

EV & Transportation Applications of Permanent Magnet Materials



IEEE Magnetics Society
Santa Clara Valley Chapter

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Permanent Magnet Materials

OUTLINE

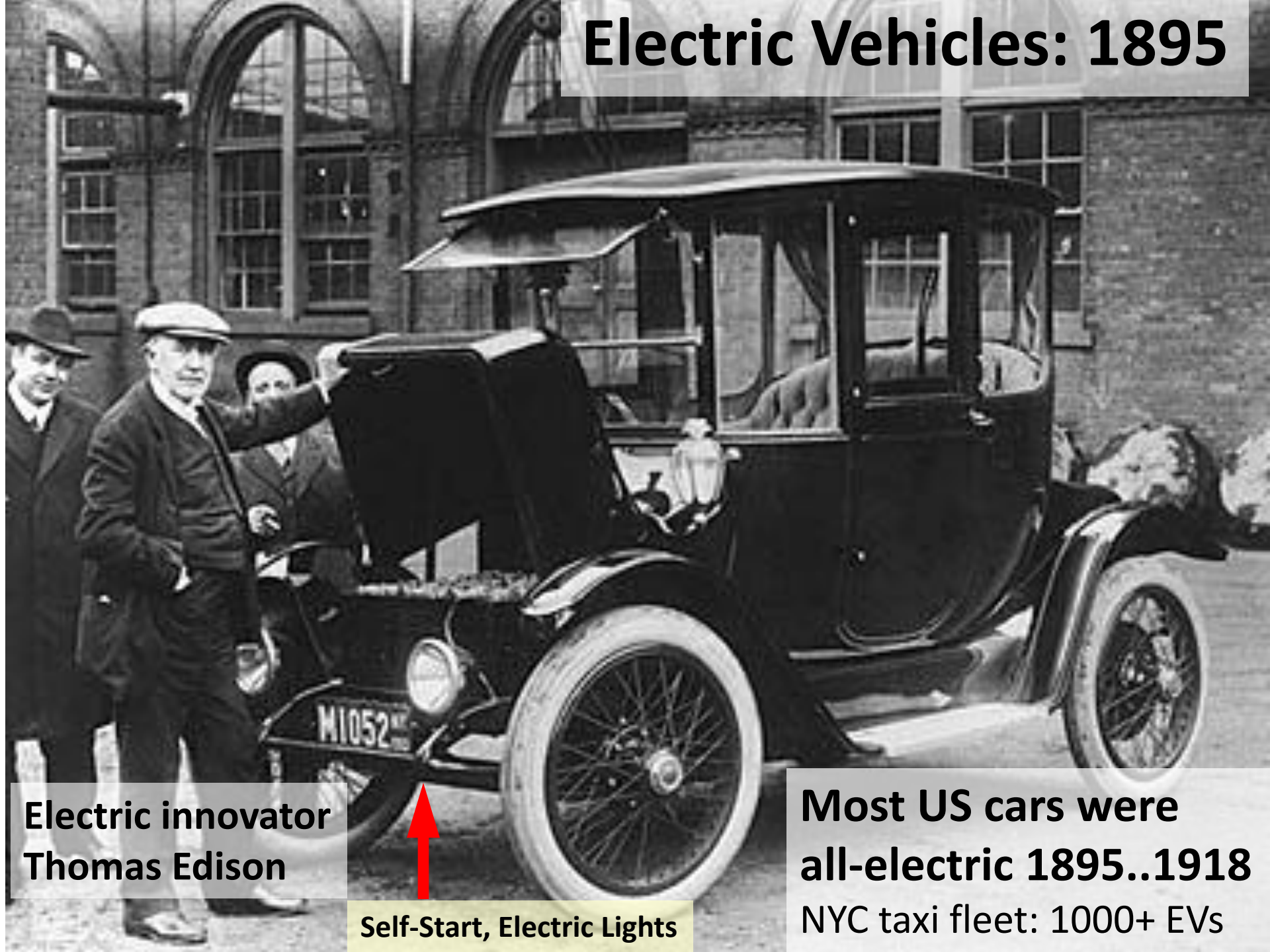
- 1. What are key Permanent Magnet motor materials?**
- 2. How are they used? Why important?**
- 3. How are the materials manufactured? What is the PM supply chain?**
- 4. What is the outlook for economy, ecology, & security?**

Permanent Magnet Materials

RECENT HISTORY

- **Electric Vehicles increasingly use Permanent Magnets made from Rare Earth material NdFeB**
- **USA no longer produces Rare Earths (since 2002)**
- **PM materials demand in transportation and many high-tech products is booming**
- **Criticality is increasing in product supply chains**
- **Few or no substitutes**
- **2011 Price Shock caused a short market alarm**
- **Prices moderate since 2012, now increasing again**

Electric Vehicles: 1895

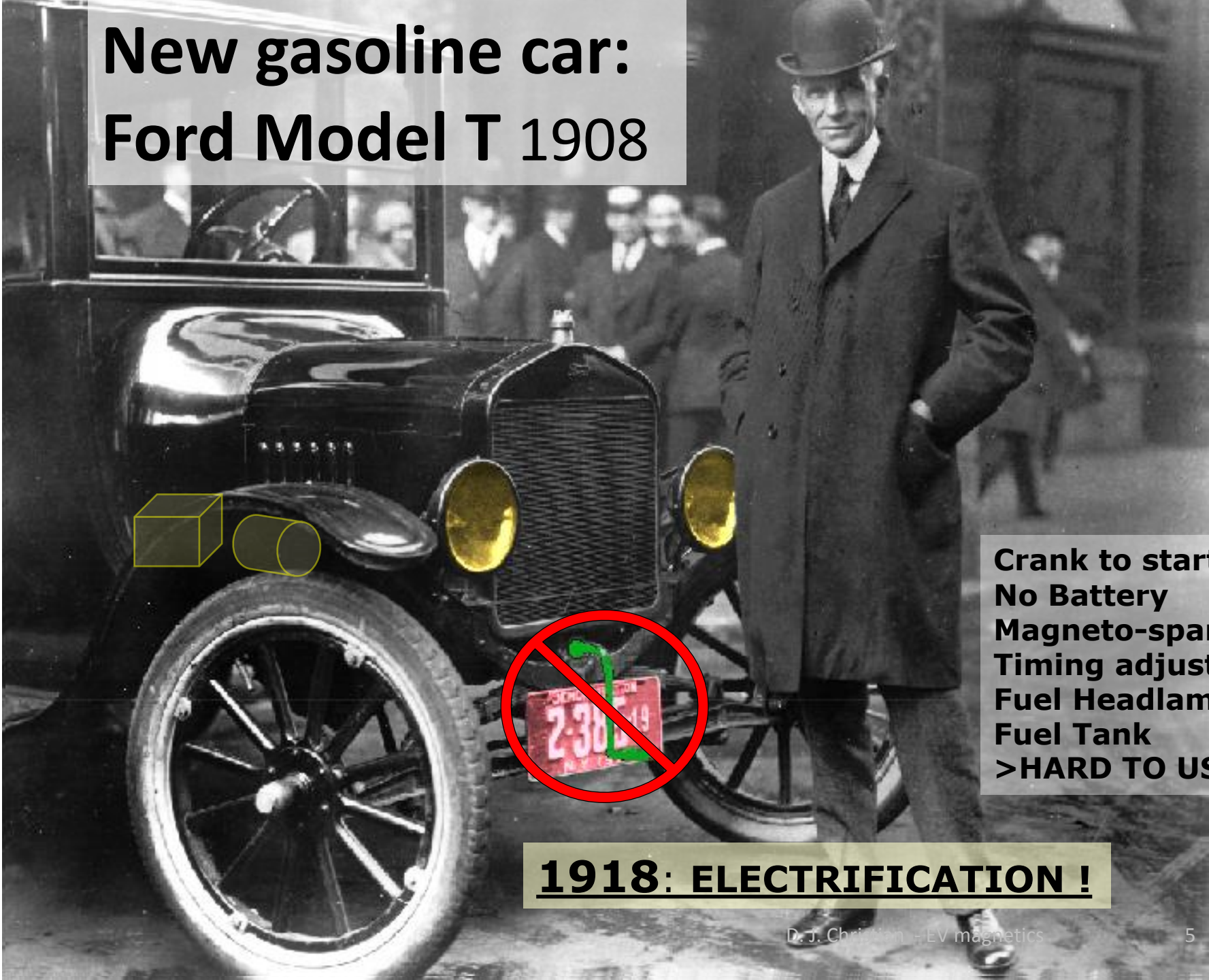


**Electric innovator
Thomas Edison**

Self-Start, Electric Lights

**Most US cars were
all-electric 1895..1918**
NYC taxi fleet: 1000+ EVs

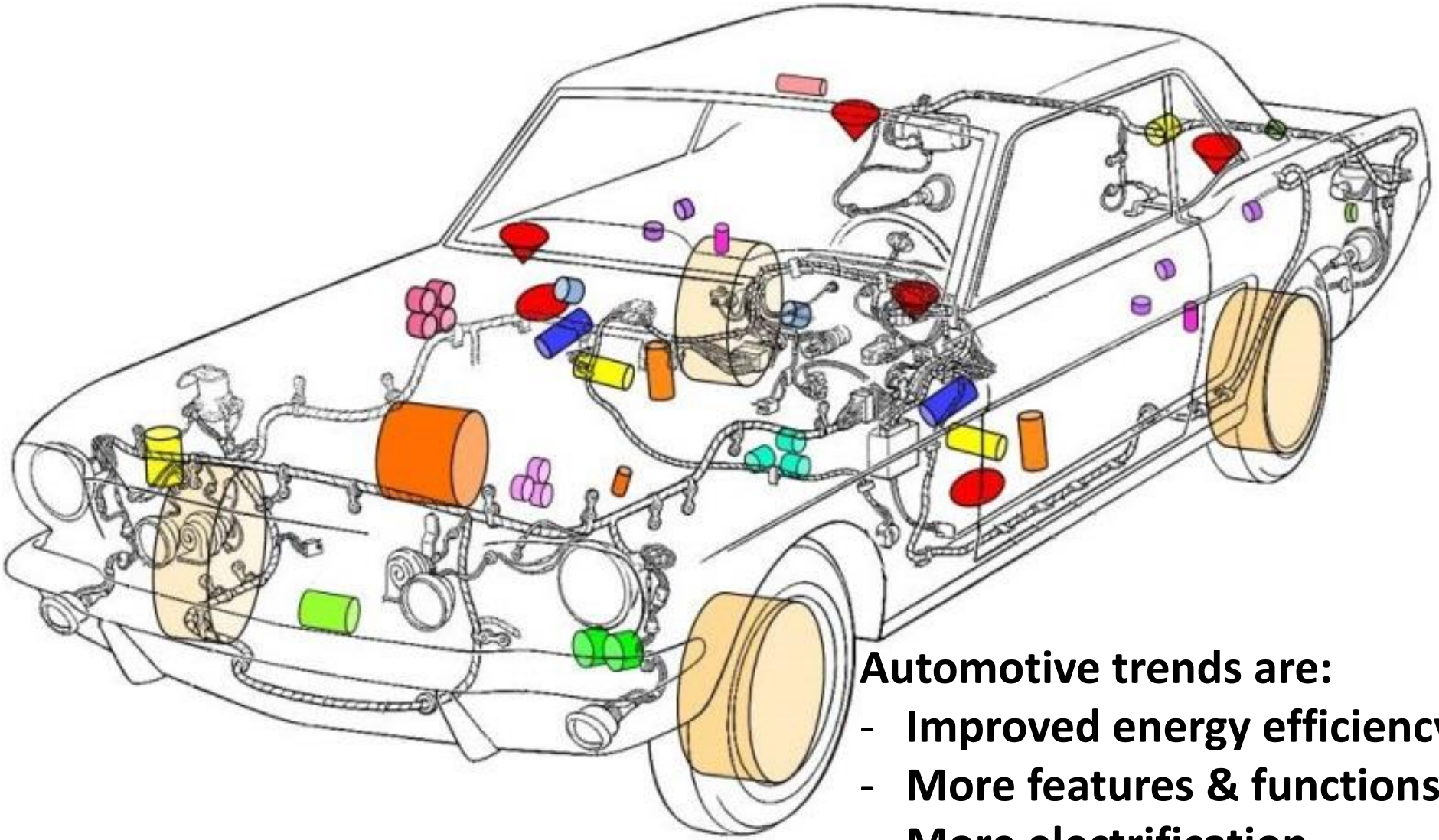
New gasoline car: Ford Model T 1908



**Crank to start
No Battery
Magneto-spark
Timing adjust
Fuel Headlamps
Fuel Tank
>HARD TO USE**

1918: ELECTRIFICATION !

Electric motors in modern cars & EVs



Automotive trends are:

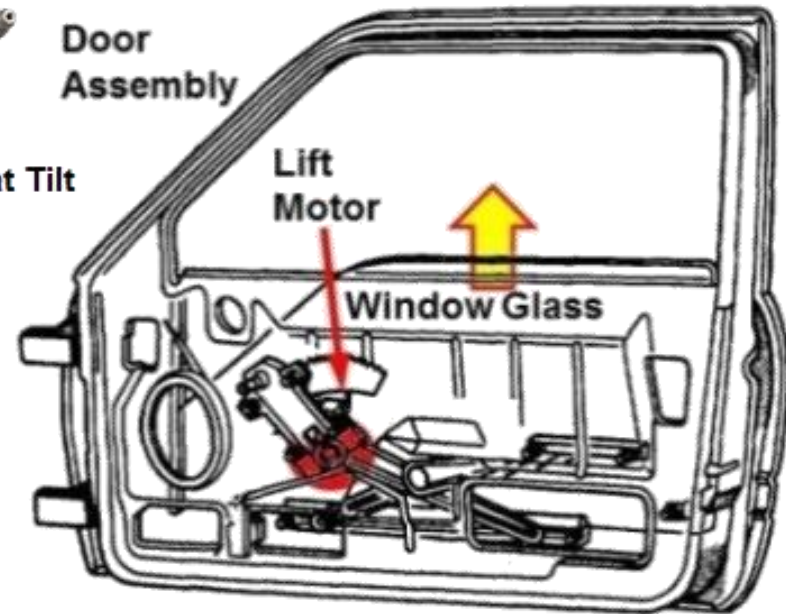
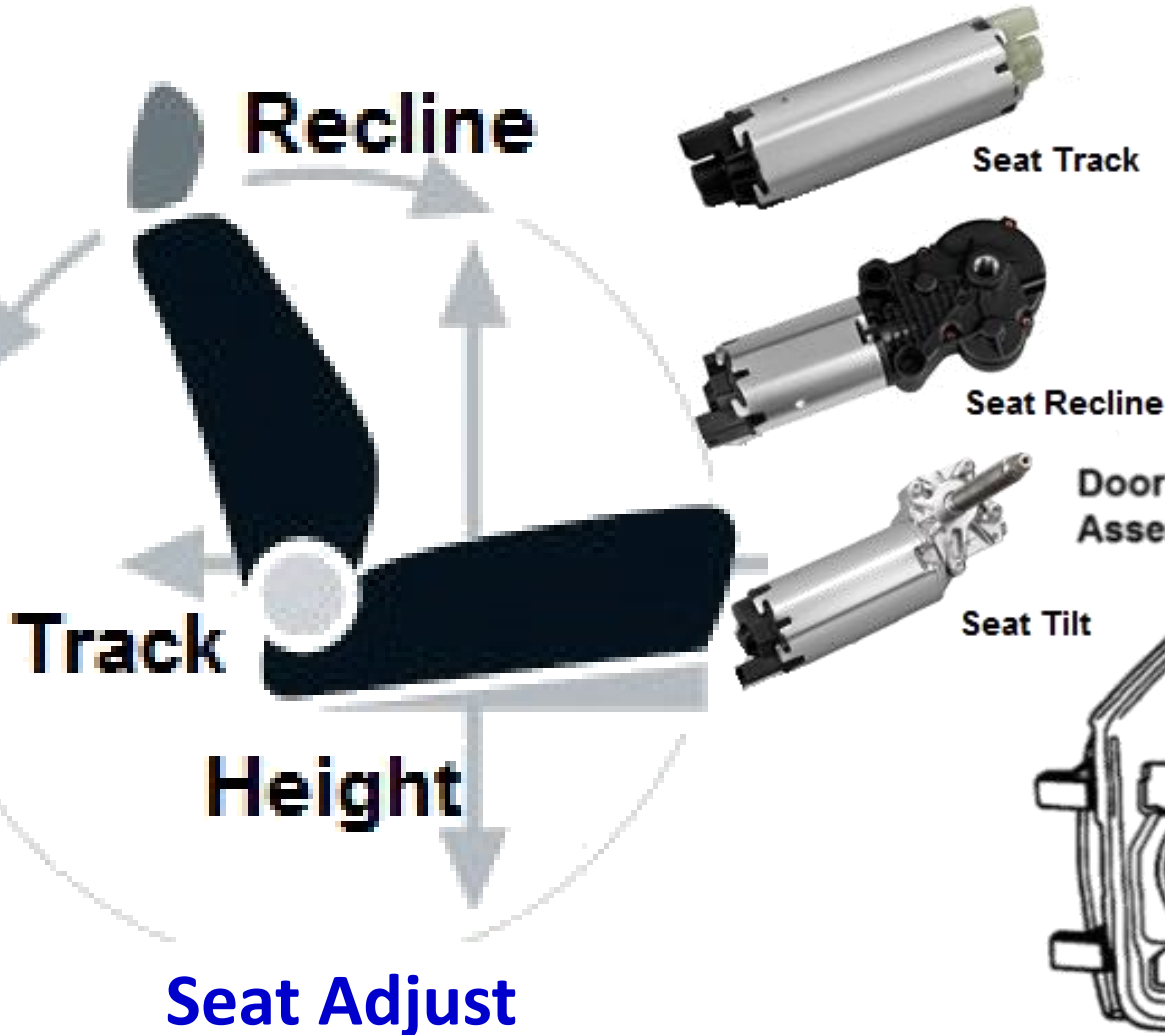
- Improved energy efficiency
- More features & functions
- More electrification
- More batteries
- More motors

Why electric motors ?

1. Wide speed range (+10kRPM..0..-10kRPM), variable
2. Directional reversibility with high bandwidth
3. High Torque. Good torque at all speeds & zero RPM
4. Small Size. Flexible: shape can be tailored to fit
5. Light weight. Down-sized to fit the job
6. High Efficiency. Low heat loss. Cool running
7. Wide environmental operating range
Temp, pressure, humidity, etc.
8. Durable. Low maintenance, little or no lubrication
9. Reliable. Long MTBF, simpler mechanicals
10. Quiet acoustic, low EM radiation emissions
11. Natural affinity with electronic controls
“intelligent” functions: safety
12. Energy scavenging through regeneration

Motors work better !

Electric motor applications in modern cars: Interior



Door Glass Lift

Electric motors in modern cars

Under-Hood



Windshield Wiper



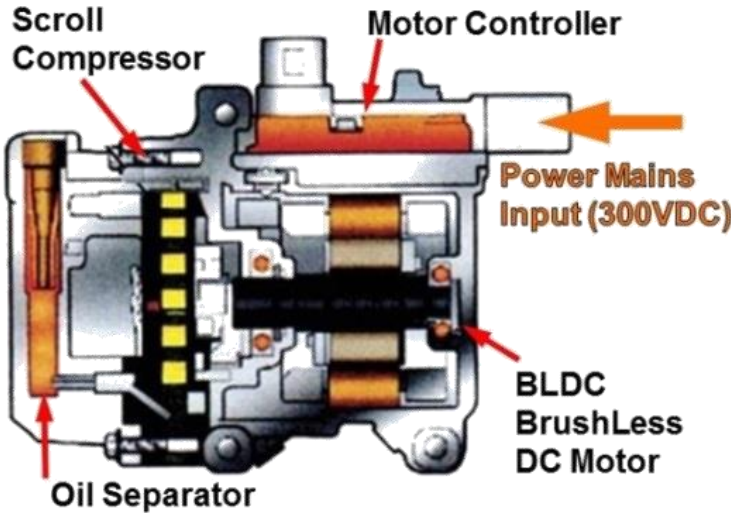
Heater Valve



Coolant Pump



Vacuum Pump

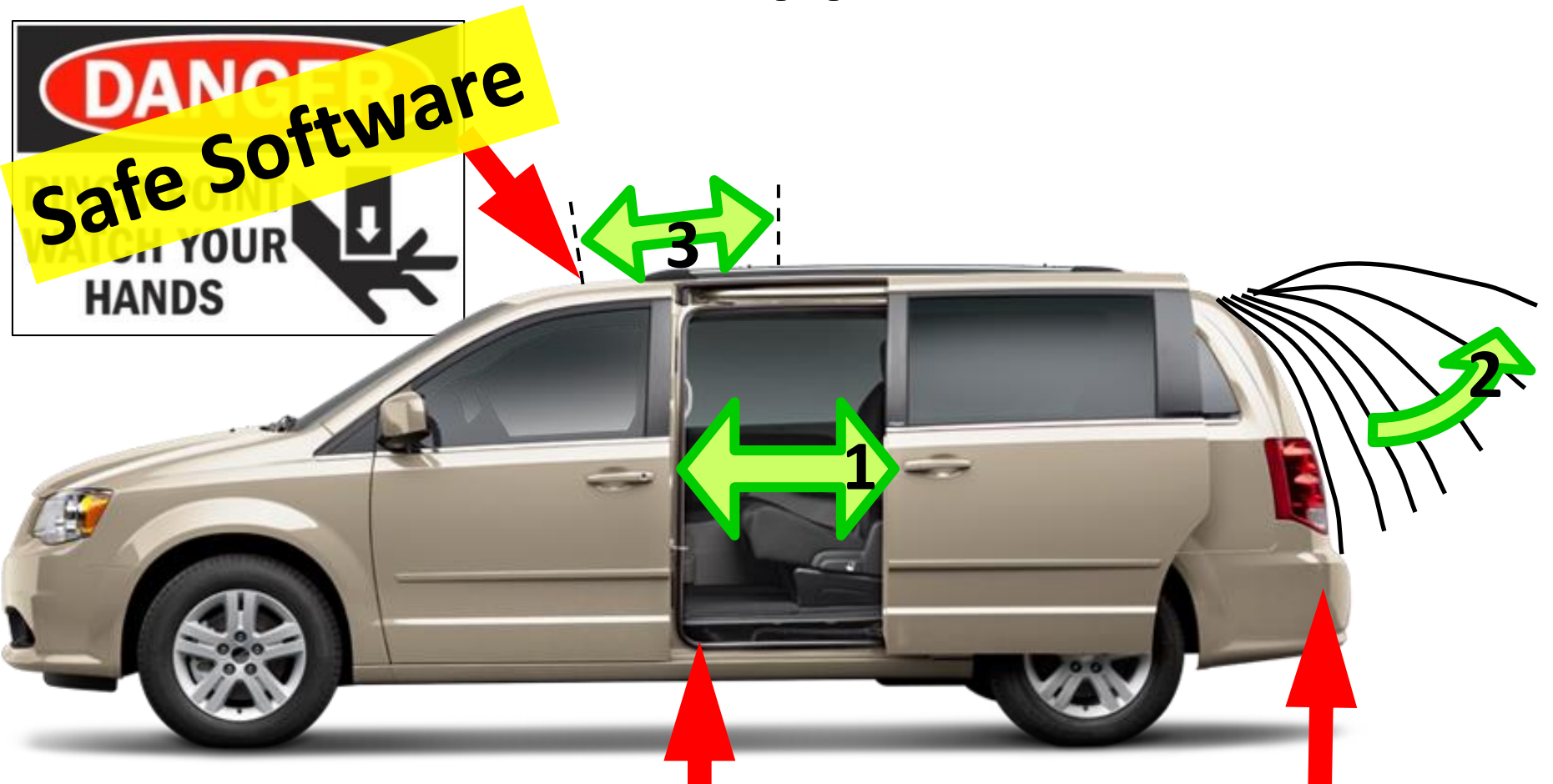


A/C Compressor



Transmission Actuators

Electric motor applications: Doors



Power Doors



Automatic Folding Side Mirrors



Motorized operation, sensor logic control

Electric motor applications in modern cars: Entertainment



Audio Speakers

This application is cost-sensitive !

After 2011 Rare Earth price shock

- >> magnet substitutes were developed**
- >> RE use was sharply reduced in speakers**
- >> Advertised as “Green RareEarth Free”**

New motor Applications

Automatic
Door Handle
Presentation

1. Normally-flush door handle

2. Motorized pop-out

3. Hand opened



Safe Software

Traction Motor Applications: EV



Larger motor = more torque = more RE materials

Hybrids & PEVs (Plug-in Electric Vehicles)

Electric propulsion

Petrol
\$1.0x



Electric
>\$0.4x!



Hybrid Propulsion reduces transport cost

New motor Applications: BEV = Battery All-Electric Vehicles

All-Electric
>\$0.4x!

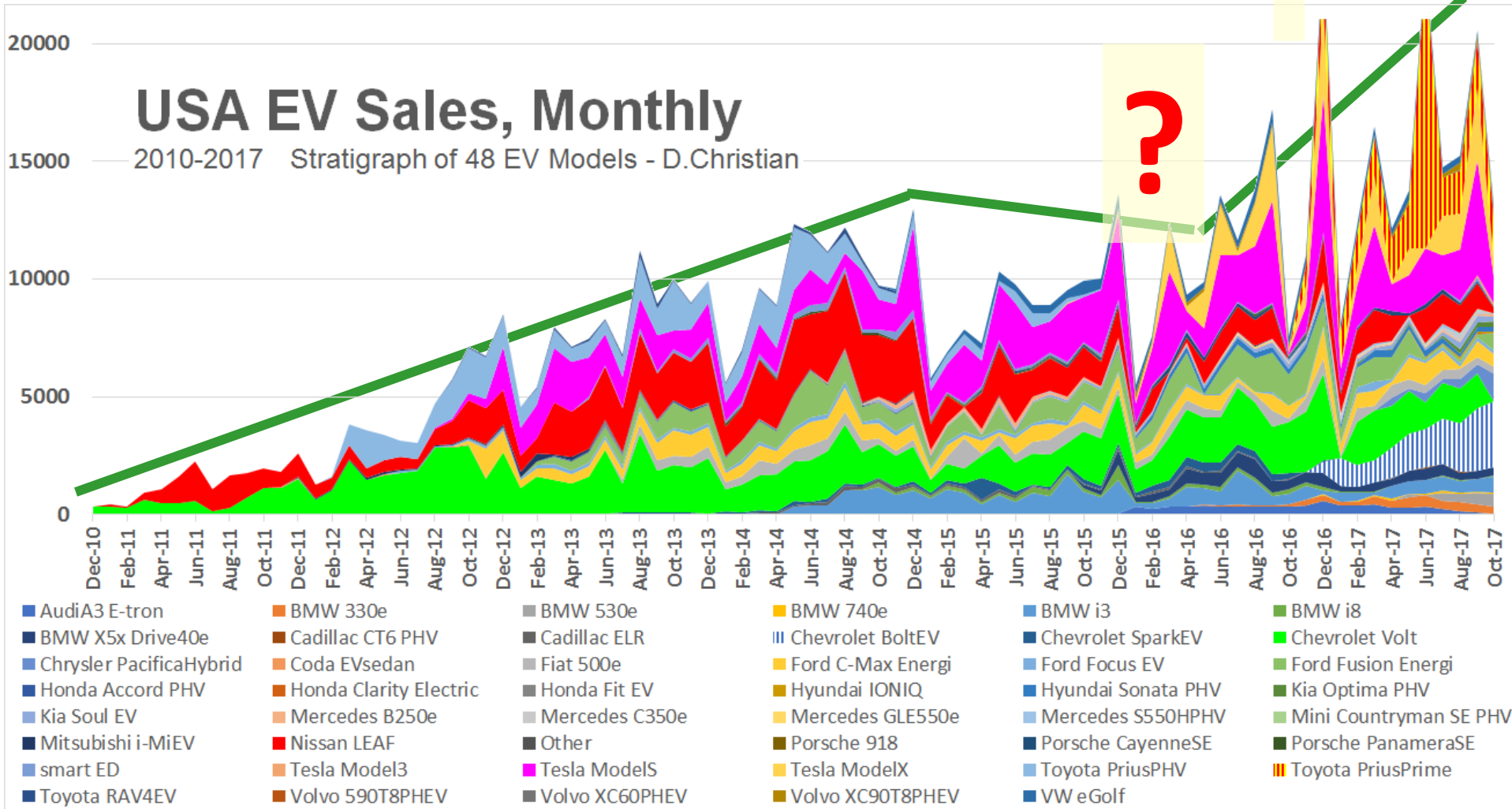


All-Electric Propulsion

Recent EV sales history (Oct 2017)

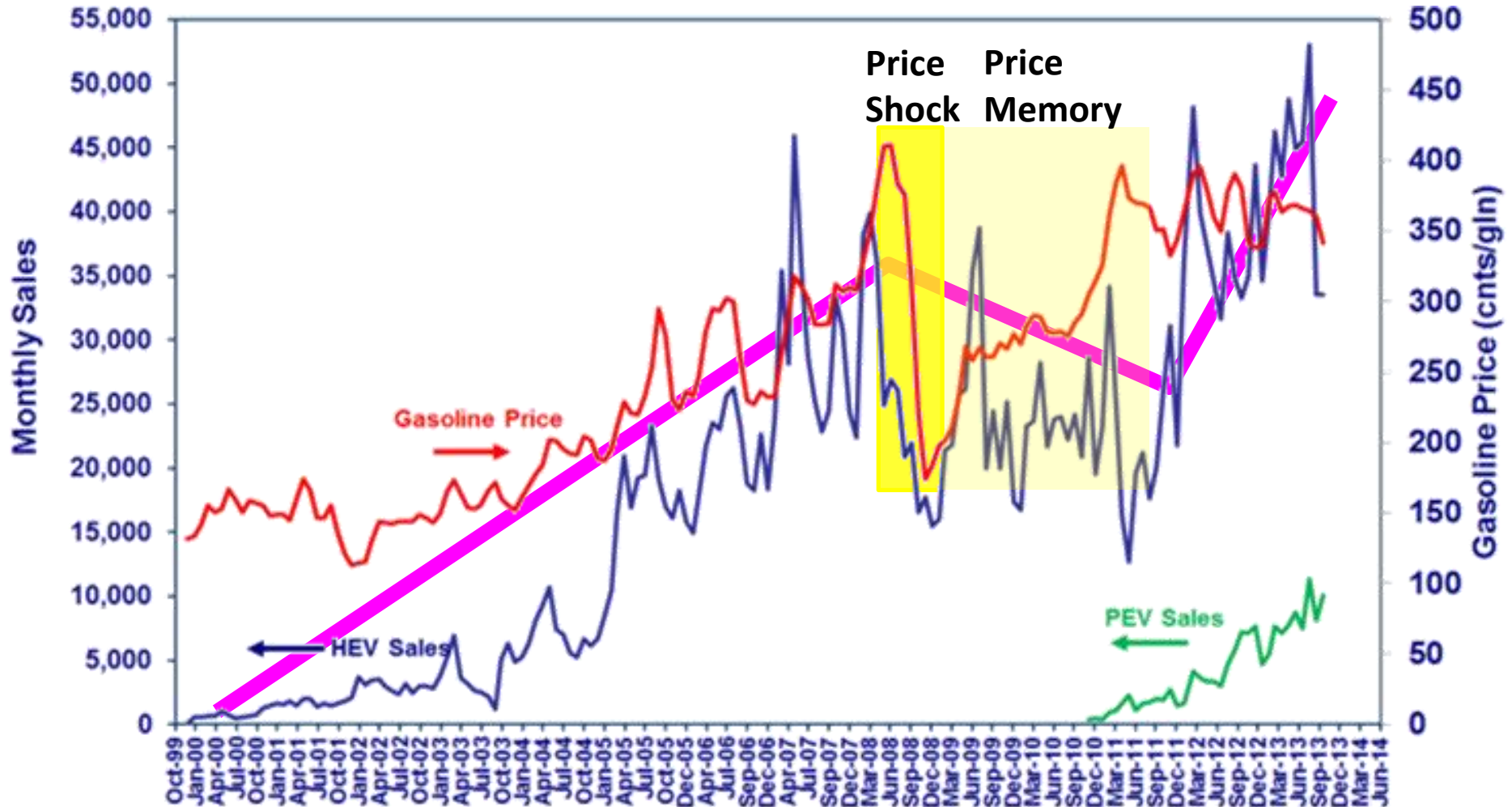
USA EV Sales, Monthly

2010-2017 Stratigraph of 48 EV Models - D.Christian



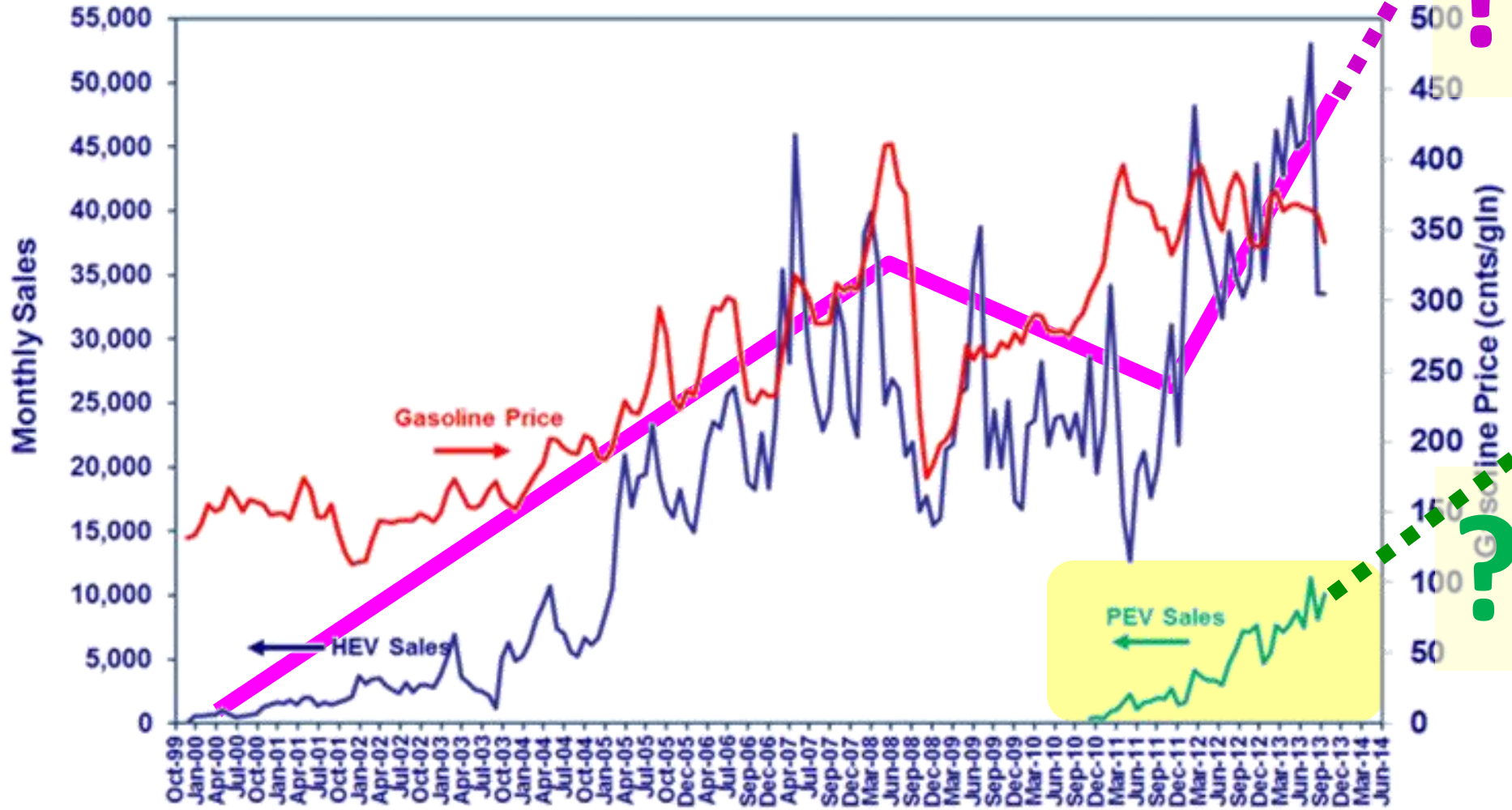
Steady sales growth

Strong Correlation in USA: Fuel prices -and- EV sales



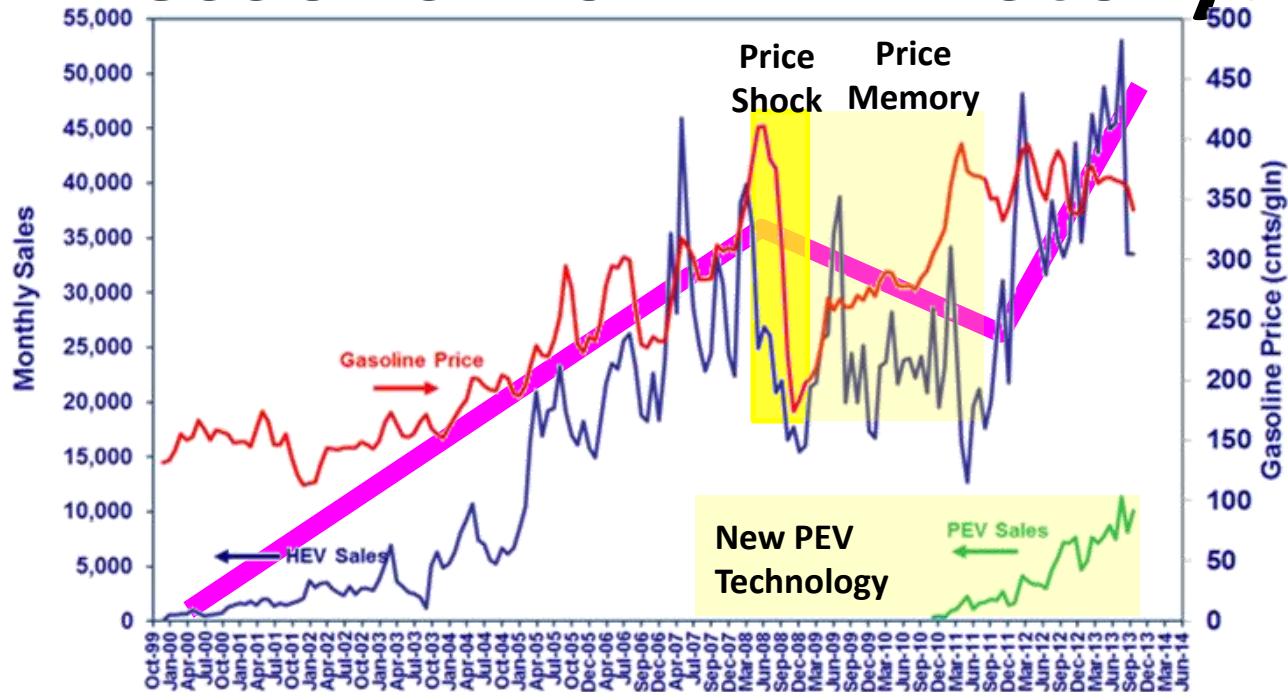
Customers remember price shocks

Strong Correlation in USA: Fuel prices -with- EV sales



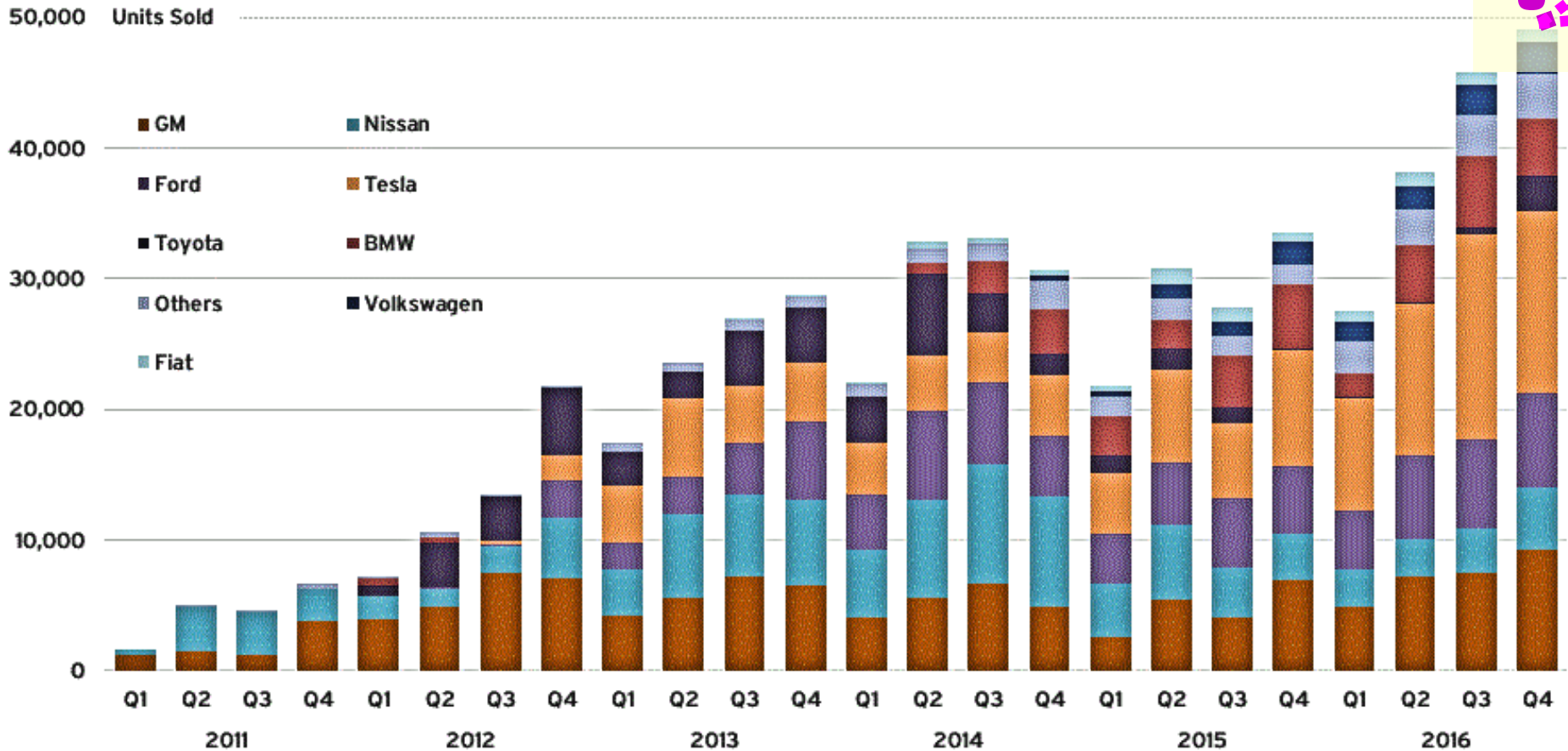
PEV reduces the risk of petrol price-shock

Lessons from EV history:



1. Customers are very sensitive to fuel cost
2. Customers remember price shock volatility
3. New PEV cars reduce total cost TCOO
 - Many US customers don't believe PEV is real
 - As PEV benefit gains confidence, sales increase

BEV sales prospects



Source: SAFE analysis based on data from HybridCars.com

Expectation: brisk EV sales growth
Primarily use PM motors

2017: OEM & Governments outlawing non-electric drivetrains !

VW, BMW, Ford

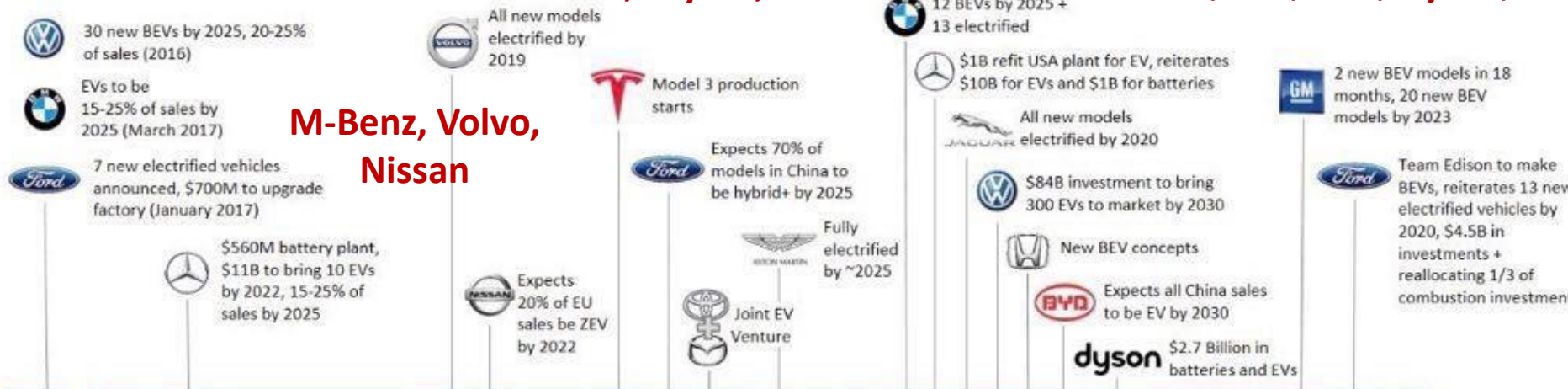
Tesla, Toyota, Mazda

Honda, GM, BYD, Dyson,

M-Benz, Volvo, Nissan

France, UK

Scotland, China



-  Netherlands – lower house passes motion to ban petrol vehicle sales by 2025 (March 2016)
-  Norway – Norway discussing ban of petrol vehicles by 2025 (June 2016)
-  Germany – passes resolution seeking to approve ZEV only by 2030 (October 2016)

BEV = Battery Electric Vehicle
 PEV = Plug-in Electric Vehicle
 ZEV = Zero Emission Vehicle
 EV or "electrified" = hybrid, plug-in hybrid, or BEV

Netherlands, Norway, Germany

Alternatives to PM/rare earth Motors?

- Automotive RE applications are cost-sensitive.
- Delicate balance: Performance vs Cost
- PM/RE Performance is good.
- Risk: future RE cost-shock?

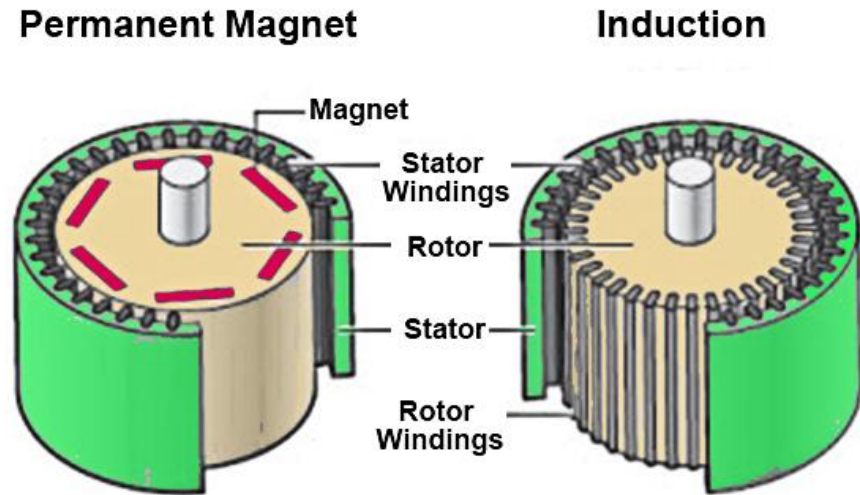
(memories of 2011 RE price shock)

> Fear of price shock motivates R&D for alternatives:

- new **Lower**-RE motors (reduced RE use)
- new **Zero**-RE motors (total elimination)

PM Technology Alternatives

- Modern Motor Designs:
 - Permanent Magnet (baseline)
 - AC Induction (popular, cheapest)
 - Switched Reluctance



- Requirements vary greatly between applications
- Motor designs have been iterated for 150 years
- PM performance is competitive or superior in all niches
- Most modern EVs use PM motors (Nissan, Ford, GM)
- Tesla's Model 3 will use PM propulsion motor
- PM continues as the the most popular technology

Electric Aircraft

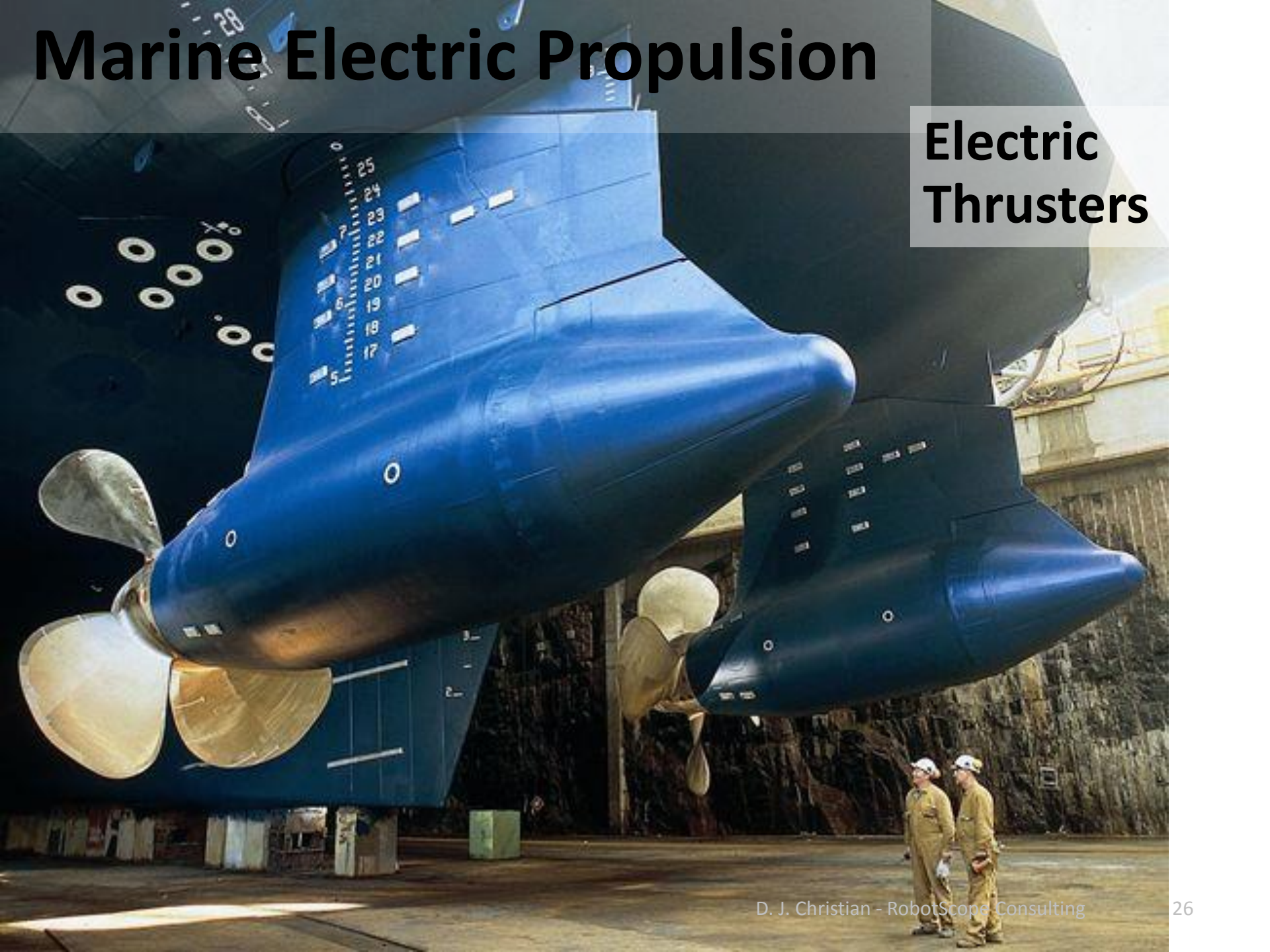


Siemens eFusion Trainer

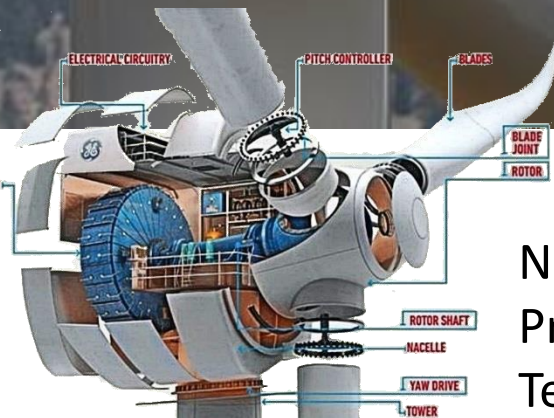
Benefits: Efficient, Silent, Clean, Light, Safe, **Economic**

Marine Electric Propulsion

Electric Thrusters

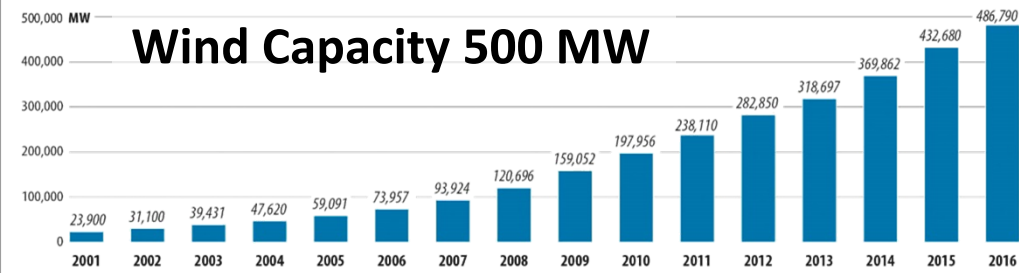


Rare Earths in Wind Energy



Neodymium
Praseodymium
Terbium
Dysprosium

Wind Capacity 500 MW



Cell Phone Rare Earths

Vibrator Magnets

Neodymium
Praseodymium
Terbium
Dysprosium

Electronics

Neodymium
Praseodymium
Dysprosium
Gadolinium

Speakers

Neodymium
Praseodymium
Terbium
Dysprosium

Display Screen

Europium
Praseodymium
Yttrium
Lanthanum
Terbium
Dysprosium
Gadolinium

Glass Polishing

Cerium
Lanthanum
Praseodymium

Headphones

Neodymium
Praseodymium
Terbium
Dysprosium

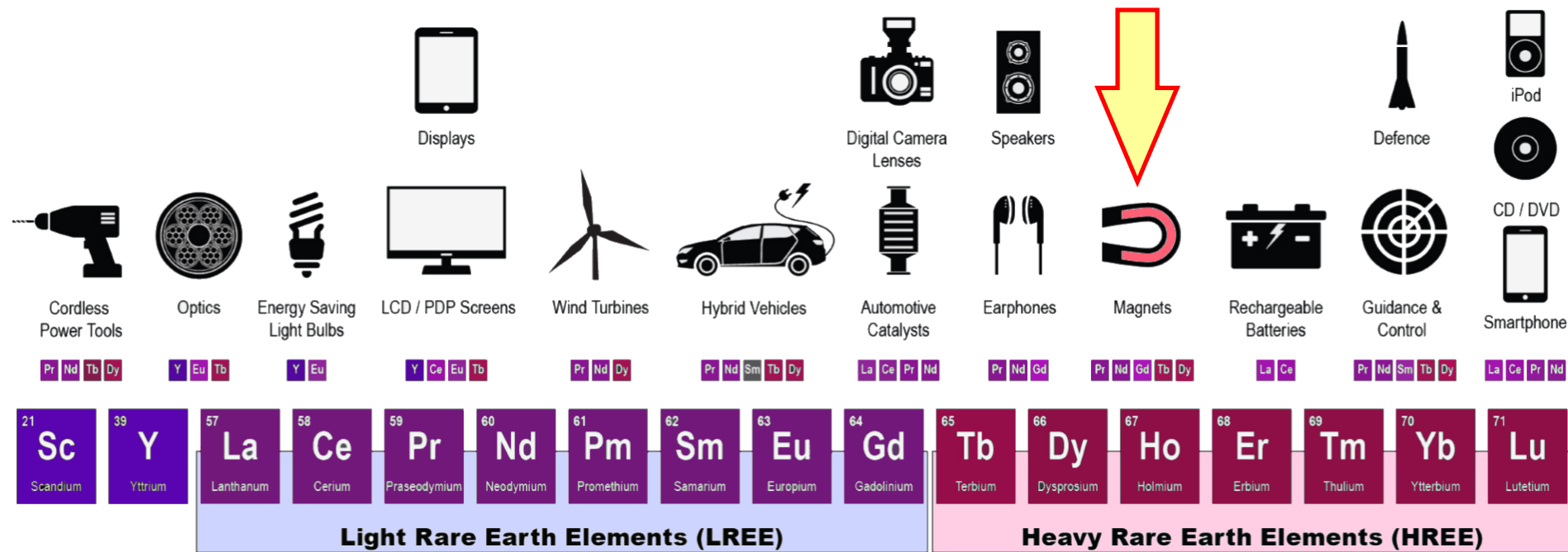
What are PM materials ?

“Super-Magnets” Neodymium Iron Boron, NdFeB
Rare Earths or Lanthanide elements

		Metals										Nonmetals							
		Alkali metals	Alkaline earth metals	Lanthanoids	Actinoids	Transition metals	Poor metals	Other nonmetals	Noble gases										
1	H Hydrogen 1.00794																		
2	Li Lithium 6.941	Be Beryllium 9.012182											B Boron 10.811	C Carbon 12.0107	N Nitrogen 14.0067	O Oxygen 15.9994	F Fluorine 18.9984032	Ne Neon 20.1797	
3	Na Sodium 22.98976928	Mg Magnesium 24.3050											Al Aluminium 26.9815386	Si Silicon 28.0855	P Phosphorus 30.973762	S Sulfur 32.065	Cl Chlorine 35.453	Ar Argon 39.948	
4	K Potassium 39.0983	Ca Calcium 40.078	Sc Scandium 44.955912	Ti Titanium 47.887	V Vanadium 50.9415	Cr Chromium 51.9961	Mn Manganese 54.938045	Fe Iron 55.845	Co Cobalt 58.933195	Ni Nickel 58.6934	Cu Copper 63.546	Zn Zinc 65.38	Ga Gallium 69.723	Ge Germanium 72.64	As Arsenic 74.92160	Se Selenium 78.96	Br Bromine 79.904	Kr Krypton 83.798	
5	Rb Rubidium 85.4678	Sr Strontium 87.62	Y Yttrium 88.90585	Zr Zirconium 91.224	Nb Niobium 92.90638	Mo Molybdenum 95.96	Tc Technetium (97.9072)	Ru Ruthenium 101.07	Rh Rhodium 102.90550	Pd Palladium 106.42	Ag Silver 107.8682	Cd Cadmium 112.411	In Indium 114.818	Sn Tin 118.710	Sb Antimony 121.760	Te Tellurium 127.60	I Iodine 126.90447	Xe Xenon 131.293	
6	Cs Caesium 132.9054519	Ba Barium 137.327	57-71	Hf Hafnium 178.49	Ta Tantalum 180.94788	W Tungsten 183.84	Re Rhenium 186.207	Os Osmium 190.23	Ir Iridium 192.2217	Pt Platinum 195.084	Au Gold 196.966569	Hg Mercury 200.59	Tl Thallium 204.3833	Pb Lead 207.2	Bi Bismuth 208.98040	Po Polonium (209.9824)	At Astatine (209.9871)	Rn Radon (222.0176)	
7	Fr Francium (223)	Ra Radium (226)	89-103	Rf Rutherfordium (261)	Db Dubnium (262)	Sg Seaborgium (266)	Bh Bohrium (264)	Hs Hassium (277)	Mt Meitnerium (268)	Ds Darmstadtium (271)	Rg Roentgenium (285)	Uub Ununbium (285)	Uut Ununtrium (284)	Uuq Ununquadium (288)	Uup Ununpentium (288)	Uuh Ununhexium (292)	Uus Ununseptium (289)	Uuo Ununoctium (294)	
				Light Rare Earths								Heavy Rare Earths							
		57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668			
		89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)			

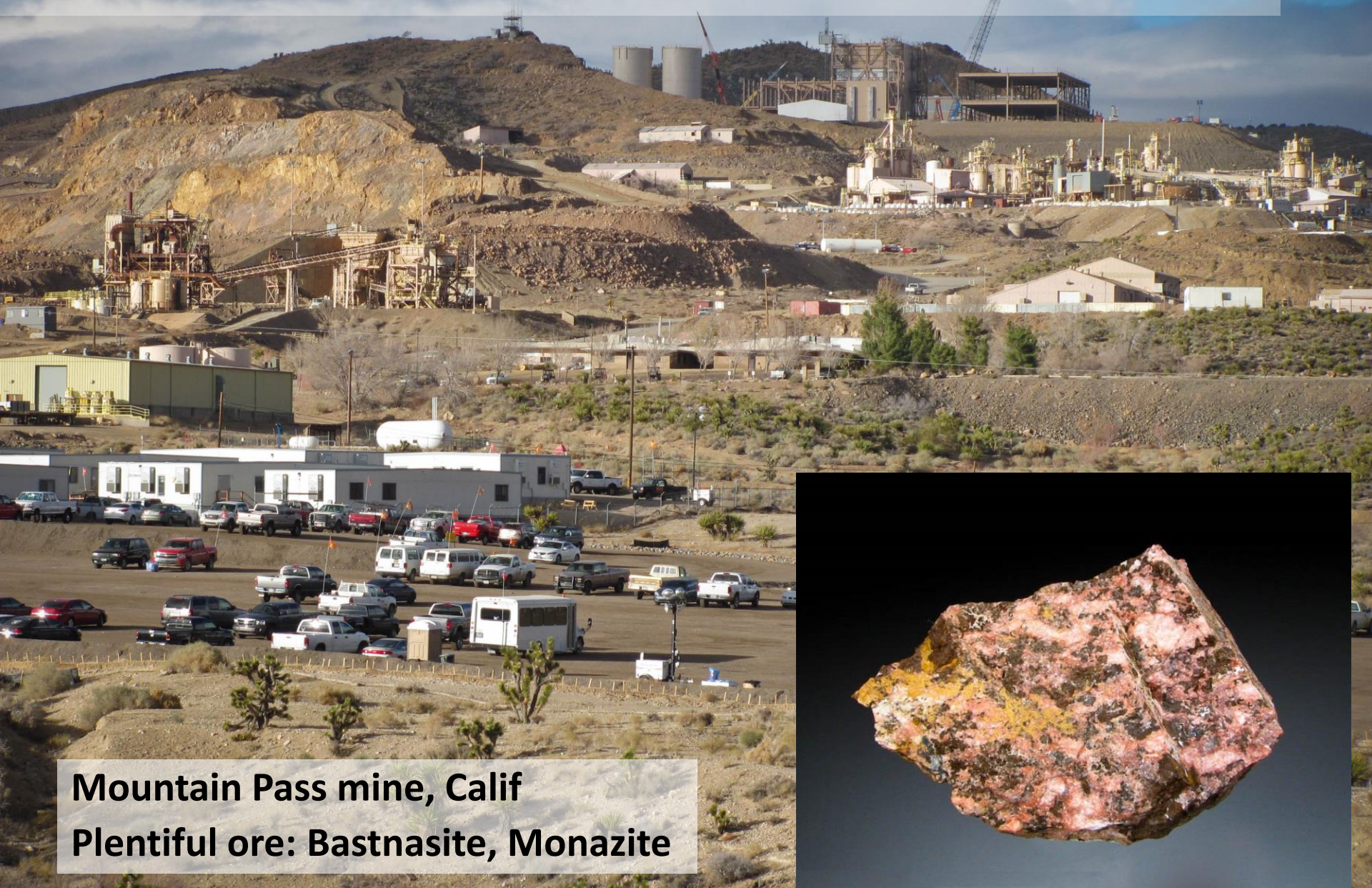
Atomic #
 Symbol
 Name
 Atomic Mass

Where are rare earths used ?



A broad range of performance-critical applications
 Power, weight, temperature, sensitivity, color,...

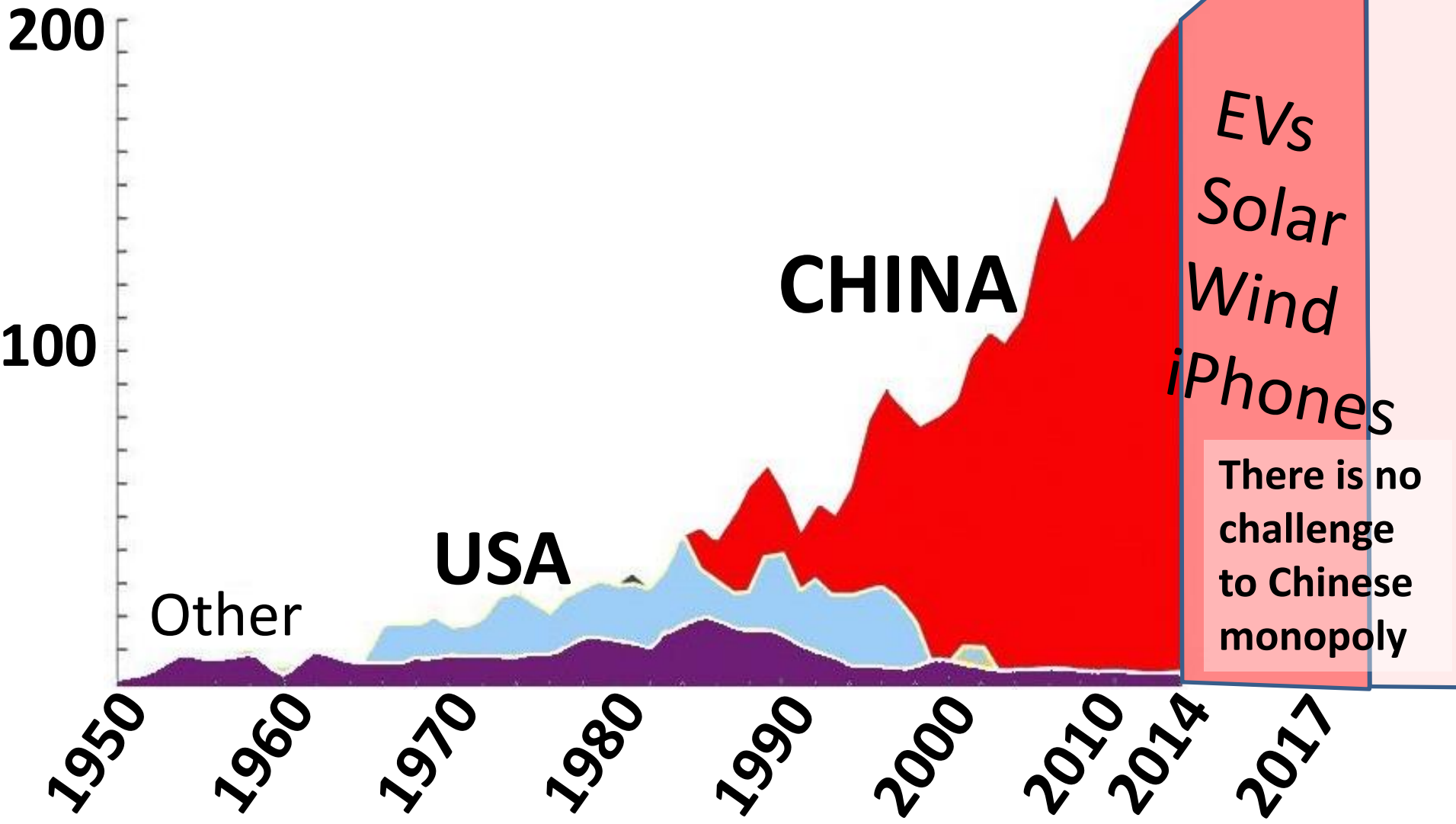
How are PM materials manufactured ?



Mountain Pass mine, Calif
Plentiful ore: Bastnasite, Monazite



Where is PM material supply chain ?



Source: USGS, CRS,

Electromagnetic Rail-Gun Artillery



Navy



Army



USNS Zumwalt
USNS Millinocket

**Bulk consumer
of Rare Earth
materials**

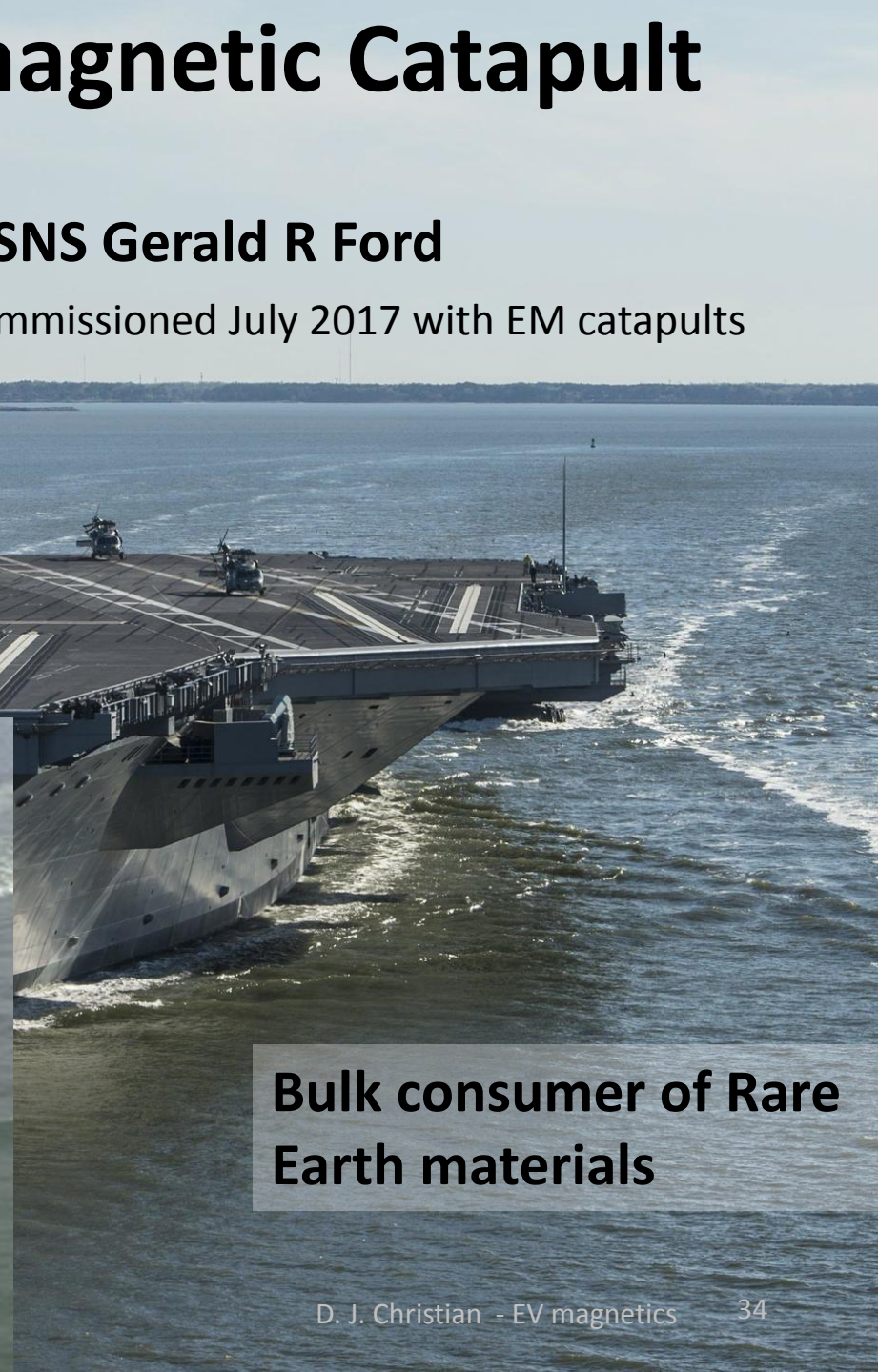
Aircraft Carrier: Electromagnetic Catapult

USNS Gerald R Ford

commissioned July 2017 with EM catapults

Chinese Navy Carrier Liaoning

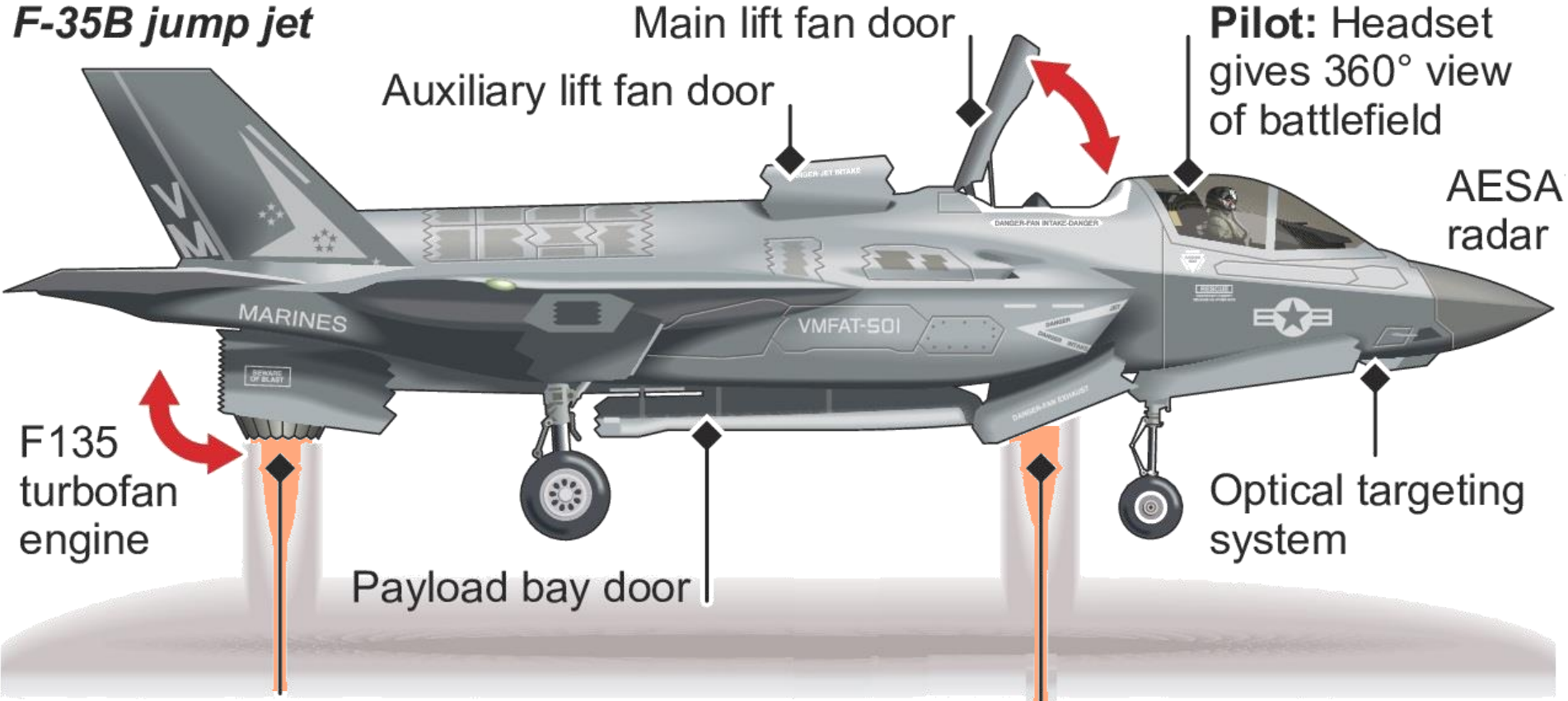
commissioned Nov 2016
upgrades in development



Bulk consumer of Rare Earth materials

F35 Fighter: "Flying Periodic Table"

F-35B jump jet



Thrust vectoring nozzle
Directs full thrust of engine down for vertical takeoff and landing

Lift fan: Powered by driveshaft from jet engine – balances lift generated at tail

F-35 orders

U.S.	2,443	Norway	52
Britain	138	Japan	42
Australia	100	South Korea	40
Turkey	100	Netherlands	37
Italy	90	Israel	33
Canada	65	Denmark	27

Bulk consumer of Rare Earth materials

Transportation Markets for Rare Earth materials

Trends are clear:

- Greater electrification for transportation
- More motors used in transportation
- More EV penetration: sales & operating fleet
- More motors electronically commutated
- More magnet rare earth material used

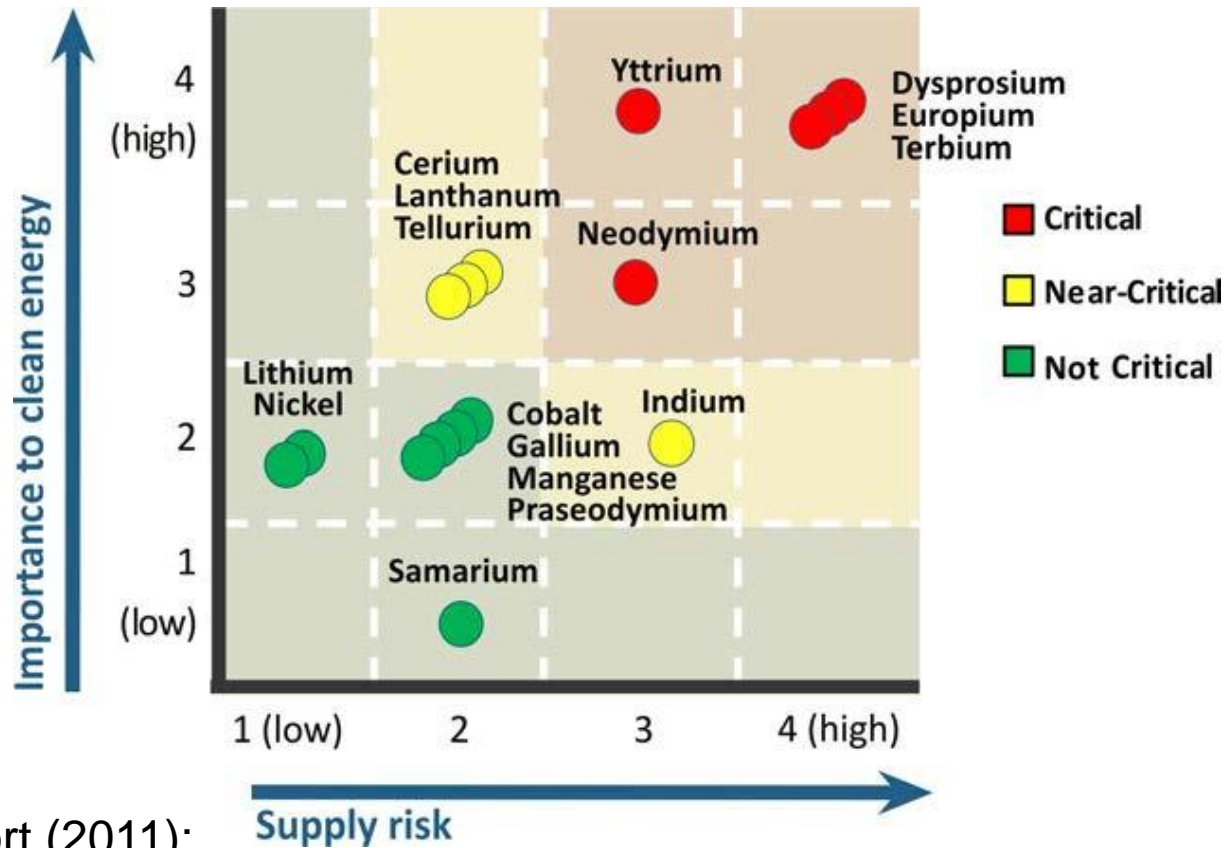
Projections (opinion):

- RE applications will continue to grow
- Some substitutes may be found, cost-driven
- If RE prices remain competitive, then
RE markets will continue to grow

Critical Materials Institute

- Study and recommend supply chain strategies
- US Dept Of Energy initiative at Ames Laboratory

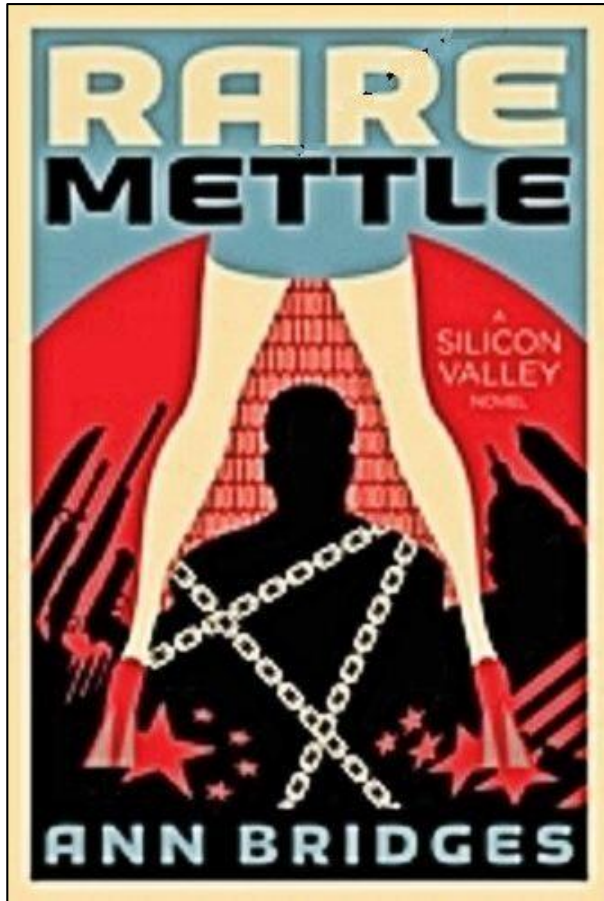
**Criticality Matrices:
Risk vs Strategic Importance**



CMI Critical Materials Report (2011):
https://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf

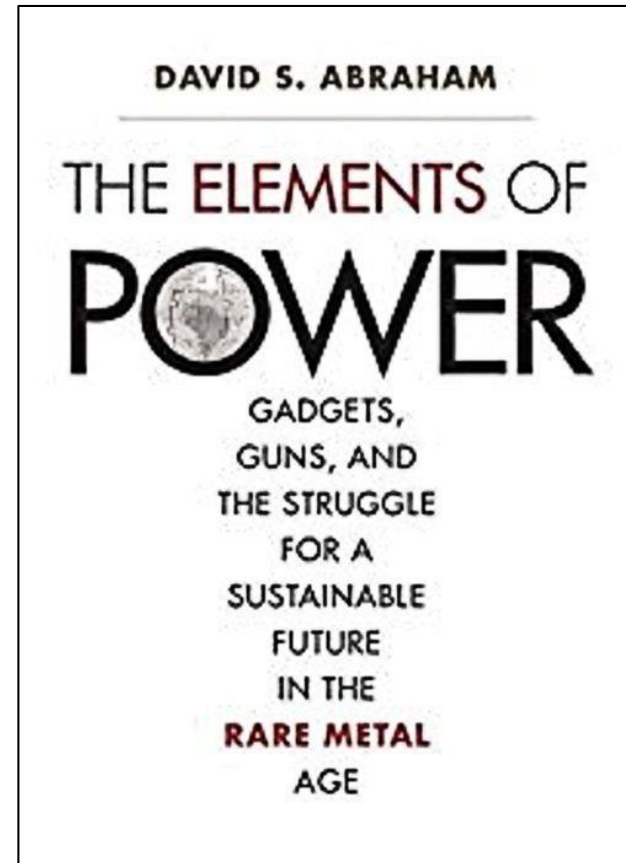
Further reading:

Fiction



**“Rare Mettle”
By Ann Bridges**

Non-Fiction



**“The Elements of
Power” by David S
Abraham**

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Thank You
for your attention !

Don Christian
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