Copper Rotor technology for electric and hybrid vehicles

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Summary

Market perspectives for electric, hybrid and plug-in hybrid vehicles

Technology options for electric and hybrid vehicles

Conclusions

Market perspectives for electric, hybrid and plug-in hybrid vehicles

Electric vehicles are here – more are coming

BMW Mini E

Citroen C-Zero

Fisker Karma

Ford Transit Connect

Daimler Smart EV

Nissan Leaf

Hyundai i10

Toyota Prius

GM Chevrolet Volt

BYD F3DM

Ford Focus EV

Mitsubishi iMiEV

- **2010**

  10 major auto manufactures with 10 production models

- **2012**

  Over 20 production models available

- **Industry Consensus**

  5 Million Plug-in Cars in use by 2017 worldwide

Source: Pike Research

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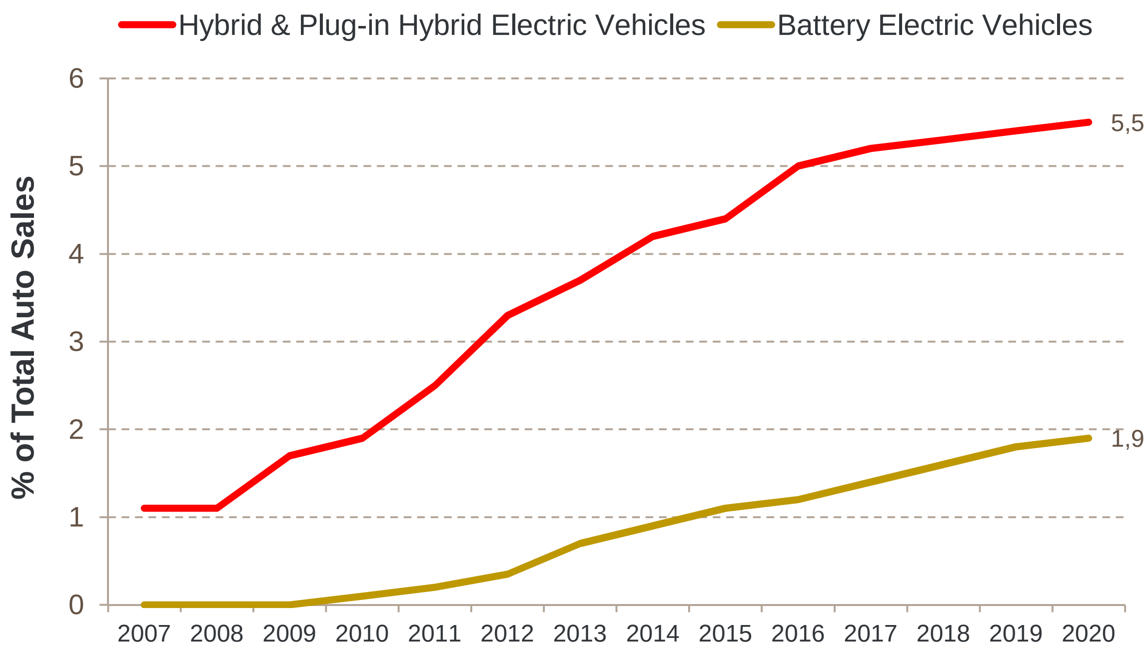
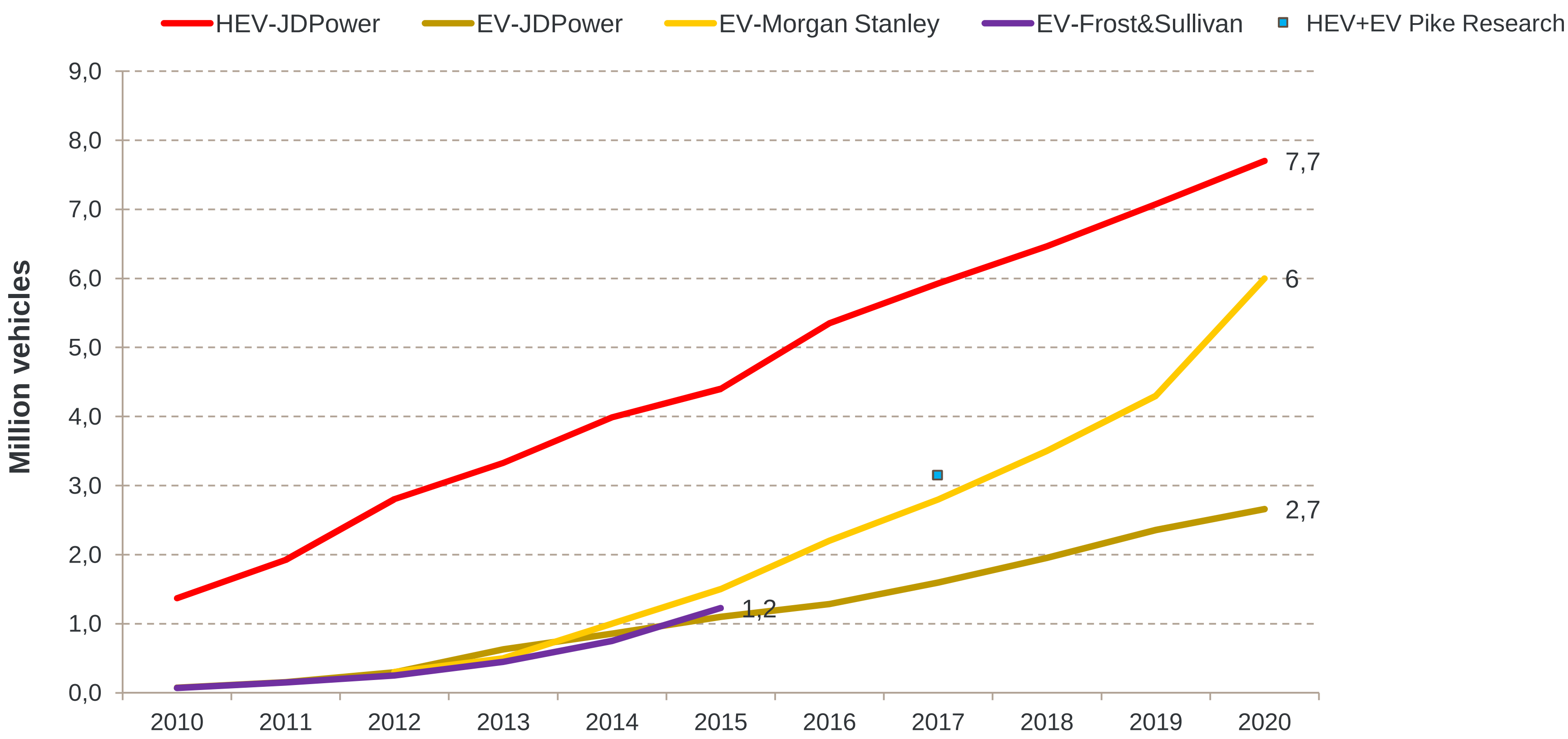
Market share of hybrid and electric vehicles
2007 – 2020 (% of overall auto sales)

The share of battery-powered vehicles will grow but is expected to remain small through 2020, largely because of high costs.



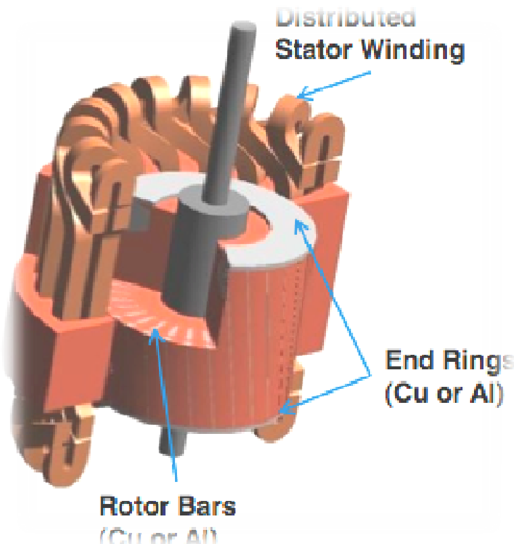
Source: J.D. Power & Associates

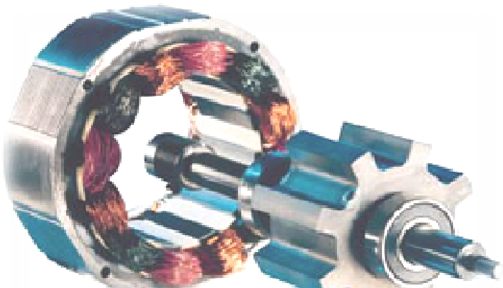
Demand forecast for hybrid and battery electric vehicles



Source: J.D. Power & Associates, Morgan Stanley, Frost & Sullivan, Pike Research

Technology options for electric and hybrid vehicles





Three-phase SR Drive® stator and rotor

Motor technology alternatives

- Internal Permanent Magnet (IPM)
  - Currently popular choice for HEV and EV applications
  - Highest efficiency with high power density
  - Wide range of constant power
  - Overall weight and volume reduced for given output power
  - Stator losses may be significant at higher speeds
  - Limited field weakening capability due to presence of PMs, makes it more difficult to go to higher frequencies (rpm
  - At very high speed range, efficiency may drop because of risk of PM demagnetization
  - Proper cooling is very important at high frequencies
  - Dependency on rare earth magnets a real concern

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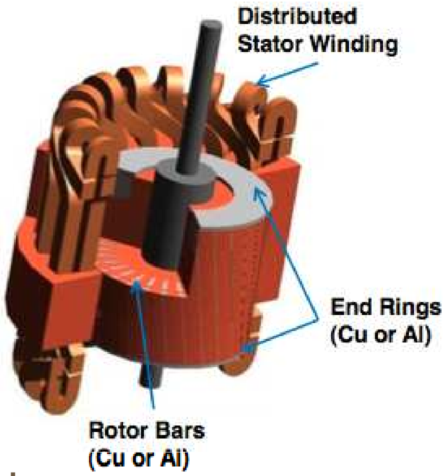
Motor technology alternatives (2)

- Induction Motor (IM)



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  - Ready and proven technology for HEV/ EV applications (GM e-Assist, Tesla)
  - No magnets
  - Readily runs at higher temperatures
  - Durable and reliable
  - Lower material cost than IPM and can be recycled
  - Lower sensor cost
  - Ability to operate in hostile environments
  - Comparable power/torque density, noise and peak efficiency to IPM
  - Can withstand higher intermittent currents than IPM
  - “Drop in” rotor replacement for IPM, avoiding total redesign of motor

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  - Slightly lower efficiency at low speeds

Motor technology alternatives (3)

- Switched Reluctance motor (SR)

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- Simple and rugged construction
- Cost effective – low tooling requirements
- Fault-tolerant operation
- Simple control
- Excellent torque-speed characteristics
- Constant power output over a wide speed range

Three-phase SR Drive® stator and rotor

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- Acoustic noise and vibration are design challenges for automotive operation
- High torque at low speed capabilities make it attractive for heavy vehicle applications (Caterpiller, Deere)

Motor technology alternatives (4)

- Synchronous Wound Field DC Motor (DC)

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  - Excellent torque-speed characteristics for propulsion
  - Simple speed controls

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  - Lower power/torque density and efficiency
  - More bulky construction
  - Low reliability
  - Usually needs brushes and slip rings which can wear and create conductive dust (and increase maintenance)
  - Rotor field windings can limit speed rating

DC motor in the Hybrid Citroën Berlingo

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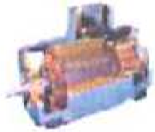
Electric propulsion systems evaluation

Induction motor has the highest rating for electric propulsion of urban HEVs

IPM
- Higher power density
- Slightly better peak efficiency

IM
- Simpler
- Lower cost
- Use of copper rotor improves power density and efficiency (not shown in chart)

Propulsion Systems / ***Characteristics***	 DC	 IM	 IPM	 SRM
Power density	*2.5*	*3.5*	*5*	*3.5*
Efficiency	*2.5*	*3.5*	*5*	*3.5*
Controllability	*5*	*5*	*4*	*3*
Reliability	*3*	*5*	*4*	*5*
Technological Maturity	*5*	*5*	*4*	*4*
Cost	*4*	*5*	*3*	*4*
Total	***22***	***27***	***25***	***23***

Source: Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study, M. Zeraoulia et al, IEEE Transactions on Vehicular Technology, Vol.55, No. 6, November 2006, pp. 1756-1764

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Copper rotors deliver better performance in IMs

- Copper rotor bars and end rings reduce rotor electrical losses
  - Smaller and/or more efficient motors offer the same output performance
- Excellent heat conduction properties make thermal management easier
- Advanced copper die casting techniques manage cost and maximize quality for production volumes
- Die cast rotors provide better mechanical properties than fabricated rotors

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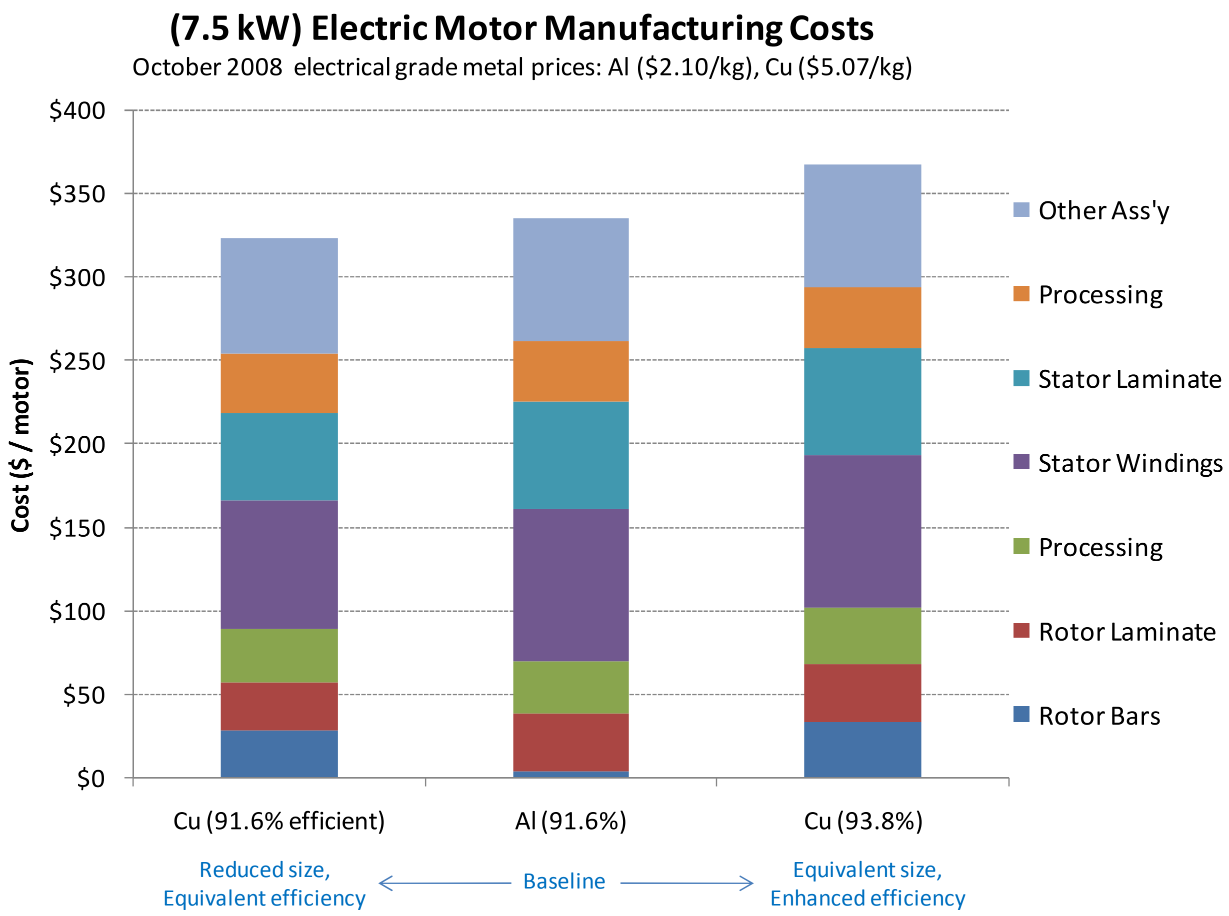
Manufacturing cost structure for three alternative designs of a 7.5 kW induction motor (needs updating to current metal prices)



Source: IBIS Associates

Cost savings of copper rotor vs aluminum rotor are 14 to 18%

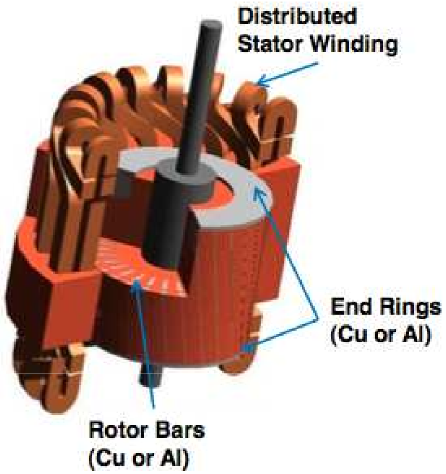
Table 1. Motor Cost Comparisons: Copper vs. Aluminum Rotors
Motors Designed for Equivalent Energy Efficiency and Performance Characteristics (See text.)

Motor Size, Rotor Type	Costs, US$					*Savings with Copper-Rotor Motors*
	Steel	*Windings*	*Rotor*	*Shaft/Housing Assembly*	*Total*	
15 hp (11 kW)						
COPPER	179	39	18	142	378	**$64 (14%)**
ALUMINUM	222	46	6	168	442	
7.5 hp (5.5 kW)						
COPPER	123	20	11	117	271	**$60 (18%)**
ALUMINUM	156	33	4	138	331	

Source: Copper Development Association, Aug 2005

IPM is now 30% more expensive than IM

IPM rotor costs $209 more than copper rotor



IPM motor +30%
IPM Rotor +$209

Induction motor with copper rotor
Rotor cost ~ $51

Internal permanent magnet motor
Rotor cost ~$260

- For equivalent power density and torque IPM will be a smaller motor than IM but 30% more expensive[1]
- Nd_{2-x} Dy_x $Fe_{14}B$ is the basic magnet composition with Neodymium 23-26% by wt, Dysprosium 3 – 12% by wt
- General Motors' IPM rotor cost $120, in January 2009.[2]
- Neodymium and Dysprosium prices have risen 22x and 25x respectively since Jan 2009, therefore the IPM rotor cost is at least $140 higher or $260.
- An average copper rotor costs $51, so the difference in cost is ~$209

Source: Copper Development Association, SEW Eurodrive Gmbh, ICA estimates

[1] IPM also requires a frequency inverter if used at the grid but not in traction applications
[2] CDA meeting at General Motors

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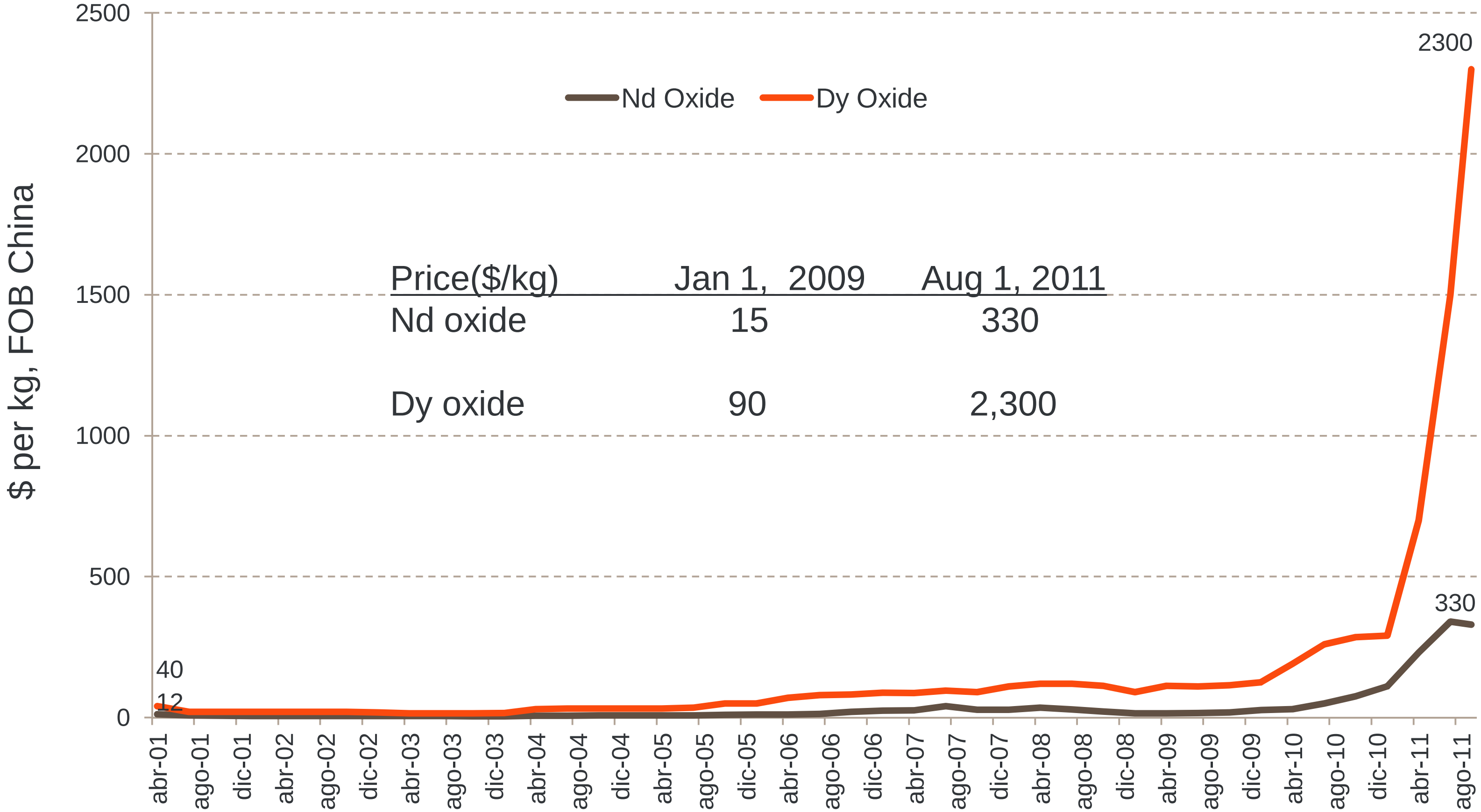
Neodymium and Dysprosium prices have risen dramatically due to limits on Chinese exports



Price($/kg)	Jan 1, 2009	Aug 1, 2011
Nd oxide	15	330
Dy oxide	90	2,300

Source: metal-pages.com, Kidela Capital

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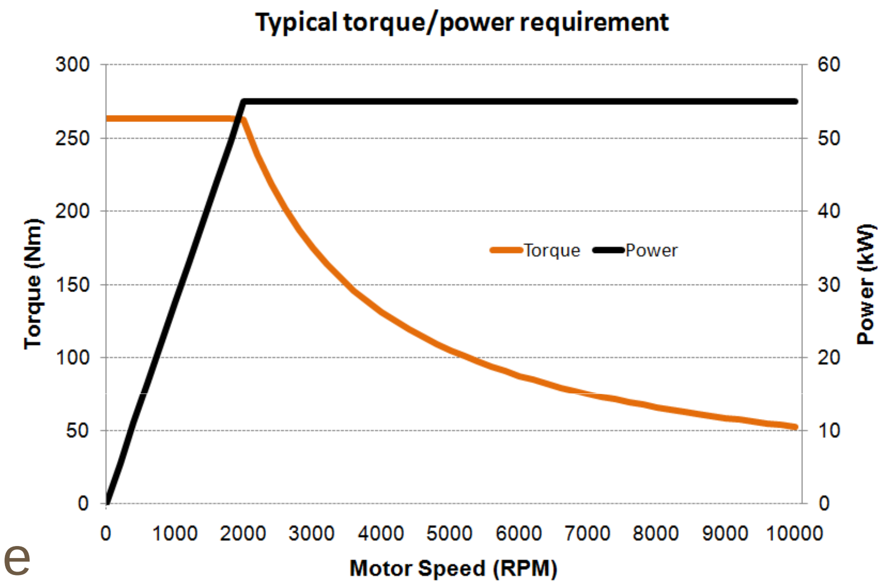
Traction motors for electric vehicles

Requirements

- Efficiency
- Reliability
- Durability
- Smaller motor size
- Reduced weight
- Reduced noise
- Better thermal management
- Operate over wide temperature range
- Operate over a wide speed/torque range
    - Constant torque at low speeds
    - Constant power at higher speeds to a maximum speed



Source: Electrical and Electronic Technical Team Roadmap, Freedom CAR fuel Partnership, November 2006

Performance comparison of IPM vs IM motors

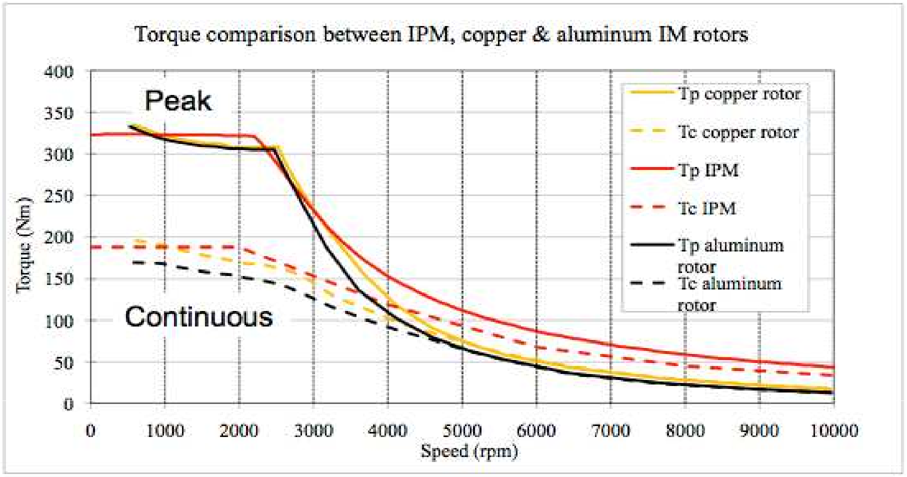
Torque comparison:
•Data taken using same battery, inverter, cooling system, and stator

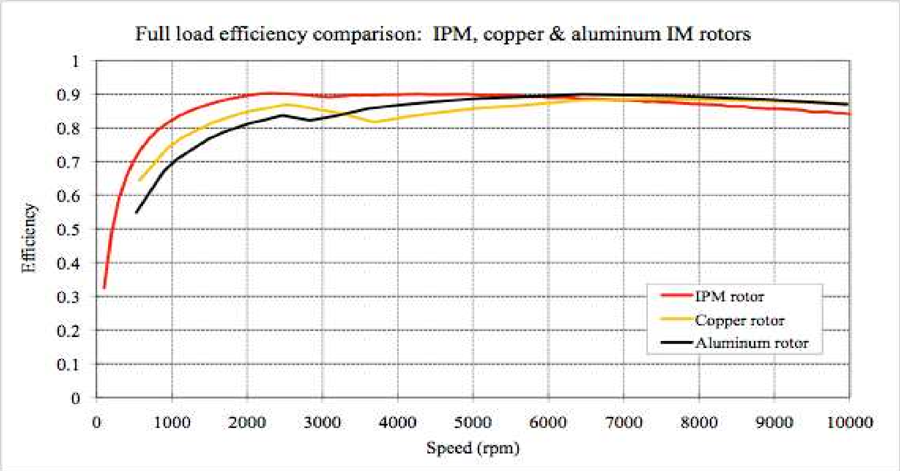
• Comparable low speed performance

• At high speed, IM dropped off faster than IPM

• System voltage could be boosted to maintain high speed performance

Full load efficiency comparison:
• IM shows some compromise in performance at low speeds, but slight improvement at high speeds versus IPM





Source: Remy International

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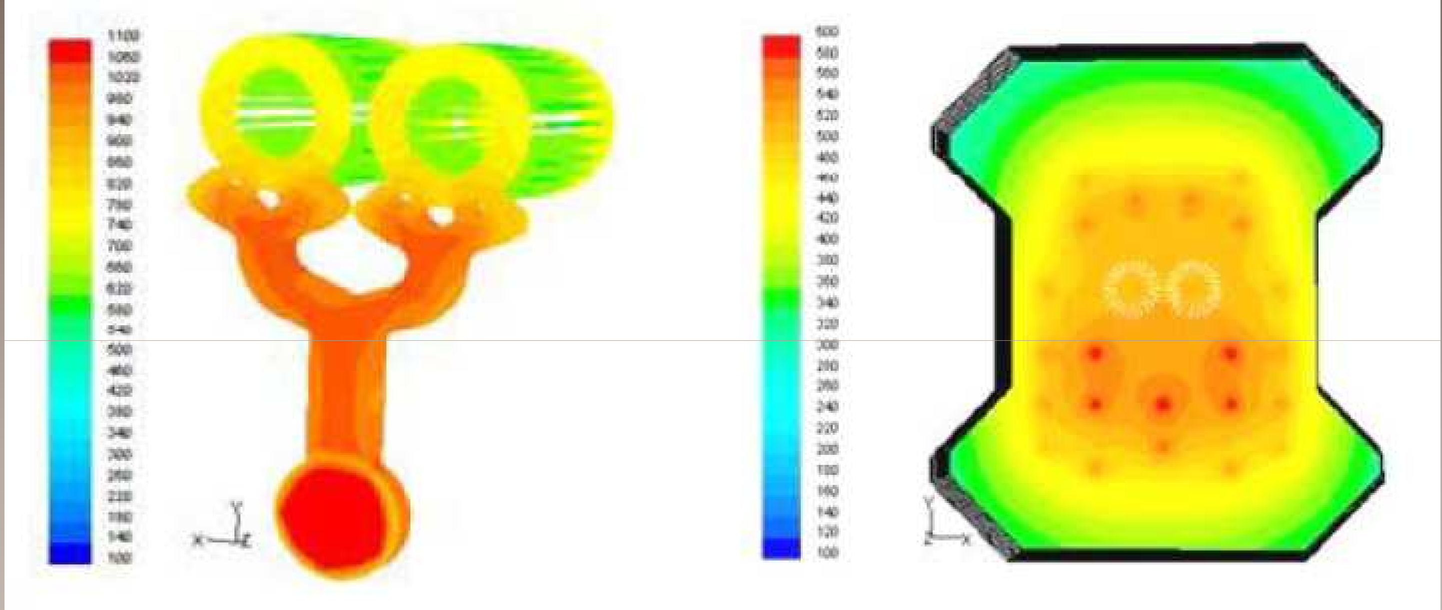
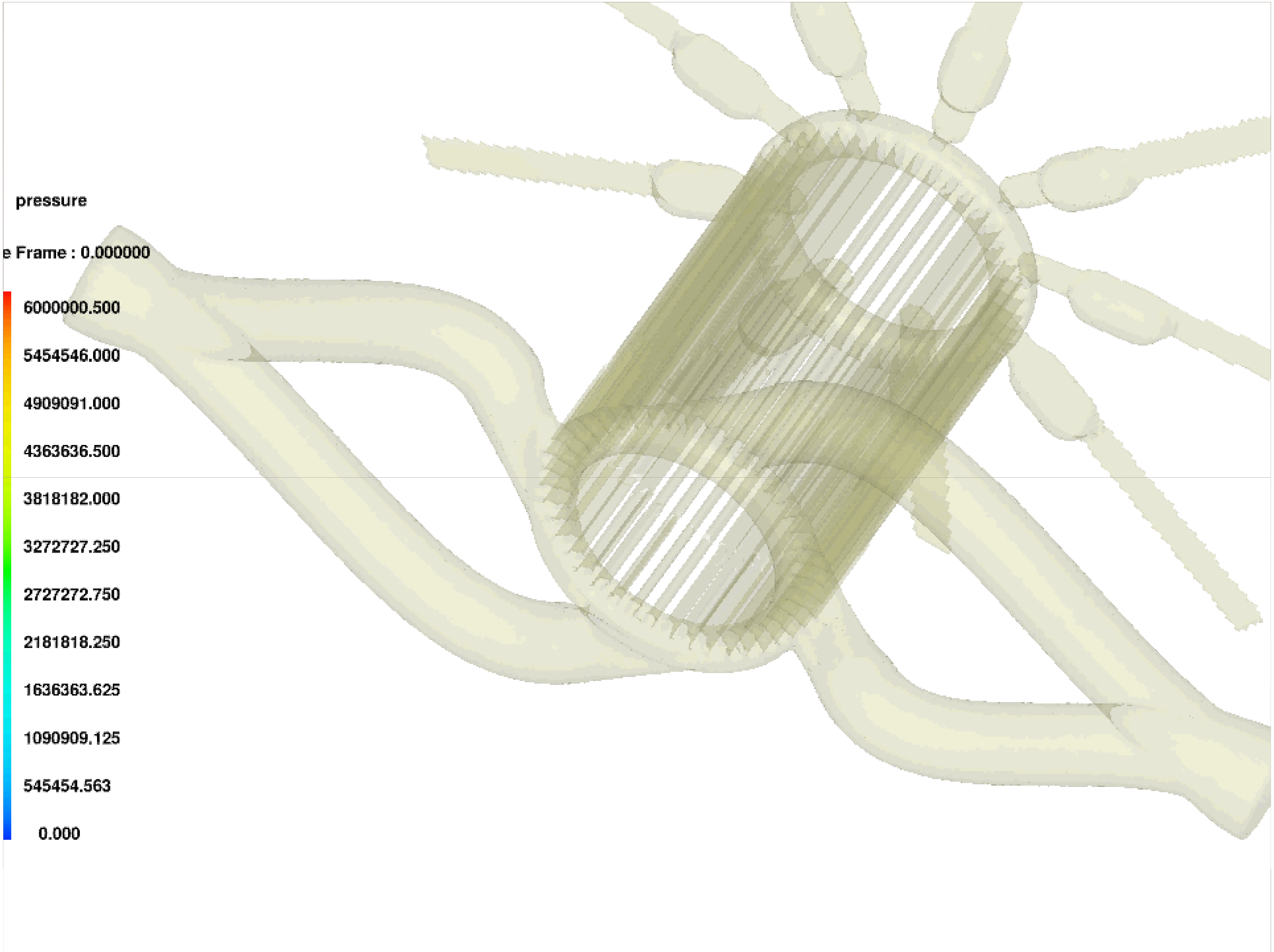


Tooling temperature simulation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4909091.000
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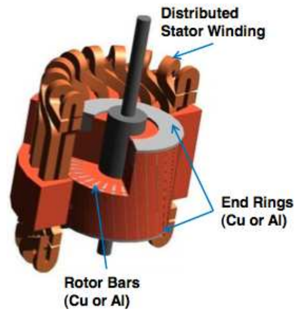
3272727.250
2727272.750
2181818.250
1636363.625
1090909.125
545454.563
0.000

Conclusiones

- **10 million electric vehicles (mostly hybrids) by 2020**

- **Internal Permanent Magnet technology has been the most reasonable choice till now, however, for cost reasons, current competitiveness is low and very sensitive to the price of rare earths.**

- **Copper Rotor Motor offers very close or higher performance, at a better price and almost no volatility**



International Copper Association develops and collaborates in the design and optimization of Copper Rotor Motors for automotive industry

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http://www.copper.org/applications/electrical/motor-rotor/index.html

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