Rare Earth Research Needs for Transportation Materials

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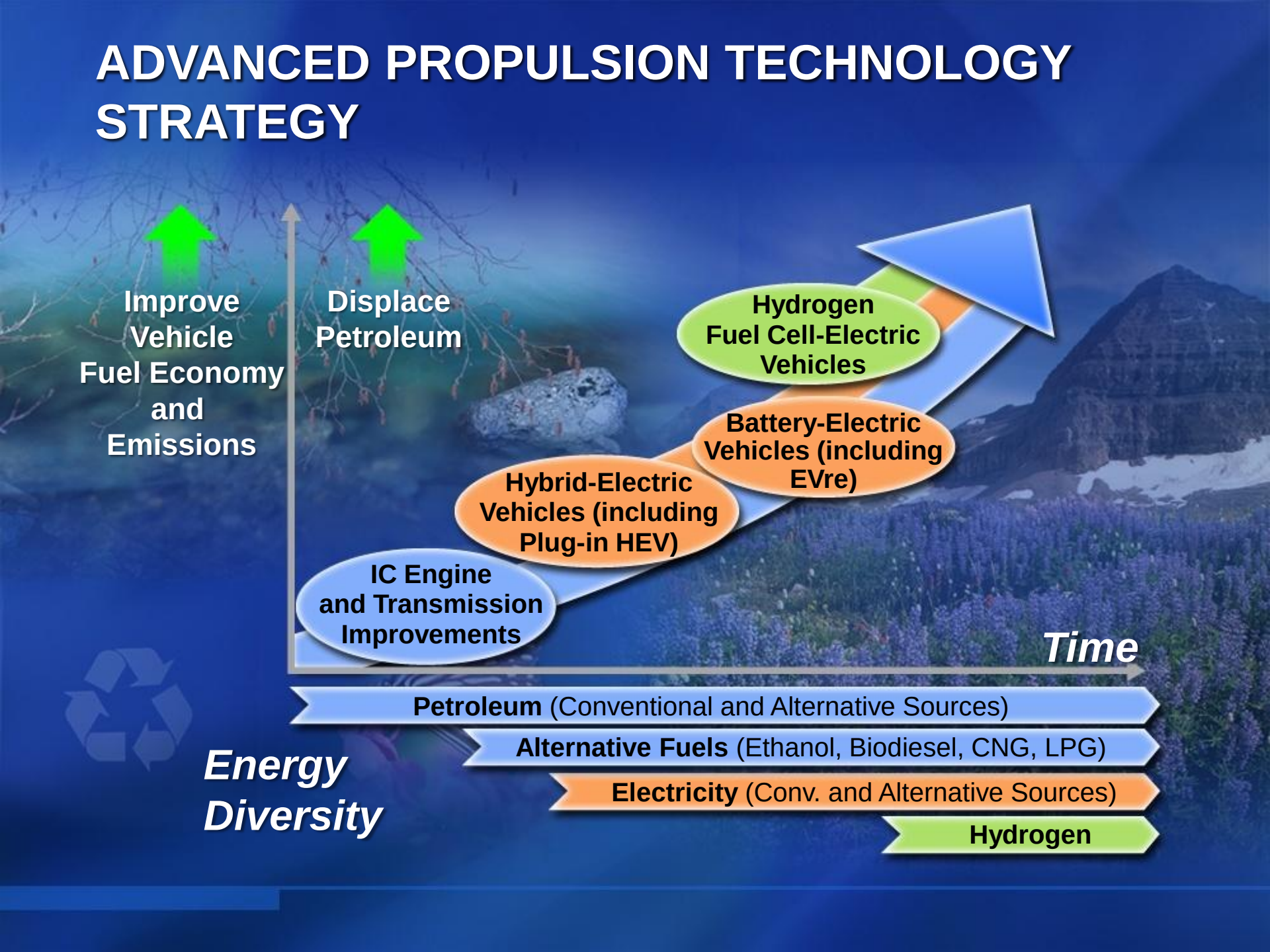
ADVANCED PROPULSION TECHNOLOGY STRATEGY



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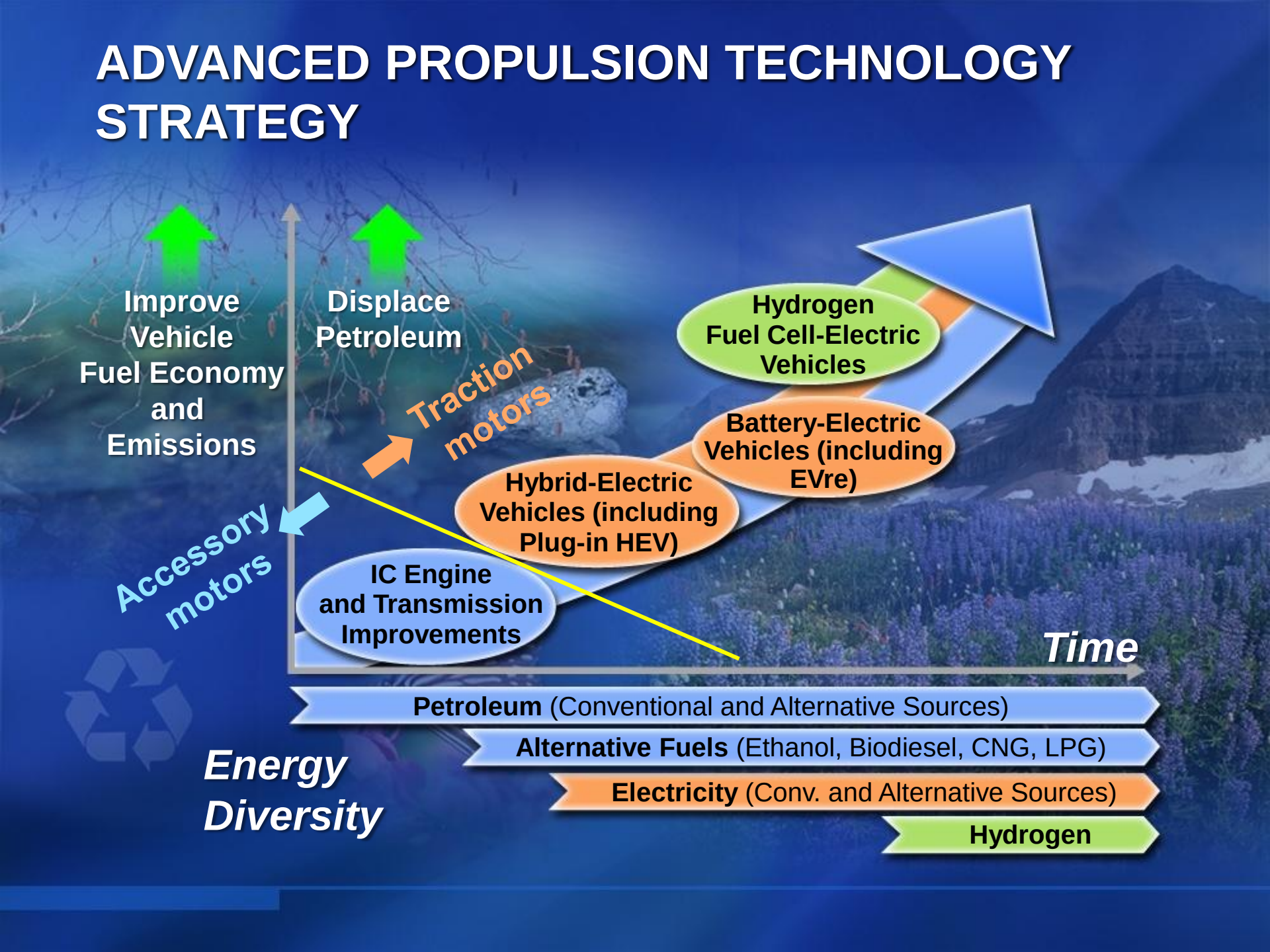


ELECTRIFICATION STRATEGY

Portfolio of solutions for full range of vehicles that provide customer choice

Petroleum and Biofuels
(Conventional and Alternative Sources)

Electricity and Hydrogen
(Zero Emissions Energy Sources)

Mild Hybrid	Strong Hybrid	Plug-in Hybrid	Extended-Range Electric	Battery Electric	Fuel Cell Electric

Increasing Electrification

Electric Motor Development and Manufacture

- GM is the first U.S.-based automaker to design, develop, process, and manufacture its own electric motors
- Facilities
  - Wixom, Pontiac, Indianapolis, Torrance – R&D and validation
  - White Marsh, Maryland – high-volume manufacturing
- GM is investing $270M in electric motors, electric drive, and components facilities
- Design and manufacture electric motors in-house, and work with our best suppliers to provide the very best electrified vehicle solutions to our customers

Automotive requirements

- FreedomCAR targets for 2010, 2015 and 2020

Requirements: 55 kW peak for 18 sec; 30 kW continuous; 15-year life; coolant (air or 105°C WEG)

Technology Targets

Year	Traction Drive System				Power Electronics			Motors		
	($/kW)	(kW/kg)	(kW/l)	Efficiency	($/kW)	(kW/kg)	(kW/l)	($/kW)	(kW/kg)	(kW/l)
2010	19	1.06	2.6	>90%	7.9	10.8	8.7	11.1	1.2	3.7
2015	12	1.2	3.5	>93%	5	12	12	7	1.3	5
2020	8	1.4	4	>94%	3.3	14.1	13.4	4.7	1.6	5.7

  - Difficult to achieve without high energy density RE permanent magnets
  - Need maximum remanence B_r
  - Need high temperature operation (> 150 C desired)
  - Must not demagnetize at high temperature (i.e., Nd-Fe-B needs high H_{ci} at room temperature to have enough left at high T)
- And of course at low cost

The auto industry is dependent on rare earths for magnets

Hybrid el. motor
- Neodymium
- Praseodymium
- Dysprosium
- Terbium

Glass, mirrors
- Cerium

Battery
- Lanthanum
- Cerium
- Praseodymium
- Neodymium

El. Motors, valves, actuators throughout vehicle
- Praseodymium
- Neodymium
- Dysprosium
- Terbium

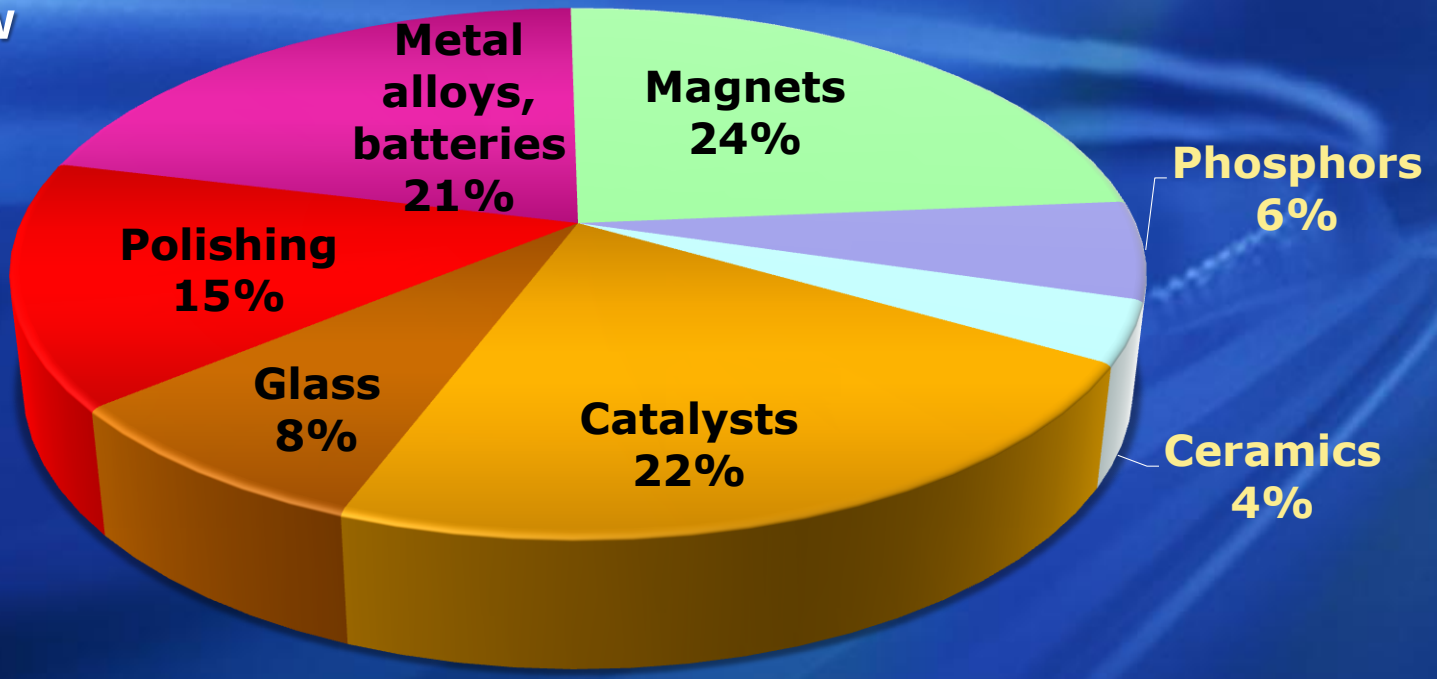
LCD screen
- Europium
- Yttrium
- Cerium

Catalytic converter
- Cerium
- Lanthanum
- Praseodymium
- Neodymium

- **Four elements – praseodymium, neodymium, dysprosium, terbium – are currently used for magnets in motors**
- **Rare earths account for ~80% of the material cost for a high coercivity Nd-Fe-B magnet (depending on magnet composition)**
  - **Dy can be more than half of the rare earth cost**
- **Currently, the alternatives to rare earths in magnets are significantly inferior**

Worldwide demand for RE magnets is expected to grow rapidly over the next few years

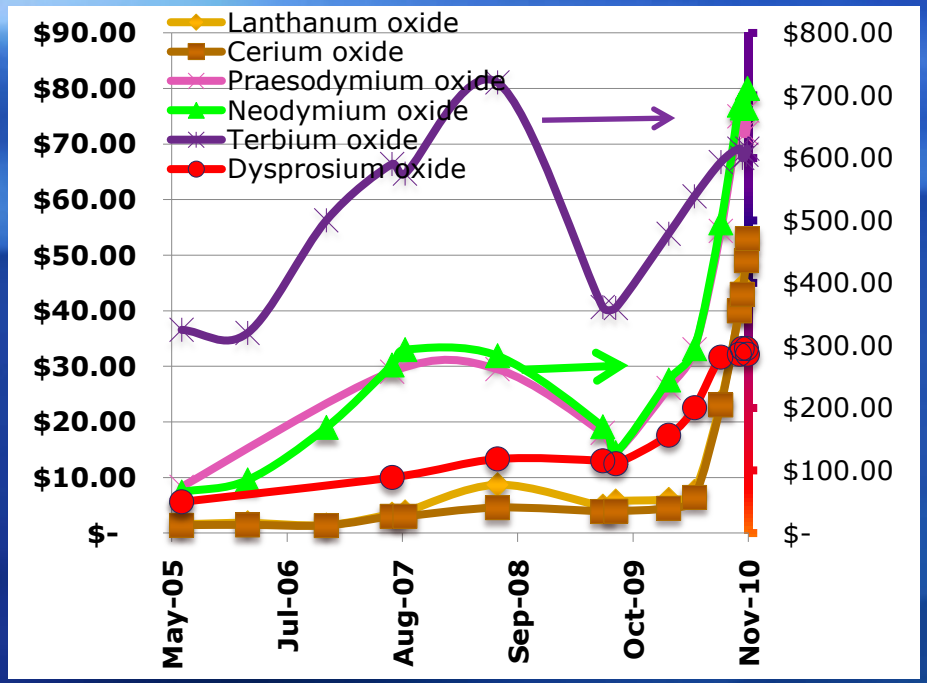
- All major OEMs will have the same rapidly increasing need for magnets
- Rare earth magnets have many applications in wind turbines and electronics, among other uses, and these demands are also expected to grow

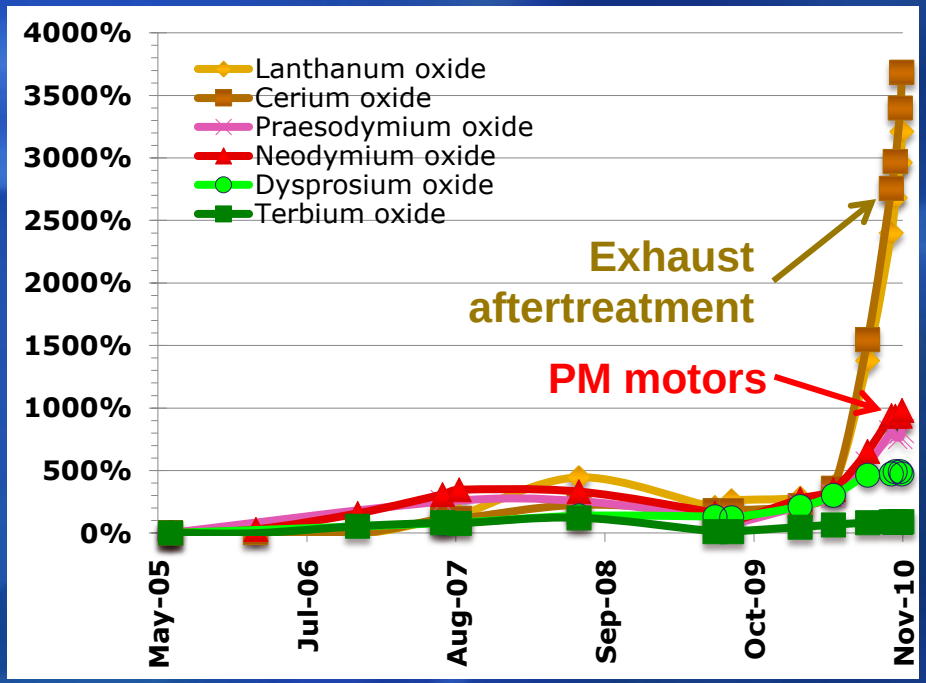


Global Rare Earths Demand in 2010

Tight market conditions led to rapidly rising RE prices over the last few years, even with the global recession

- Price for neodymium oxide has risen by 900% since 2005
- The price increase was larger outside China than inside, due to export controls





The auto industry can tolerate expensive technology… *IF*

- Justified by performance
  - *Customer experience*
  - Regulatory requirements
- Cost is *stable* (predictable economics)
- Supply is *reliable* (non-strategic resource)
- Expected long-term trend toward lower cost
  - With increasing volume
  - With progressive technology improvements

The auto industry can tolerate expensive technology… *IF*

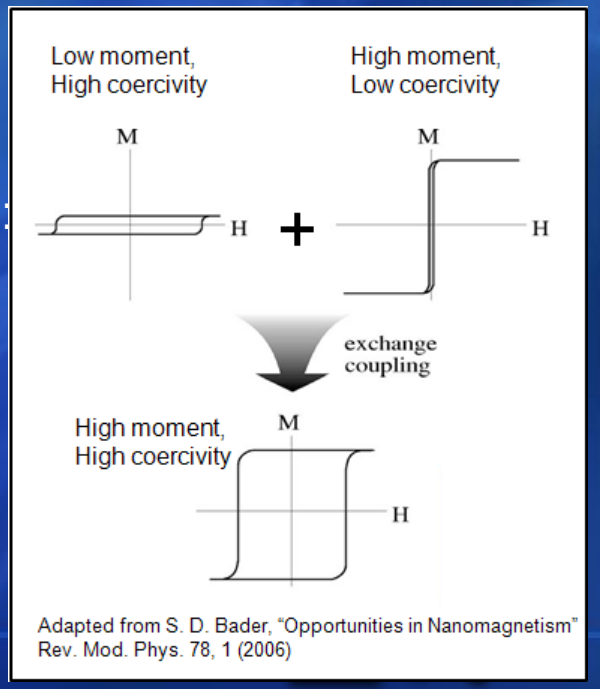
For Nd-Fe-B and Sm-Co:

- ✓ Justified by performance
  - *Customer experience*
  - Regulatory requirements
- X Cost is *stable* (predictable economics)
- X Supply is *reliable* (non-strategic resource)
- X Expected long-term trend toward lower cost
  - With increasing volume
  - With progressive technology improvements

Nd-Fe-B and Sm-Co permanent magnet technology is mature

Mitigation

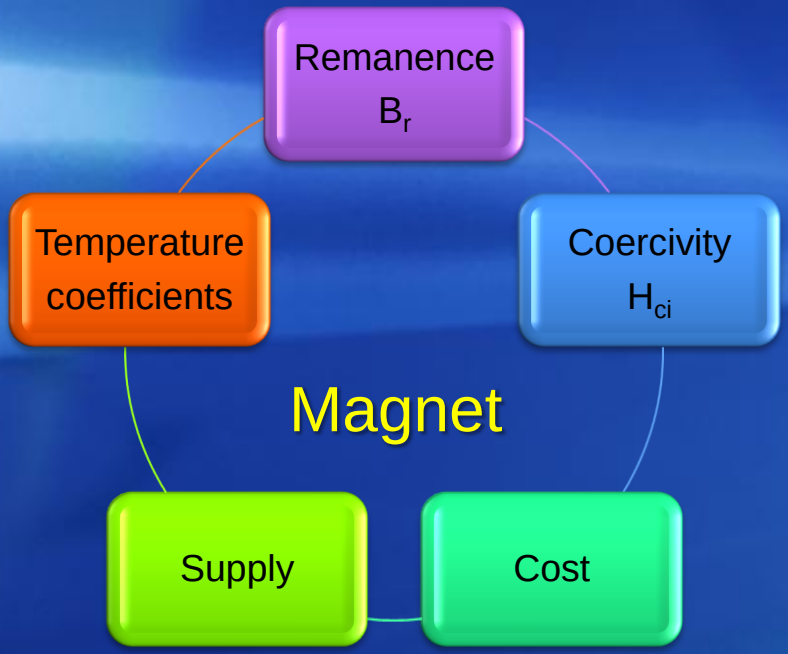
- Sourcing strategy
- Fall-back technologies (sacrifice performance for certainty)
- Motor design tradeoffs
  - Run at lower temperature, more cooling, etc.
- Reduce or eliminate Dy and other heavy rare earths
  - Dy replacements
- Reduce total rare earth content of Nd-Fe-B based magnets
  - Aligned exchange-coupled magnets with less RE
  - Hybrid magnets
- Disruptive technologies
  - New non-rare earth magnet materials
  - New motive technologies

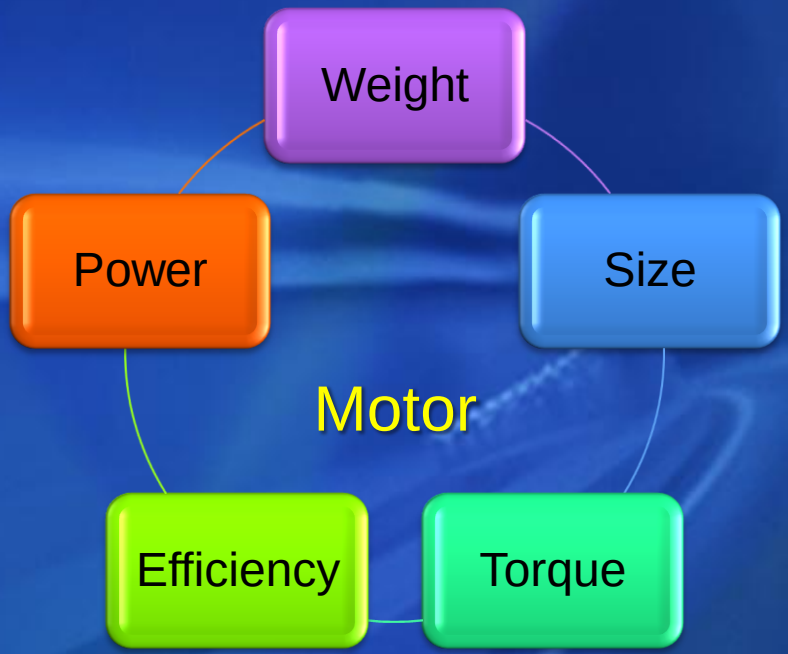


Adapted from S. D. Bader, "Opportunities in Nanomagnetism" Rev. Mod. Phys. 78, 1 (2006)

Solutions will involve compromise…

We do not expect to equal or exceed Nd-Fe-B on all properties (the no-free-lunch theory)





Magnet property tradeoffs expected
No one solution for all applications

We will design to a material

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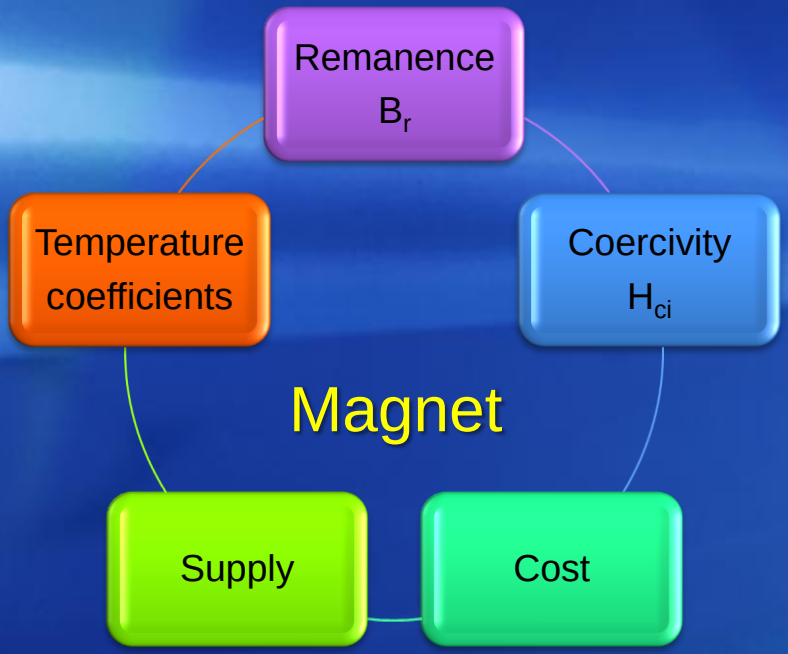

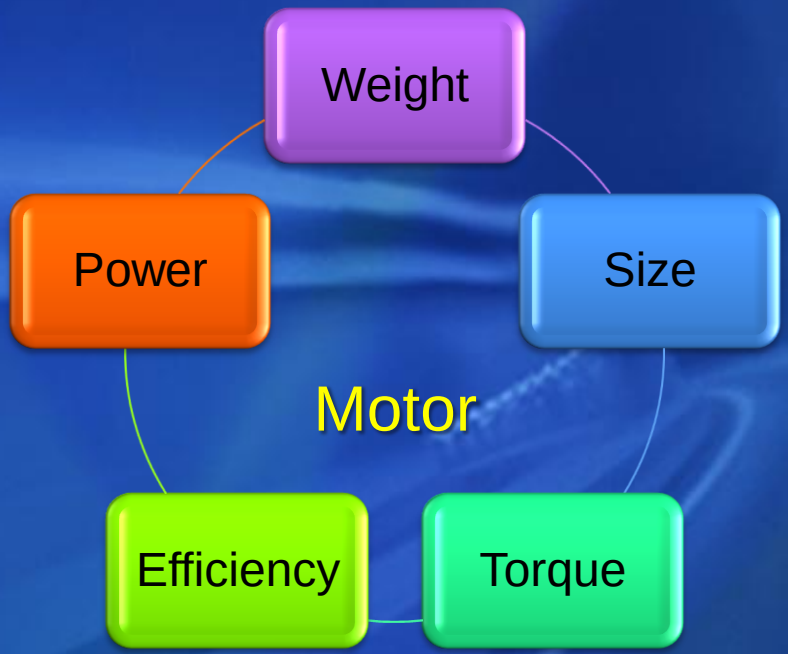

Magnet property tradeoffs expected
No one solution for all applications

We will design to a material

… but we'll take a cheap drop-in replacement for Nd-Fe-B.

Bottom line: automotive perspective

- High performance permanent magnets
  - Maximum B_r, high temperature performance, enough H_{ci} to not demagnetize, minimum cost
- The auto industry will be increasingly dependent on rare earth magnets as hybrid and electric vehicles grow market penetration
- Demand for RE magnets is growing rapidly for many uses, particularly wind turbine generators and vehicles, and demand is inelastic
- Supply of the heavy rare earths is limited and heavily concentrated in one geographical region, creating both business and political risks
- Tight market conditions led to sharp price increases over the last five years, with the Nd oxide price rising by 900% and Ce oxide rising by 3700%
- Rising demand and limited, inelastic, concentrated supply creates a high risk of a sustained RE price spike
- Mitigation should have high priority