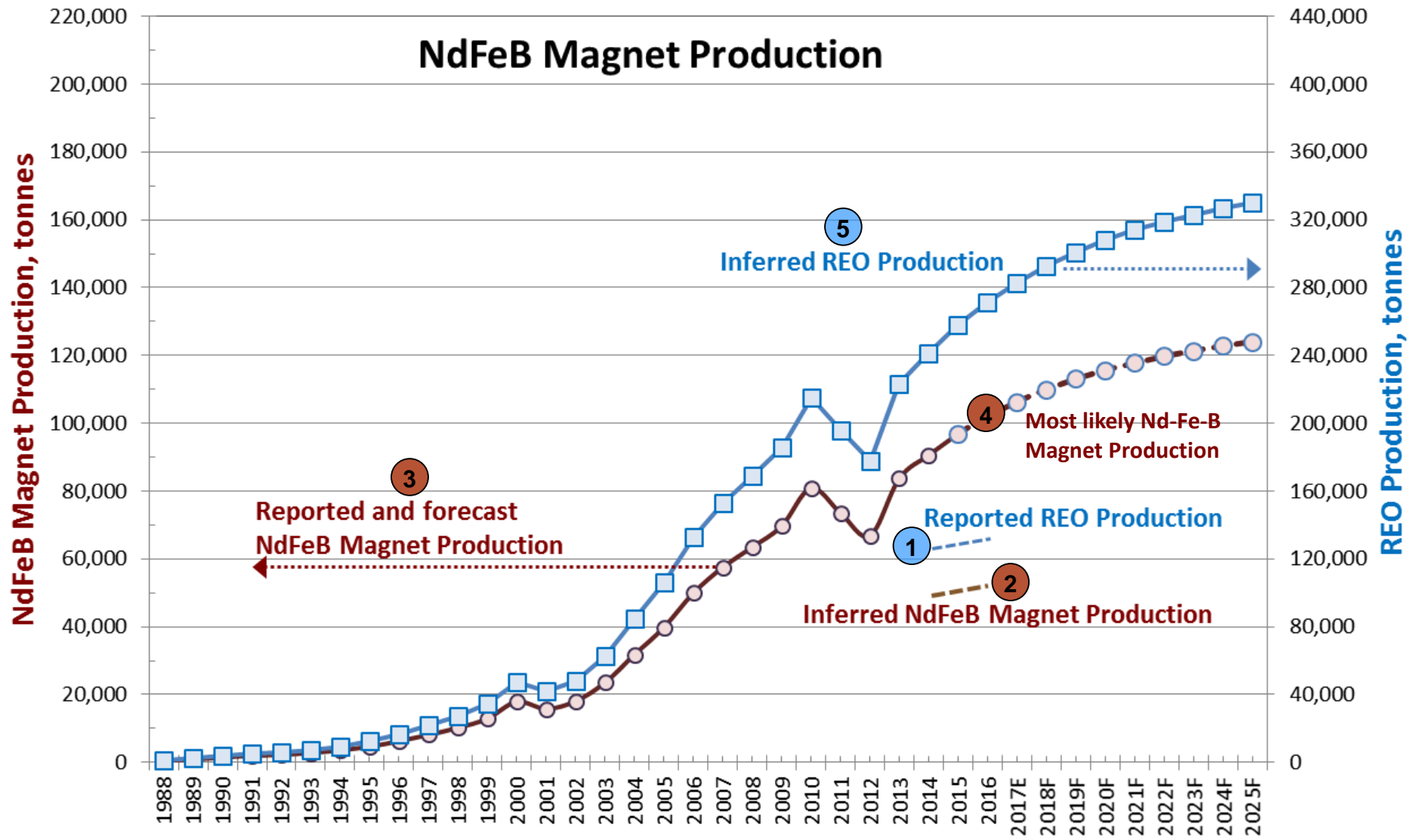
Sources: Multiple including Benecki, Clagett and Trout; JL Mag; Yang Luo; Wang et al; numerous industry sources.

Global production of REO (USGS)

Rare Earth Global Mine Production



NdFeB Magnet Production



Revised as of 2/1/17

Lynas Production of REO

- Malawi operations
 - Since fiscal year 2012, no further capital investment has been made on the Kangankunde Rare Earths (“K GK”) resource development in Malawi
 - Project remains on hold
- Ready-for-Sale tonnage

	FY14	FY15	FY16	FY17
Ready for sale production volume total (REOt)	3,965	8,799	12,631	16,003
Ready for sale production volume NdPr (REOt)	946	2,258	3,896	5,223 ¹





Magnet Production & Material Supply

Applications

Hard Disk Drives

Transportation

Wind Power

Magnetic Refrigeration

Summary Comments

Major and Developing Uses of Neo Magnets

- **HDD (Global)**: Magnet total weight consumed in 2016 was = 6,370 tonnes
- **Hybrid and electric cars & trucks (Global)**: in growth phase
 - Total neo magnet usage in 2015 = 3,850 rising to 18,025 tpa in 2020
- **EB (electric bicycles, primarily in Asia)**: large and growing application
 - Annual neo magnet usage in 2015 = 9,580 rising to 13,000 tpa by 2020
- **Wind turbines (Global)**: use of PM generators mostly in China until 2020
 - Global 2015 consumption = 16,600 tonnes rising to 29,000 tpa in 2020
- **Cooling, Refrigeration** (rapid growth primarily **southeast Asia** and **India**)
 - Neo usage in 2015= >5,000 tpa growing to 7,000 tpa om 2020
 - Magnetocaloric cooling potential new application starting in early 2020s
- **Acoustic transducers and miniature applications**
 - Speakers in transportation – more than 280 million speakers per year (ferrite+Neo)
 - Speakers, ear buds, headphones Neo usage in 2015 = 7,470 tpa

2015: 6.8 billion cell phones are connected

- **Other applications using permanent magnets**
 - Motors and generators in aircraft
 - Oil and gas well directional drilling
 - Building elevators (lifts)
 - Over 100 magnets in a typical car – more than a dozen applications



Magnet Production & Material Supply

Applications



Hard Disk Drives

Transportation

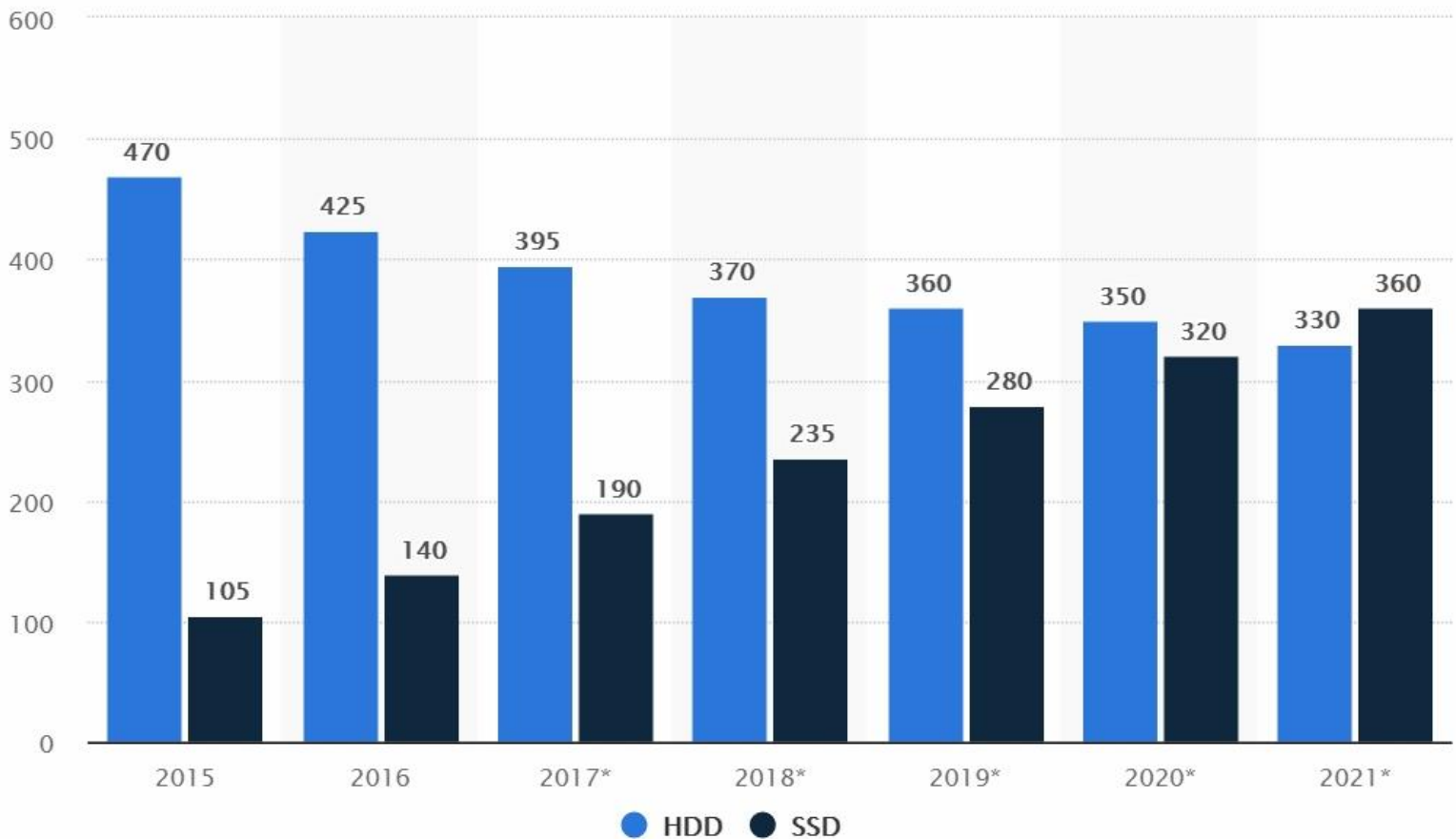
Wind Power

Magnetic Refrigeration

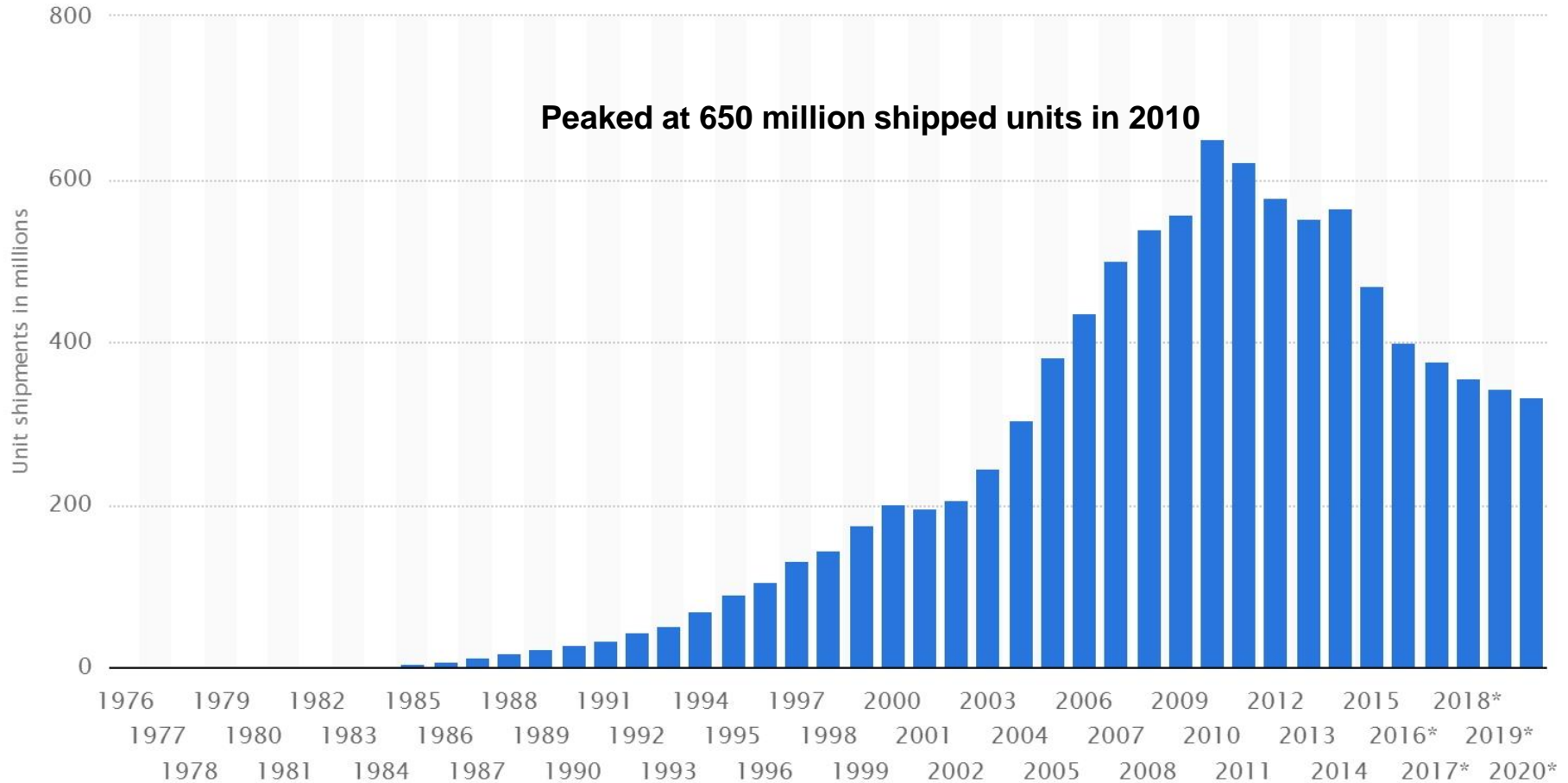
Summary Comments

HDD to SSD Conversion

Shipments of hard and solid state disk (HDD/SSD) drives worldwide from 2015 to 2021 (in millions)



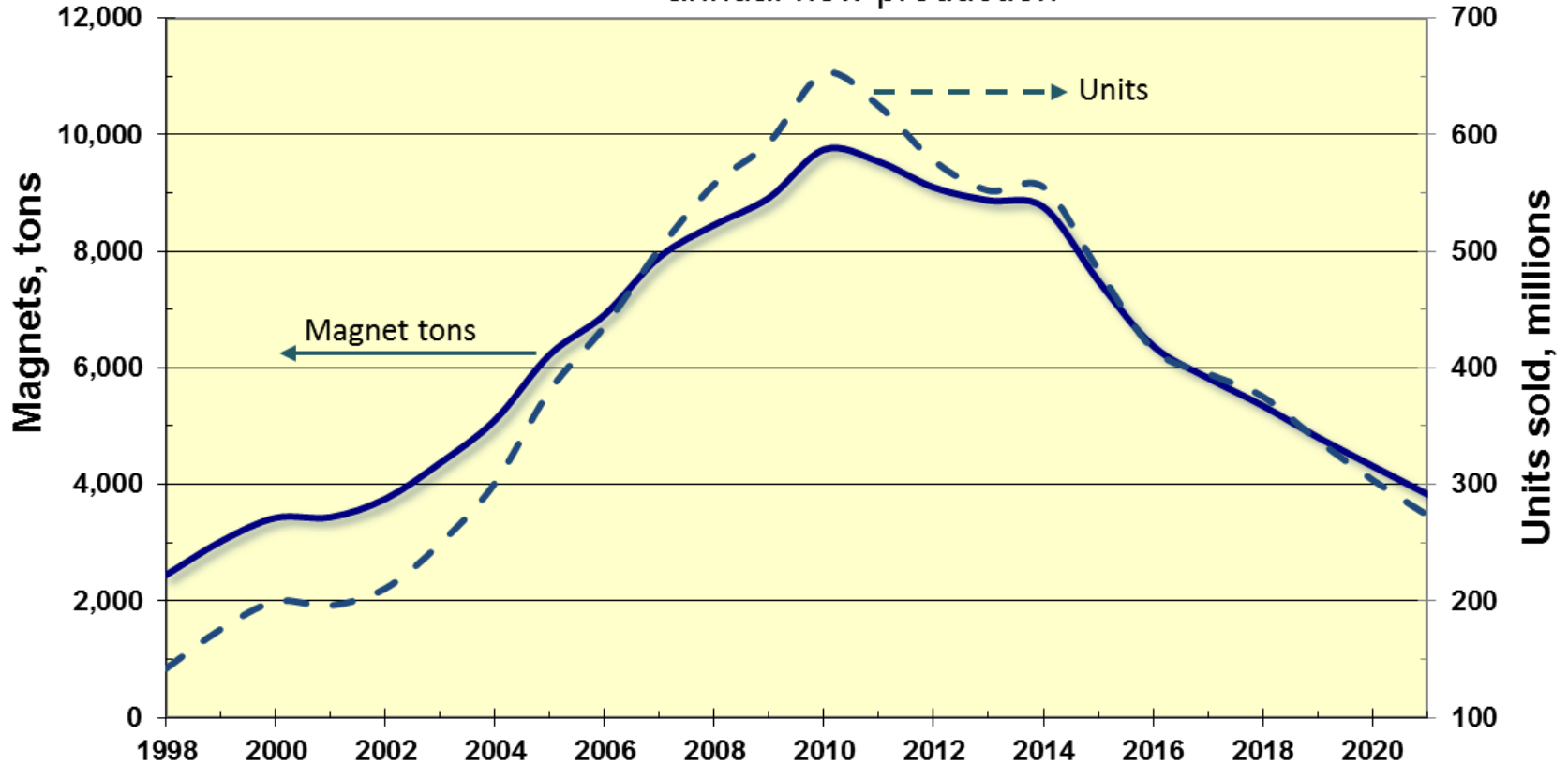
HDD Production (per Statistica)



© Statista 2016

Hard Disk and Optical Drive Production

Neo Magnets in HDDs, CDs and DVDs
annual new production



Unit volumes shown only for HDDs; optical drive Nd-Fe-B magnet quantities included in magnet tons.

Data from Tom Coughlin, John Rydning, Statistica, iHS Global, etc.

Magnet Production & Material Supply

Applications

Hard Disk Drives

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Wind Power

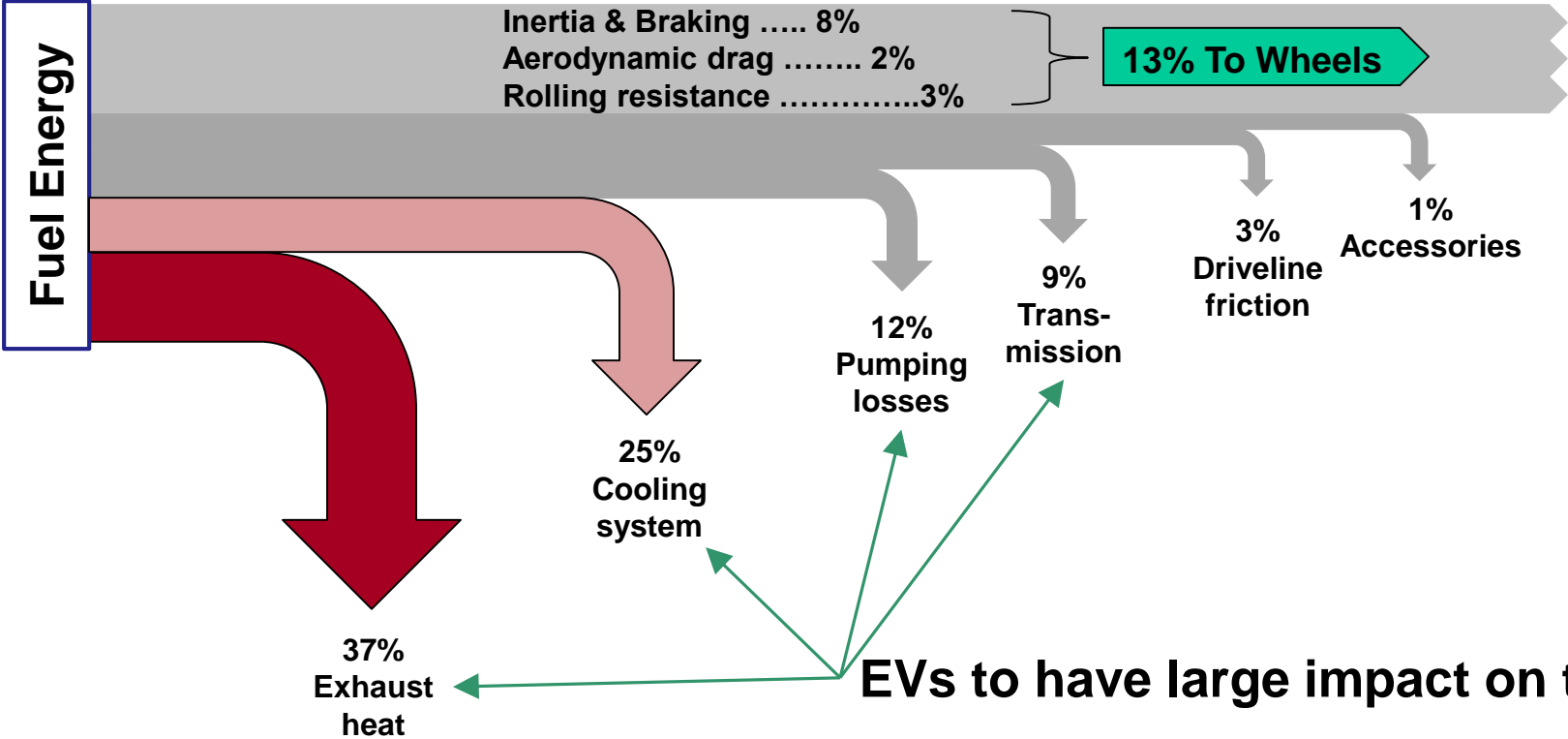
Magnetic Refrigeration

Summary Comments



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

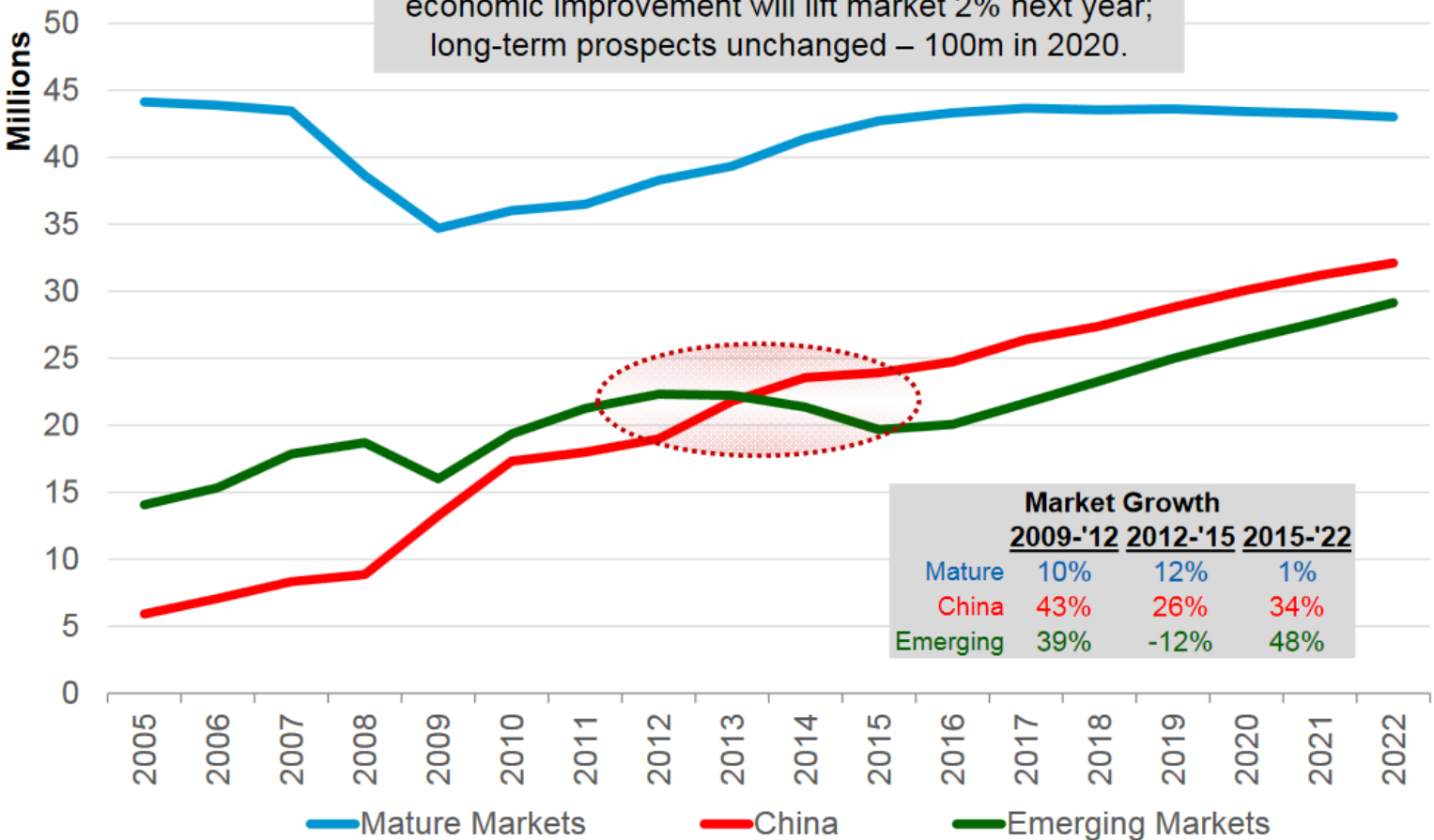


Growth forecast for emerging markets

Global Light Vehicle Sales Forecast

Market now flat in 2015, but weakness in emerging markets only temporary

Global sales remain at 86 million in 2015, but economic improvement will lift market 2% next year; long-term prospects unchanged – 100m in 2020.



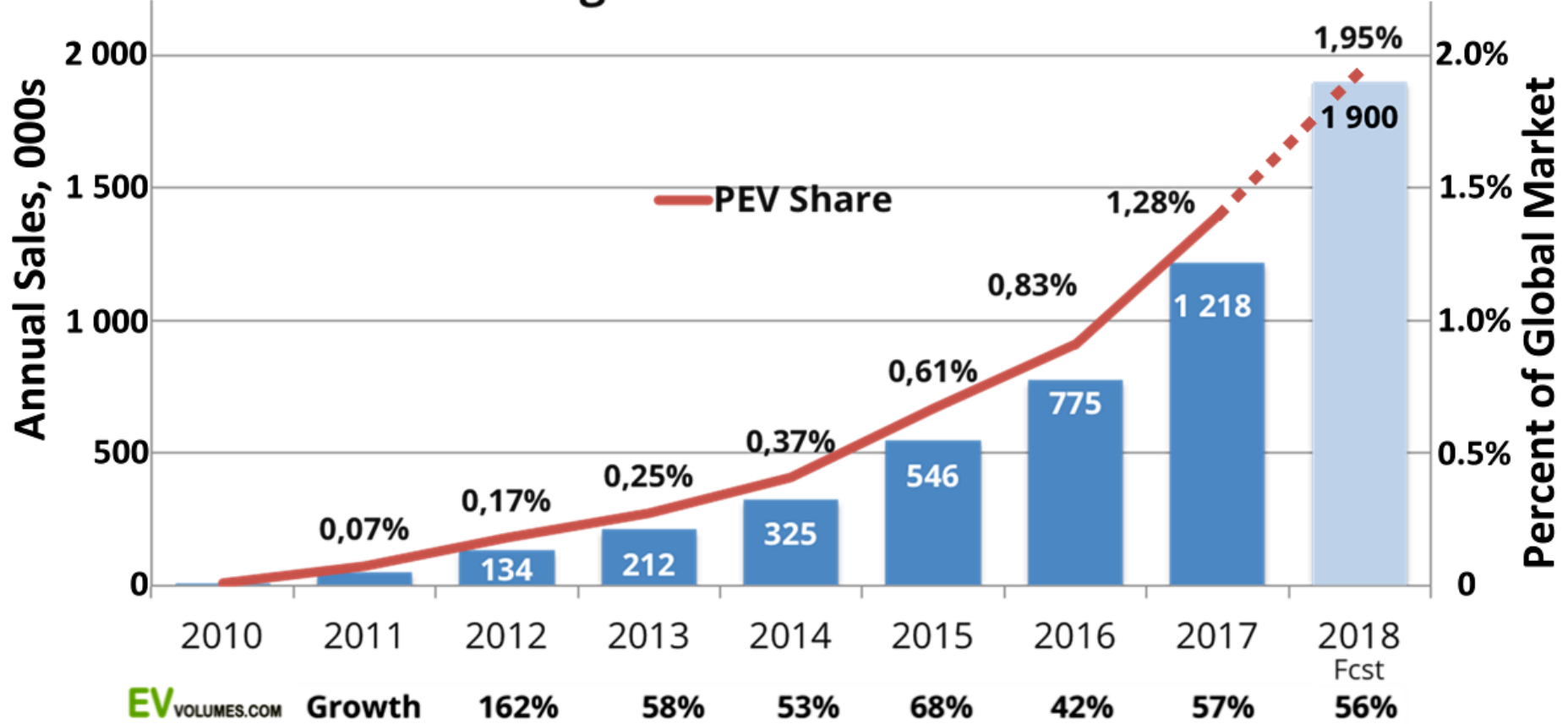
Sales of alternative drive cars and small trucks, USA

2017 annual sales based on sales through December

Manufacturer	Hybrid	PHEV	BEV	CNG	FCEV	Diesel	Total	Total%
Accura	2,680	-	-	-	-	-	2,680	0.41%
Audi	-	2,877	-	-	-	415	3,292	0.50%
BMW	-	14,457	6,276	-	-	5,211	25,944	3.96%
GM	5,902	20,573	23,320	-	-	14,597	64,392	9.82%
Fiat - Chrysler	-	2,981	3,336	-	-	7,839	14,156	2.16%
Ford	73,655	17,772	1,817	-	-	44,576	137,820	21.02%
Honda	22,781	903	1,121	-	432	-	25,237	3.85%
Hyundai	20,315	1,092	432	-	28	-	21,867	3.33%
Infiniti	1,226	-	-	-	-	-	1,226	0.19%
Jaguar	-	-	-	-	-	4,565	4,565	0.70%
Jeep	-	-	-	-	-	725	725	0.11%
Kia	32,774	1,512	2,157	-	-	-	36,443	5.56%
Land Rover	-	-	-	-	-	5,707	5,707	0.87%
Lexus	22,144	-	-	-	-	-	22,144	3.38%
Mercedes	3	1,946	744	-	-	106	2,799	0.43%
Mini Cooper	-	475	-	-	-	-	475	0.07%
Mitsubishi	-	-	6	-	-	-	6	0.00%
Nissan	1,455	-	11,230	-	-	-	12,685	1.93%
Porsche	-	1,592	-	-	-	-	1,592	0.24%
Smart	-	-	544	-	-	-	544	0.08%
Subaru	45	-	-	-	-	-	45	0.01%
Tesla	-	-	49,970	-	-	-	49,970	7.62%
Toyota	181,124	20,936	-	-	1,838	-	203,898	31.09%
Volkswagen	70	-	3,534	-	-	11,069	14,673	2.24%
Volvo	-	2,876	-	-	-	-	2,876	0.44%
TOTAL	364,174	89,992	104,487	0	2,298	94,810	655,761	100.00%
% of alt. fuel	55.53%	13.72%	15.93%	0.00%	0.35%	14.46%	100.00%	
2017 → % of total Mkt	2.13%	0.53%	0.61%	0.00%	0.01%	0.55%	3.83%	
2016 → % of total Mkt	1.99%	0.42%	0.48%	0.00%	0.01%	0.79%	3.68%	

Global Market for BEV & PHEV

Global Plug-in Vehicle Sales & Share

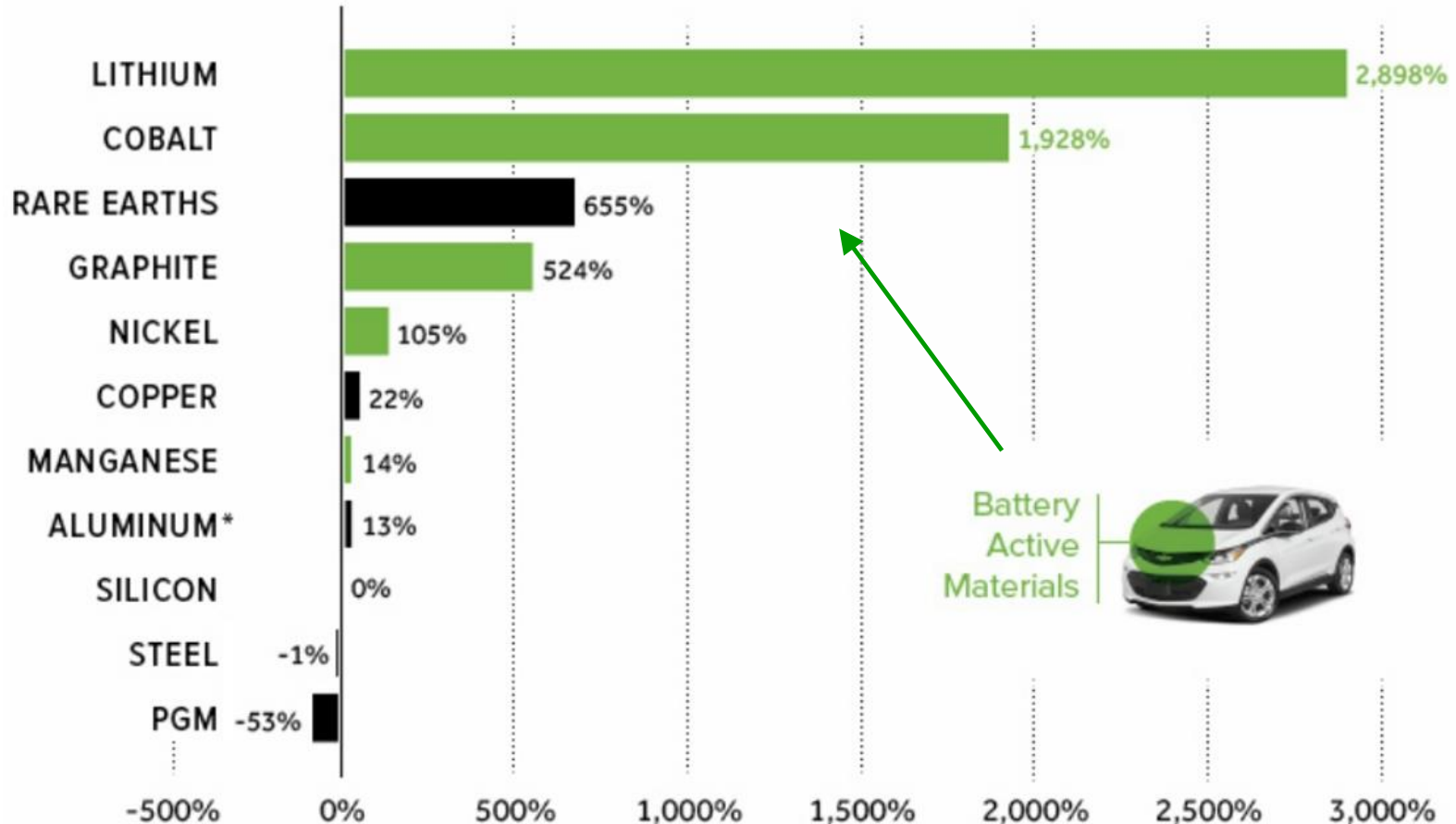


These include all global BEV and PHEV passenger cars sales, light trucks in USA/Canada and light commercial vehicle in Europe.



Commodity Requirements for EVs

INCREMENTAL COMMODITY DEMAND IN A 100% EV WORLD
Percentage of today's global production



*Small amounts of aluminum are used in NCA batteries, but this change in demand stems mostly from replacing steel in the body.

Incremental Commodity Demand in a 100 percent EV World - UBS – 2017
Also see page 74 of: http://www.advantagelithium.com/_resources/pdf/UBS-Article.pdf

Buffet on ICE

Buffett Bets on the Fossil-Fuel Highway

“The oracle of Omaha knows a policy bubble when he sees it-and electric vehicles are a prime case.”

BUSINESS WORLD by Holman W. Jenkins, Jr.
Wall Street Journal, 7-October 2017

↙ Bloomberg New Energy Finance

According to BNEF, the world's biggest auto manufacturers are only planning to sell a combined 8 million electric cars per year by 2030.
Stephen Lacey July 17, 2017

On the other hand...



Global EV Outlook 2017
Two million and counting



<https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook2017.pdf>

Steve's Forecast - USA market



New car and small truck sales

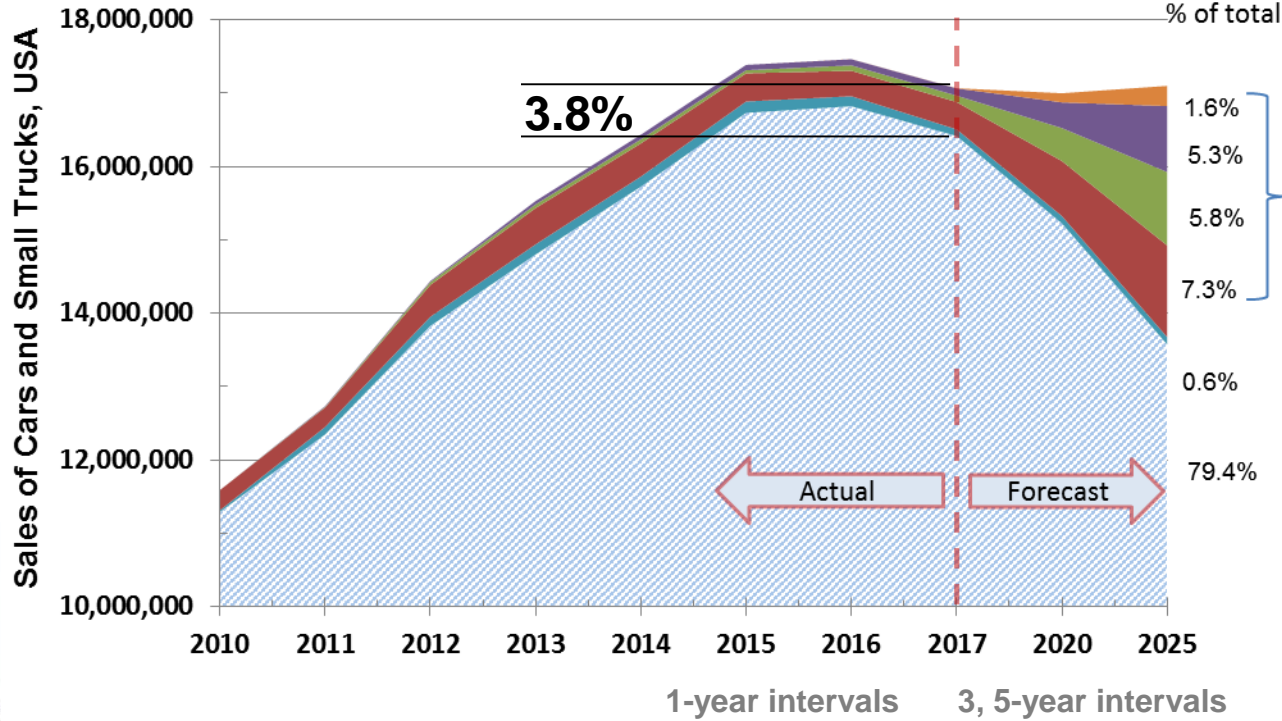


Photo Courtesy of Drayson Racing

These technologies use electric traction drive motors

- FCEV
- BEV
- EREV, PHEV
- HEV
- Diesel
- Conventional Gas



Magnet Requirements for EVs

Annual, new production; traction drive motor only

Year	Total Market, millions		% EV (inc. hybrid)		# EV (inc. hybrid)		Magnets Req'd, tons		TREO Req'd
	USA	Global	USA	Global	USA	Global	USA	Global	Global
2015	17.4	88.0	2.9%	3.5%	0.5	3.1	631	3,850	9,810
2020	17.2	103.0	9.7%	14.0%	1.7	14.4	2,086	18,025	44,020
2025	17.1	113.0	20.1%	25.0%	3.4	28.3	4,296	35,313	86,700
2030	17.0	119.0	25.0%	28.0%	4.3	33.3	5,313	41,650	102,800
2035	16.5	122.0	30.0%	30.0%	5.0	36.6	6,188	45,750	113,690
2040	16.5	125.0	35.0%	35.0%	5.8	43.8	7,219	54,688	135,510
2045	16.3	130.0	40.0%	40.0%	6.5	52.0	8,150	65,000	160,120
2050	16.0	132.0	50.0%	50.0%	8.0	66.0	10,000	82,500	202,470

Vehicle quantities shown in millions

Average kg NdFeB magnets per traction drive system = 1.25

Extreme case in 2040:

All cars are EV = 125,000,000 vehicles

1.25 kg per vehicle traction drive = 156,250,000 kg = 156,250 tons of magnets

156,250 tons of NdFeB magnets requires 342,000 tons of REO

Magnet Production & Material Supply

Applications

Hard Disk Drives

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Wind Power

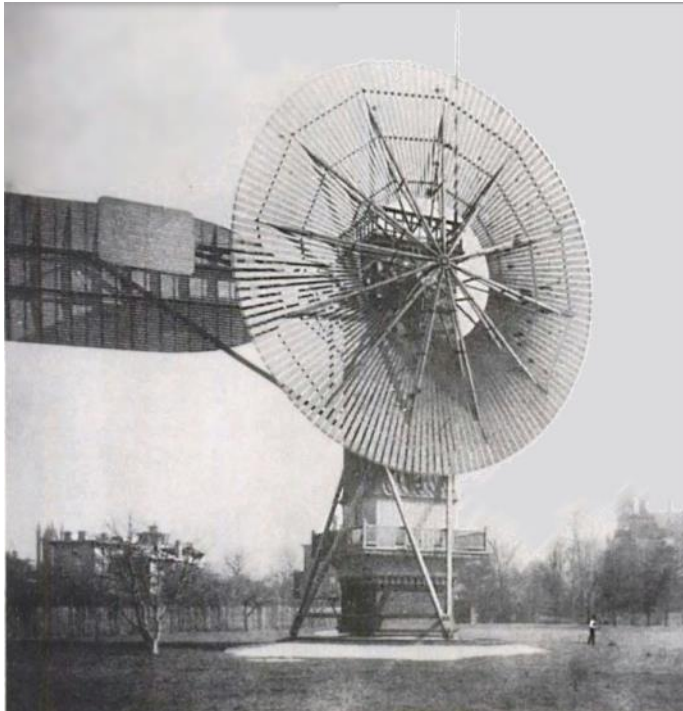
Magnetic Refrigeration

Summary Comments

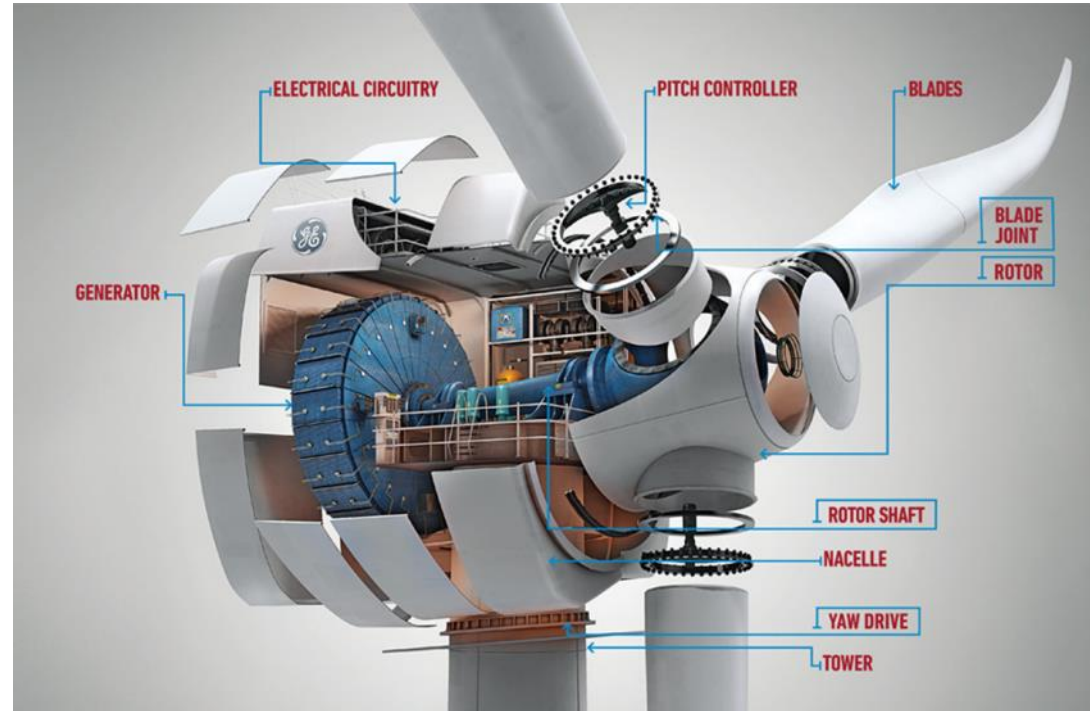


Wind Energy

Producing electricity from wind

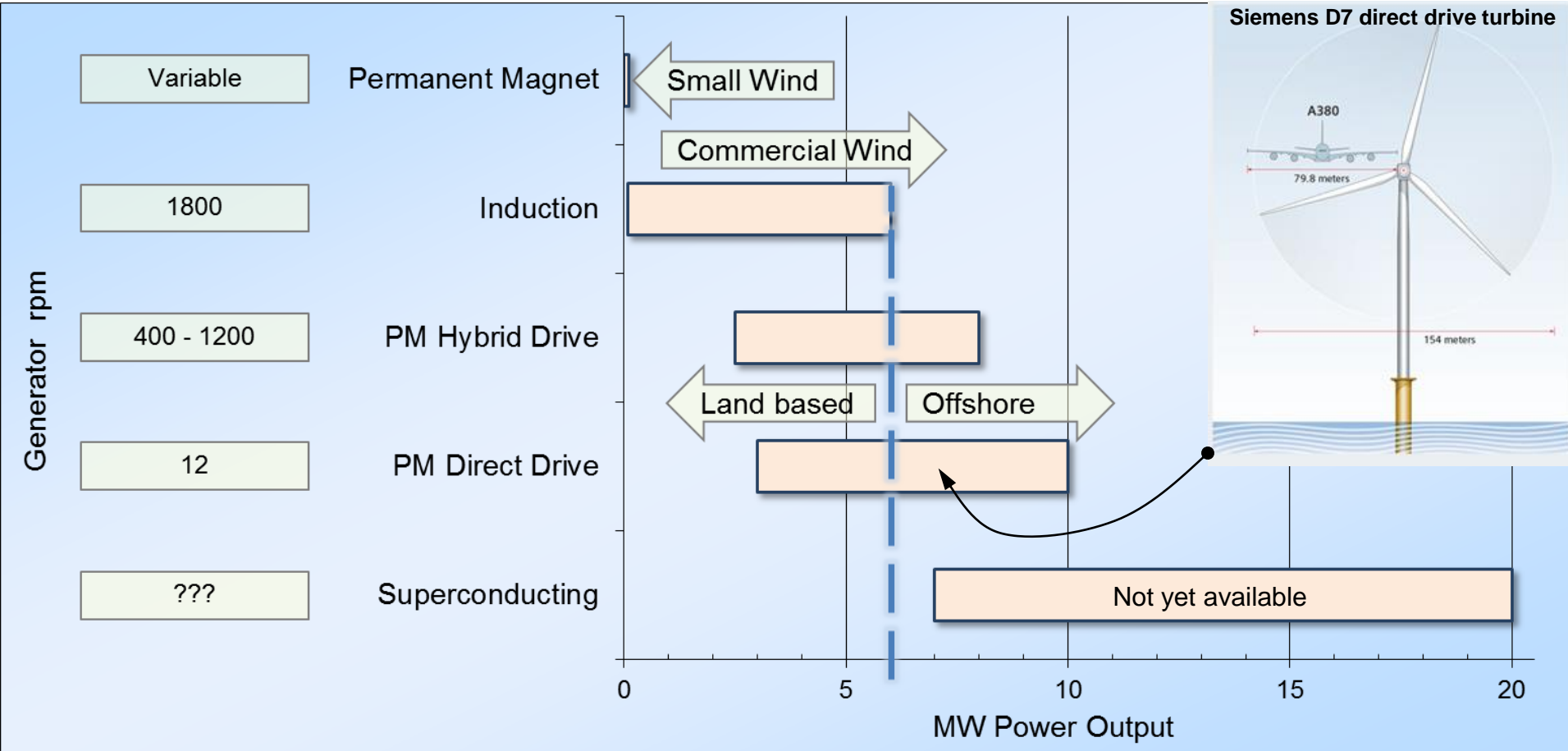


Charles Francis Brush wind mill from 1888



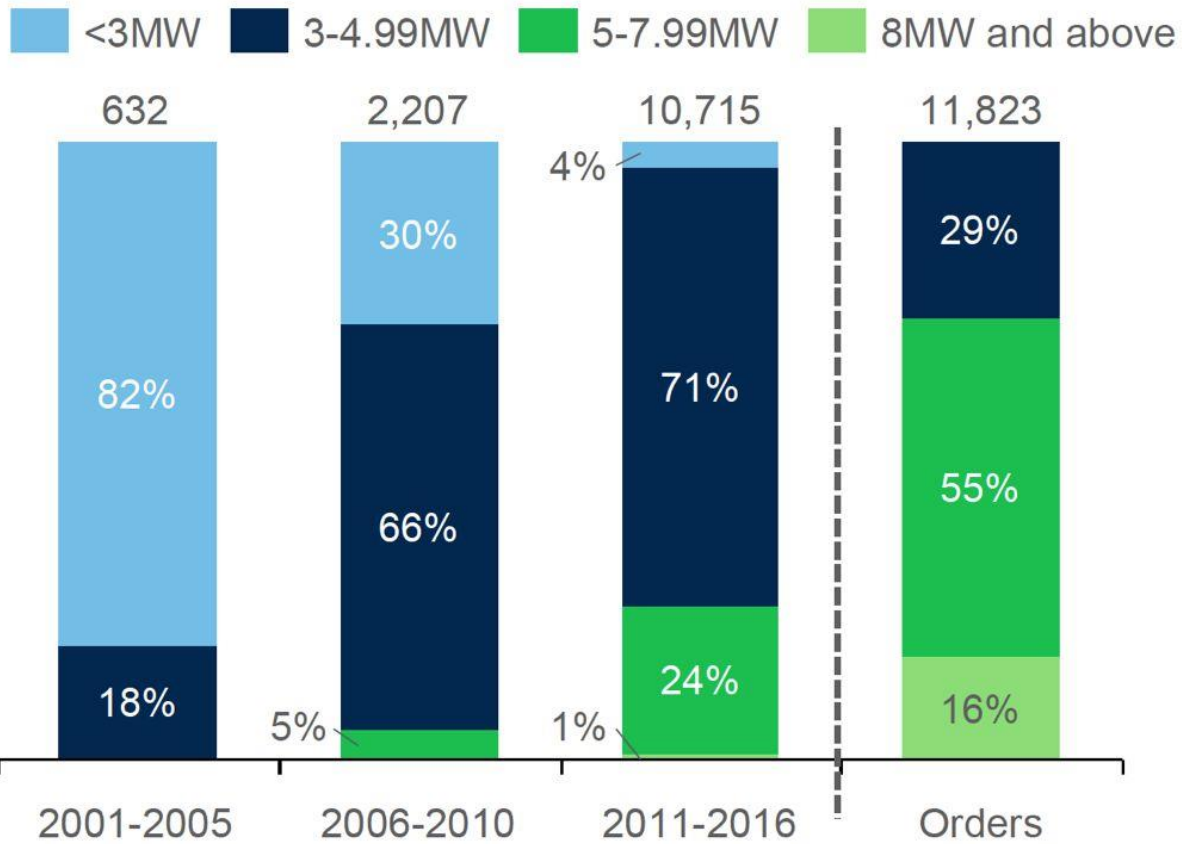
GE Gen-4 Permanent magnet generator

Wind Power - Types and Locations



Offshore Wind Turbine Size

Rapid offshore turbine size development



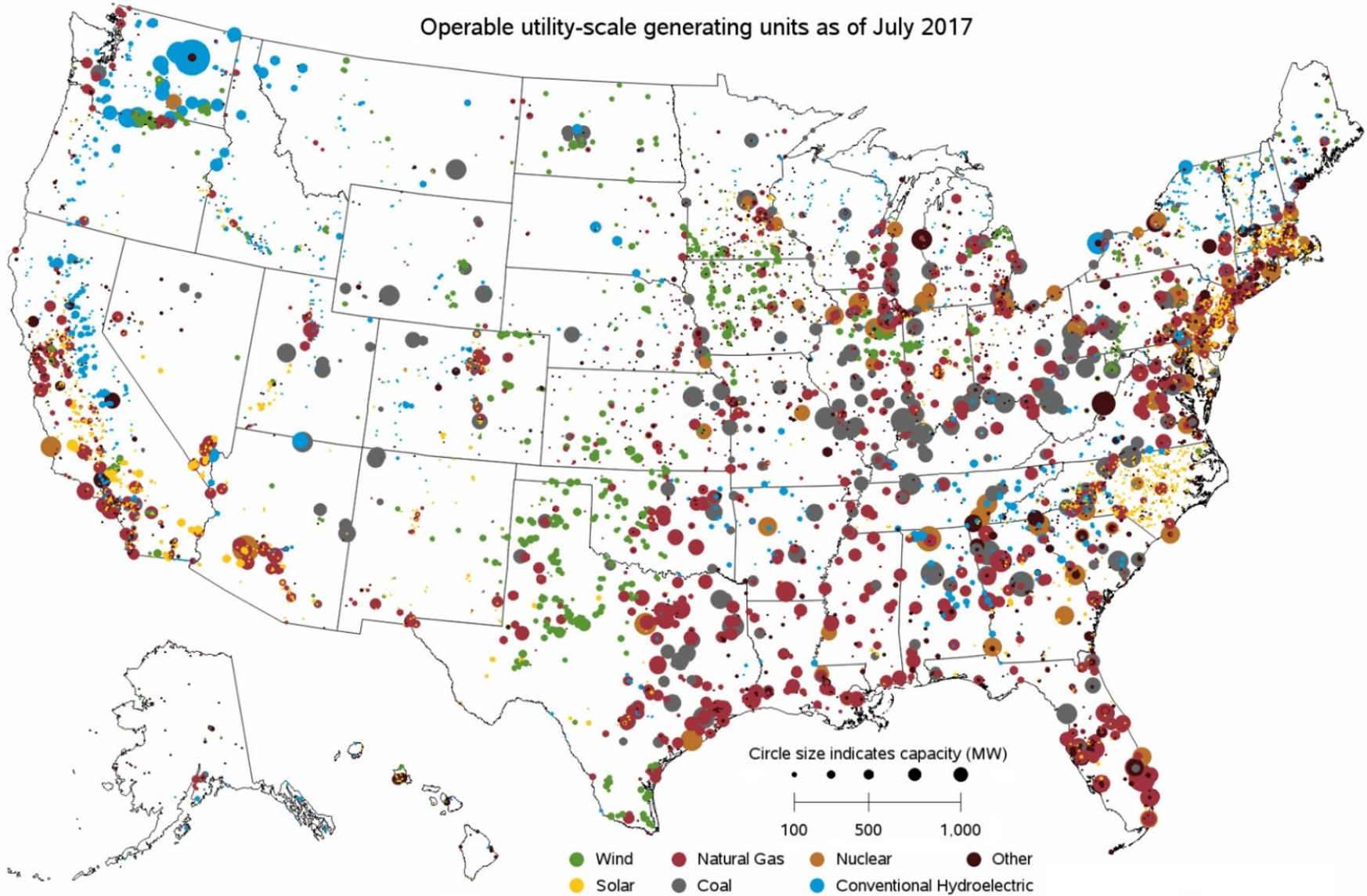
Note: Segmented by grid connected date.

Orders include firm and unconditional to be installed during 2017 and beyond

<https://www.greentechmedia.com/articles/read/an-illustrated-guide-to-the-growing-size-of-wind-turbines#gs.MGcuL8E>



Electricity Generation in the USA



Sources: U.S. Energy Information Administration, Form EIA-860, 'Annual Electric Generator Report' and Form EIA-860M, 'Monthly Update to the Annual Electric Generator Report.'

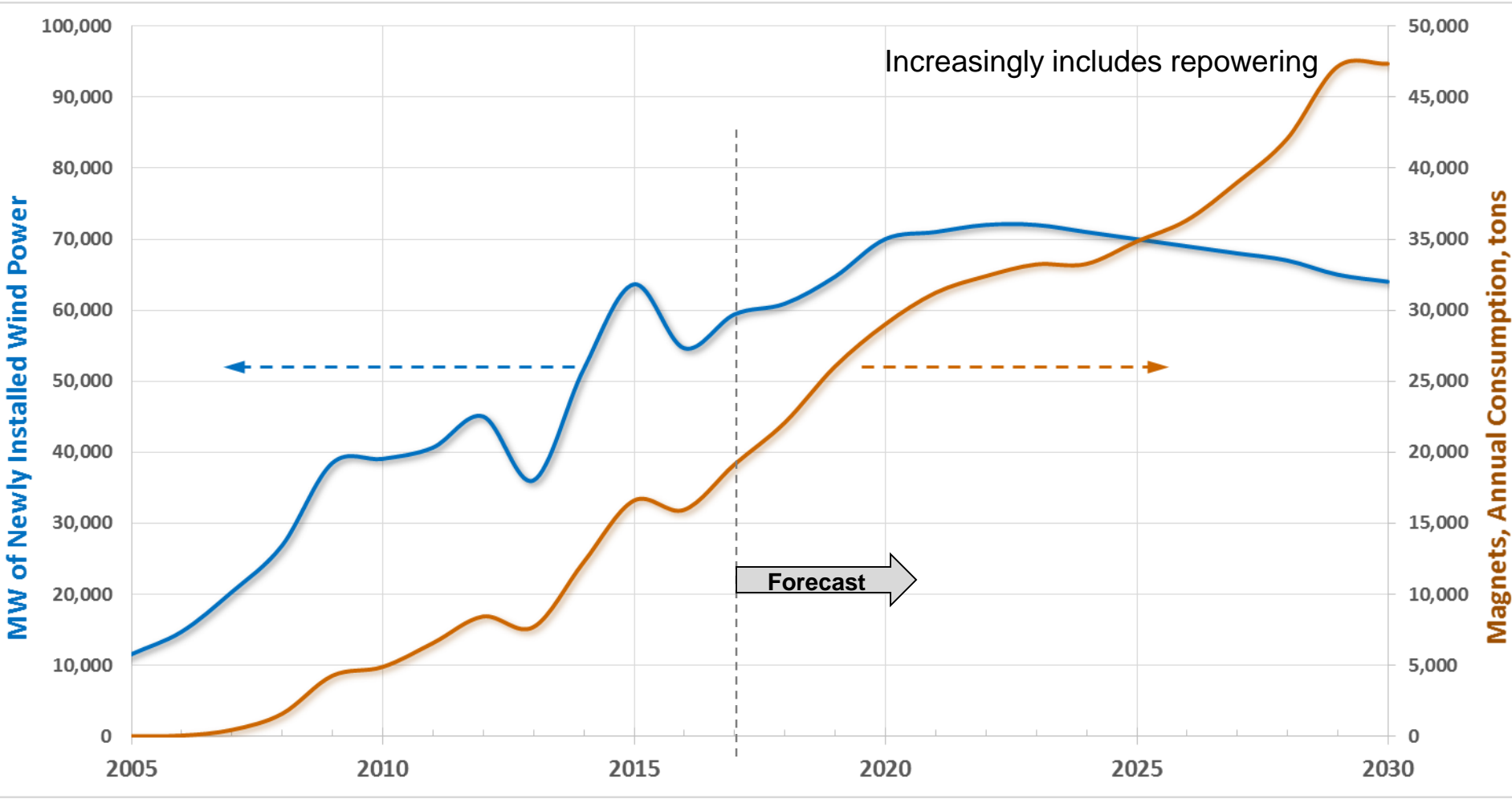
Global wind power installations

Year	Global Cumulative Capacity [GW]	Global Annual Growth Rate [%]	Annual Installations [MW] incl. Repowering	Capacity factor [%]	Production [TWh]	Wind power penetration of world's electricity in % (IEA demand projection)
2013	318		35,787	28	714	3
2015	433	0	63,350	28	868	4
2020	797	11	79,005	28	1,955	8
2025	1,182	7	76,810	28	2,900	
2030	1,676	7	107,488	30	4,404	14
2035	2,169	5	111,800	30	5,701	
2040	2,767	5	125,397	30	7,273	20
2045	3,386	4	123,975	30	8,897	
2050	3,984	3	118,604	30	10,470	25

Source: GWEC Wind Power Outlook 2016, Moderate Scenario

Direct and Hybrid Drive Generator: Magnet Requirements

Annual New Installed Capacity and Magnet Weight



Magnet Production & Material Supply

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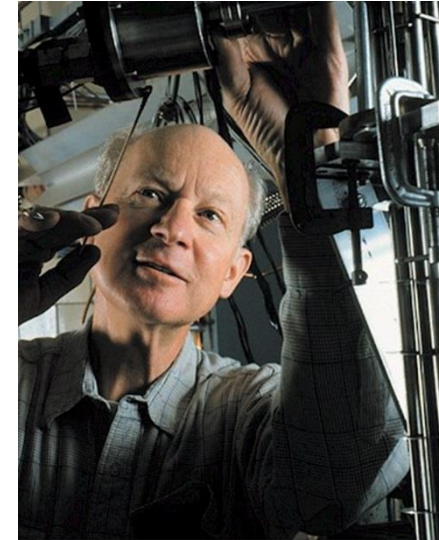
Summary Comments



Agenda – from MCMA Fall TechCon Presentation

The **Big Chill** –
the coming of age of magnetic refrigeration

- Conventional Refrigeration
- Markets for Cooling Technology
- MCE & GMCE
- MCE System and Materials
- Status and Opportunity



Karl Gschneidner
Ames Laboratory, 1997



THE
BIG CHILL

By Mark Bowman

Mark Bowman of Ames Laboratory
Inquiry Online Magazine. "The Big Chill" about the discovery of the GMCE
<http://www.external.ameslab.gov/News/Inquiry/fall97/bigchill.html>. 1997 [Ref.8]

Refrigerators & Consumption of Electricity

“Households all round the world are currently using **1.4 billion** refrigerators, fridge freezers and freezers.

The average annual consumption of all these cold appliances amounts to about 453 kWh.

In total, this causes an annual electricity consumption of 649 TWh, which is more, for example, than the total electricity consumption of Germany”.

From: The overall worldwide saving potential from domestic refrigerators and freezers with results detailed for 11 world regions; Authors: Dr. Claus Barthel Thomas Götz; December 2012

Samsung Electronics has produced over 200 million compressors, which are the heart of any refrigerator.



Global Markets for Cooling, 2016 data

- Refrigerators and Freezers

- Residential 130 million units/year
- Commercial 12 million units/year
- Food processors
- Warehouses
- Grocery stores
- Convenience stores
- Restaurants
- Trucks, trains, ships 175,000 thousand units/year
- Aircraft

Globally, more than 1.4 billion are in use

500,000 ref trucks are on the road in the USA

- Air Conditioning

- Aircraft, cars and trucks 75 million units/year
- Residential 85+ million units/year
- Office
- Retail, commercial and factory
- Manufacturing atmosphere control



Who is Pursuing MCE Cooling

- Astronautics, BASF, (GE>) Haier (consortium)
- CaloriCool (Ames Lab) (consortium)
- Camfridge (UK) www.camfridge.com
- Cooltech (France) (www.cooltech-applications.com)

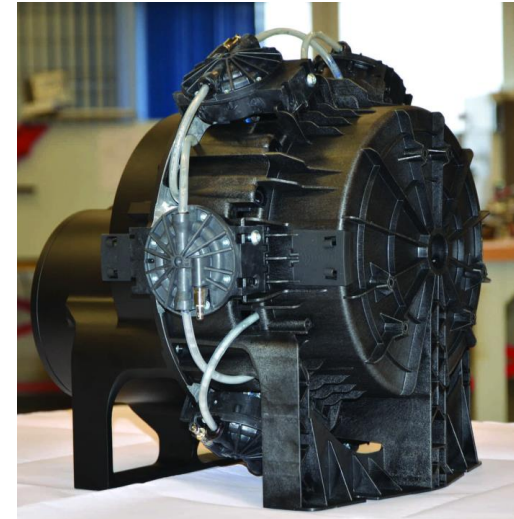


Camfridge



And other major appliance manufacturers

- Electrolux
- LG Electronics
- Samsung Electronics
- Whirlpool



Magnetic Structure

Design and Performance of a Permanent Magnet Rotary Refrigerator; Zimm et al.; IIF-IIR International Conference on Magnetic Refrigeration at Room Temperature, September 2005; <http://www.sciencedirect.com/science/article/pii/S0140700706001526>

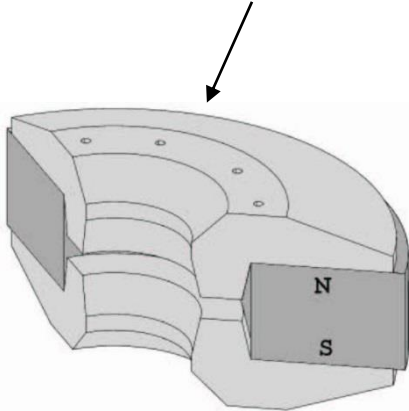
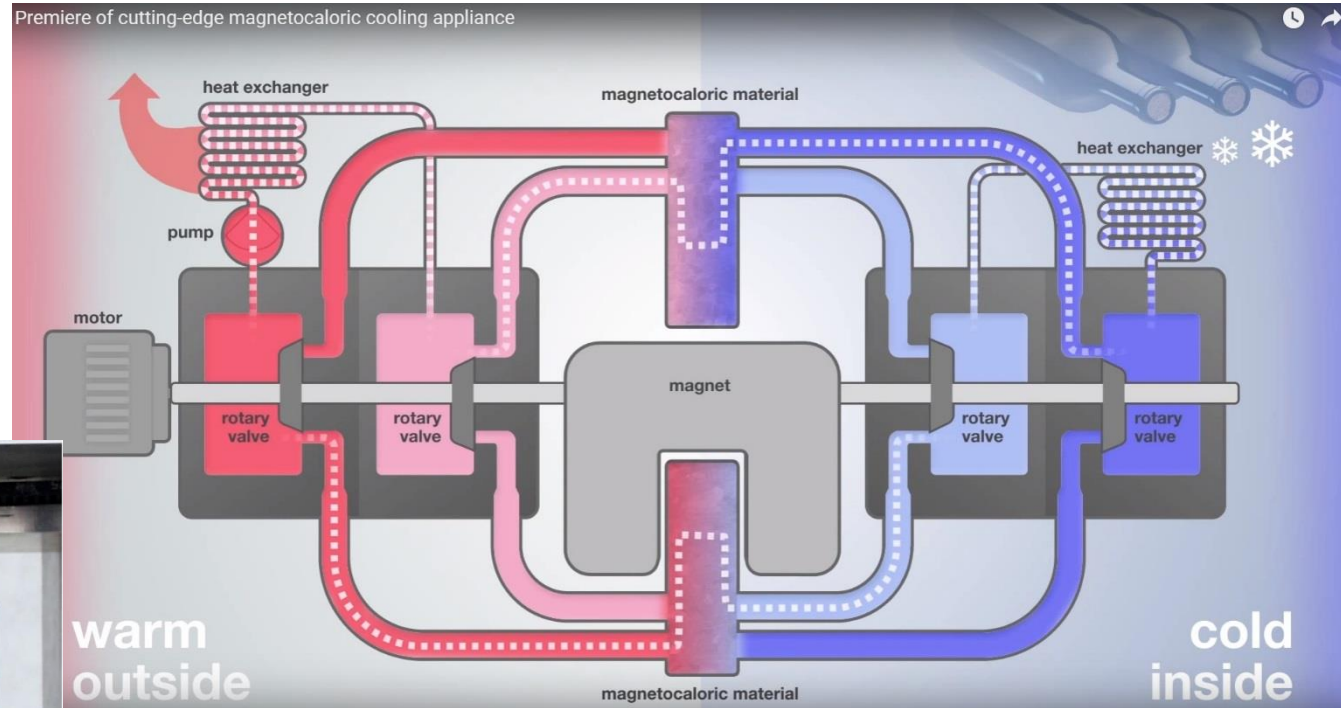
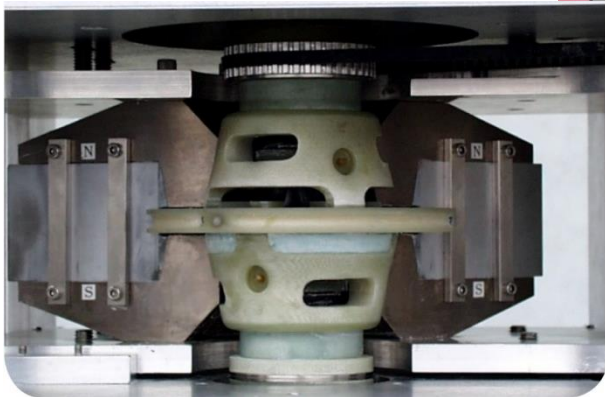


Figure 3: Permanent magnet. Dark gray is $\text{Nd}_2\text{Fe}_{14}\text{B}$. Light gray is steel.



Astronautics, BASF, Haier; <https://www.youtube.com/watch?v=Py9lazpKzs>



Room-Temperature Magnetic Refrigeration; MagFridg Foundation, Ames Laboratory, September 2009

Magnetic Cooling: Refrigeration & Air Conditioning

Complete replacement of Freon and Ammonia refrigerants



Current Magnet Tons of Magnets per year; Units are in millions

Ann'l
millions

	Ann'l millions	Magnet kg/unit	2020		2025		2030		2035		2040		2045		2050	
			Units	Magnets	Units	Magnets	Units	Magnets	Units	Magnets	Units	Magnets	Units	Magnets	Units	Magnets
Refrigeration																
Residential*	130	0.75	0.05	37.5	2	1,500	20	15,000	50	37,500	100	75,000	120	90,000	203	152,400
Commercial*	12	1	0	-	0.05	50	1	1,000	5	5,000	10	10,000	10	10,000	19	18,757
Food Processors	1	1	0	-	0	-	0.5	500	1	1,000	1.5	1,500	2	2,000	2	1,563
Warehouses	1	1	0	-	0	-	0.5	500	1	1,000	1.5	1,500	2	2,000	2	1,563
Grocery Stores	2	1	0	-	0	-	0.5	500	1.5	1,500	2	2,000	3	3,000	3	3,126
Convenience Stores	2	1	0	-	0	-	0.5	500	1.5	1,500	2	2,000	3	3,000	3	3,126
Restaurants	1	1	0	-	0	-	0.5	500	1	1,000	1.5	1,500	2	2,000	2	1,563
Transportation**	2	1	0	-	0	-	0.5	500	1.5	1,500	3	3,000	4	4,000	3	3,126
Air Conditioning																
Transportation**	75	2	0	-	0	-	5	10,000	30	60,000	50	100,000	70	140,000	117	234,462
Residential	85	2	0	-	0	-	10	20,000	35	70,000	60	120,000	75	150,000	133	265,724
Office	50	2	0	-	0	-	5	10,000	25	50,000	40	80,000	60	120,000	78	156,308
Retail, commercial, factory	20	2	0	-	0	-	5	10,000	10	20,000	20	40,000	20	40,000	31	62,523
Total Magnet Demand, tons				37.5		1,550		69,000		250,000		436,500		566,000		904,242
TREO demand, tons				100		4,100		182,540		661,375		1,154,760		1,497,355		2,392,175

904,242
2,392,175

* Residential and Commercial: Refrigerators and Freezers

** Transportation=trucks, trains, ships, airplanes

Is Alnico an Alternative?

For example

Alnico 5 Br: 1.3 tesla

Bd at Pc=18 is ~1.2 tesla



Commercial product from Arnold Magnetic Technologies, Marengo, Illinois

Magnet Production & Material Supply

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Summary Comments



Putting it Together...

Applications	2015	2020	2025	2030	2035	2040	2045	2050
Motors, industrial, general auto, etc	26,367	30,271	34,753	39,899	45,807	52,589	60,375	69,315
Wind Power Generators	16,600	29,020	34,850	47,375	45,000	40,000	38,000	35,000
Electric Bicycles & Scooters	9,580	13,000	14,000	11,000	7,500	5,000	4,000	3,000
Acoustic Transducers	7,471	9,000	11,000	12,500	13,500	13,000	12,500	12,000
HDD, CD, DVD	6,372	4,309	3,000	1,200	600	200	50	25
MRI	5,933	5,500	5,000	3,500	3,000	2,500	2,000	500
Air conditioning compressors and fans	5,054	7,000	12,000	25,000	35,000	30,000	25,000	20,000
Magnetic Separation	4,175	5,000	6,500	7,000	7,500	7,500	7,500	7,500
Hybrid & Electric Traction Drive	3,850	18,025	35,310	41,650	45,750	54,688	65,000	82,500
Unidentified	3,296	3,675	4,097	4,568	5,093	5,679	6,331	7,059
Torque-coupled drives	3,186	3,658	4,199	4,821	5,535	6,354	7,295	8,376
Sensors	2,966	3,523	4,184	4,970	5,902	7,010	8,326	9,889
Energy Storage Systems	2,747	2,788	2,830	2,873	2,916	2,960	3,005	3,050
Generators	2,637	2,954	3,310	3,709	4,155	4,655	5,216	5,844
Hysteresis Clutch	2,417	2,540	2,670	2,806	2,949	3,100	3,258	3,424
Magnetic Braking	1,758	1,847	1,942	2,041	2,145	2,254	2,369	2,490
Gauges	1,648	1,700	1,500	1,100	750	250	100	20
Relays and Switches	1,648	1,665	1,681	1,698	1,715	1,732	1,750	1,767
Magnetically Levitated transportation	560	572	583	595	607	619	632	644
Holding and Lifting	505	600	625	650	675	700	725	750
Reprographics	439	400	450	400	400	400	400	400
Wave guides: TWT, undulators/wigglers	412	422	433	444	455	467	478	491
Pipe Inspection Systems	99	99	100	100	101	101	102	102
Advertising	82	75	65	60	50	30	15	5
Magnetic Refrigeration	66	70	90	500	750	1,000	1,500	2,000
Totals	109,868	147,714	185,173	220,459	237,856	242,789	255,928	276,151
TREO Demand	257,840	346,660	434,570	517,370	558,200	569,780	600,610	648,070



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