Advanced Magnetics: The Key to Higher Energy Efficiency

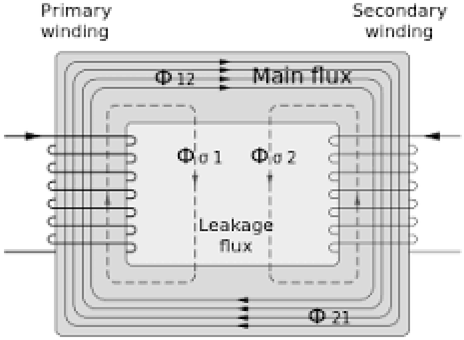
John Petro

Santa Clara, February 2017

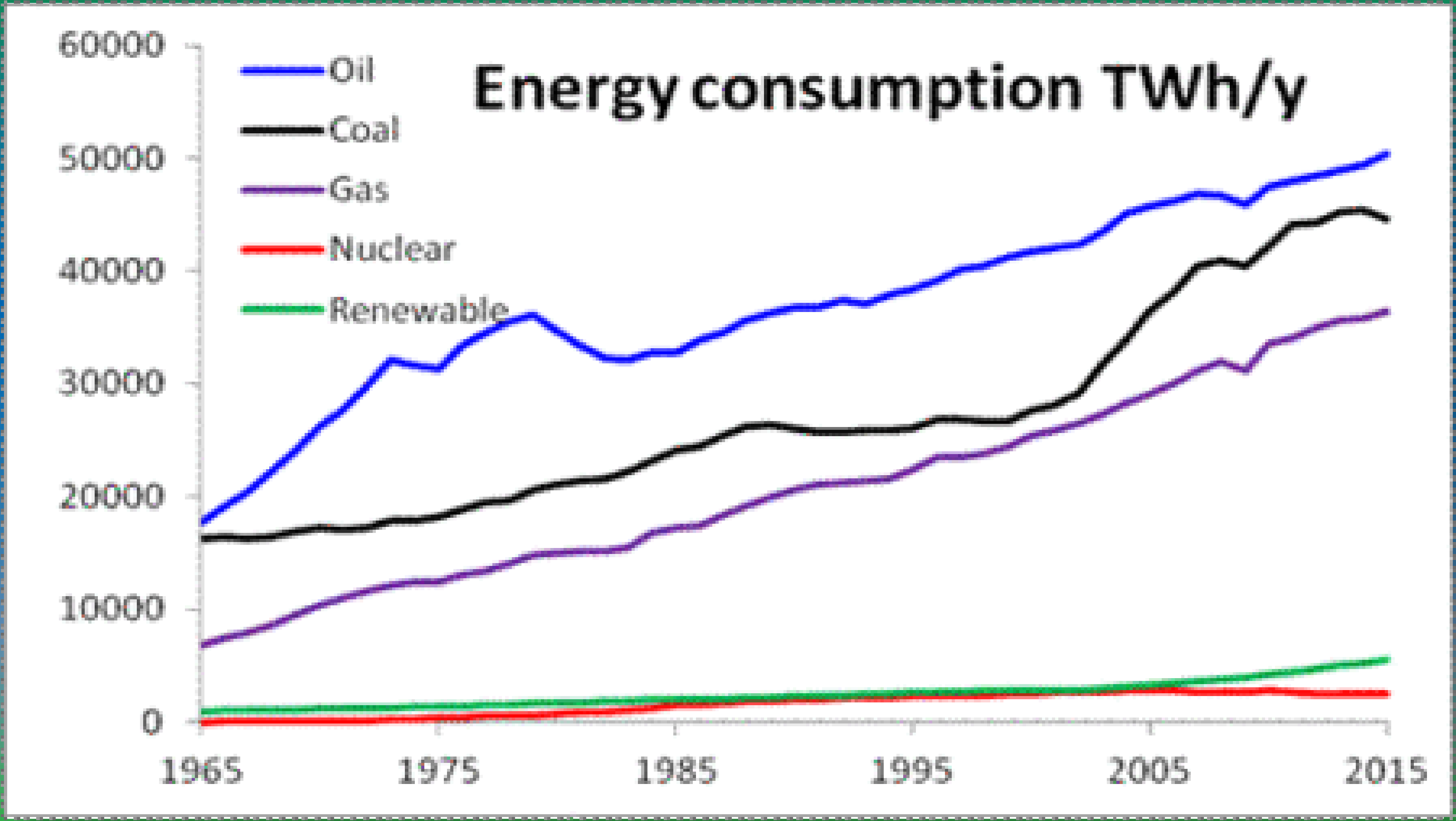
Outline

The next path to higher electrical efficiency

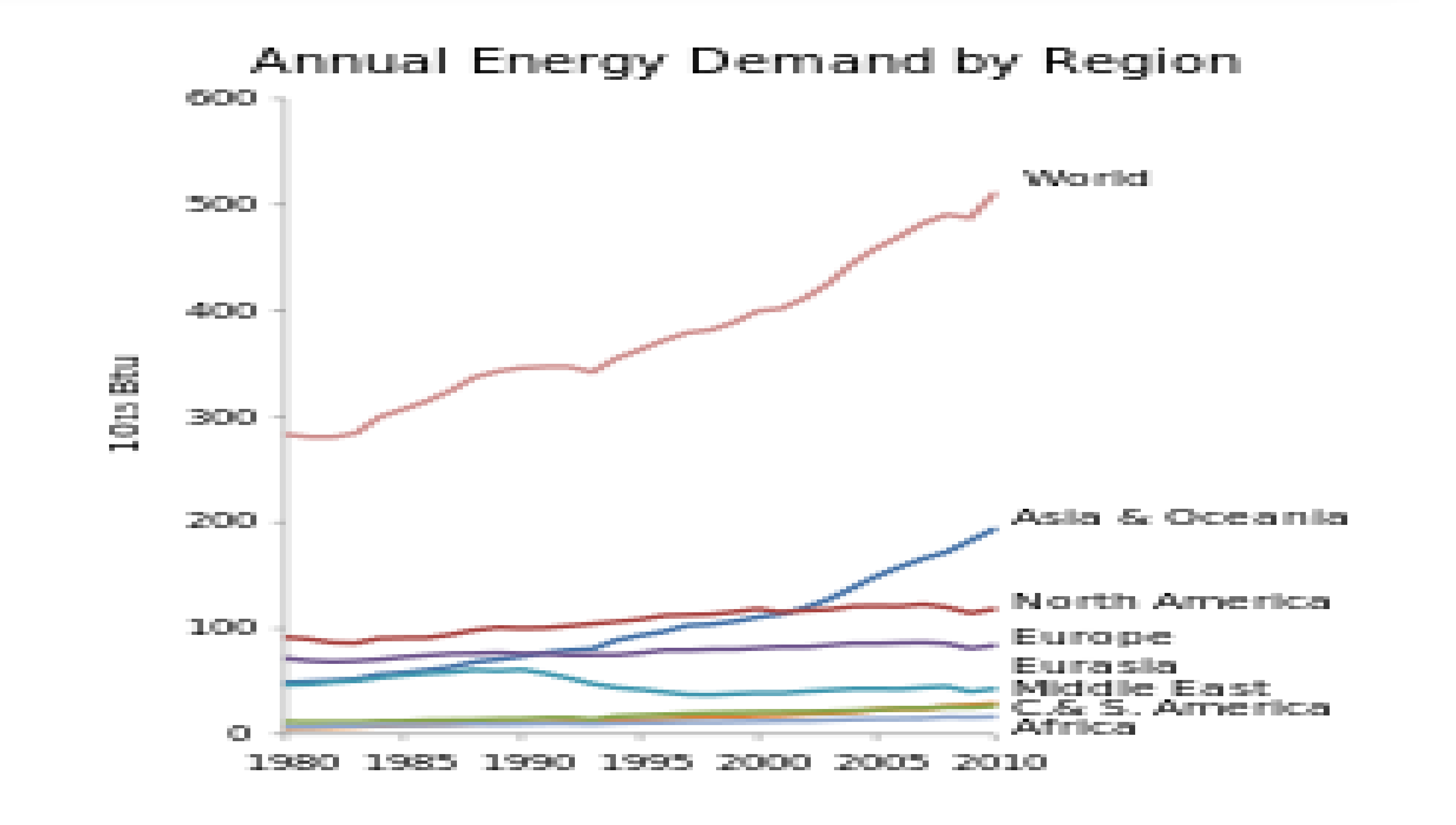
- Energy Consumption
- Efficiency Benefits
- Motor Efficiency
- Role of Magnetics
- Magnetic Materials
- Other Improvements



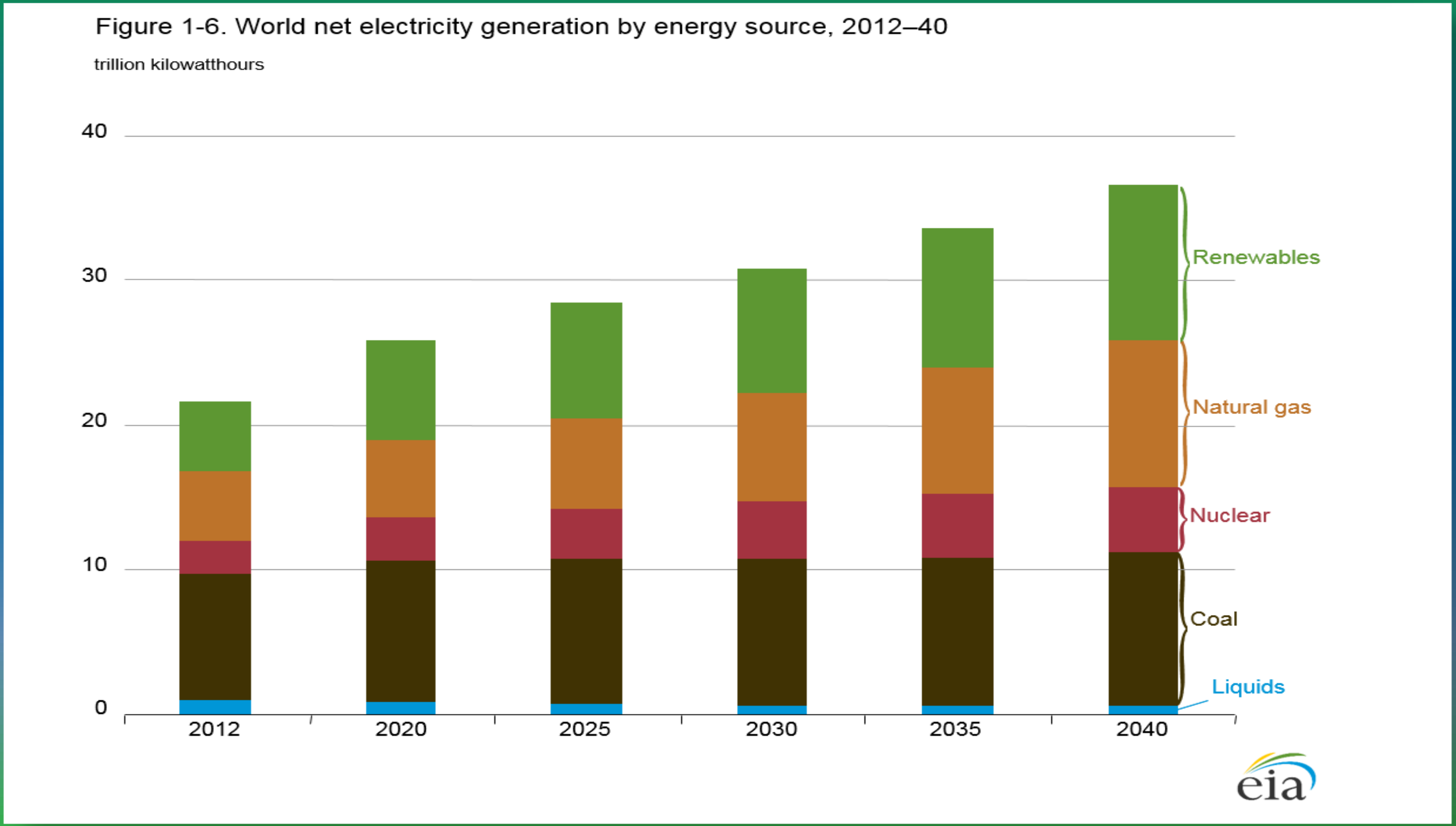
World Energy Consumption – All Uses



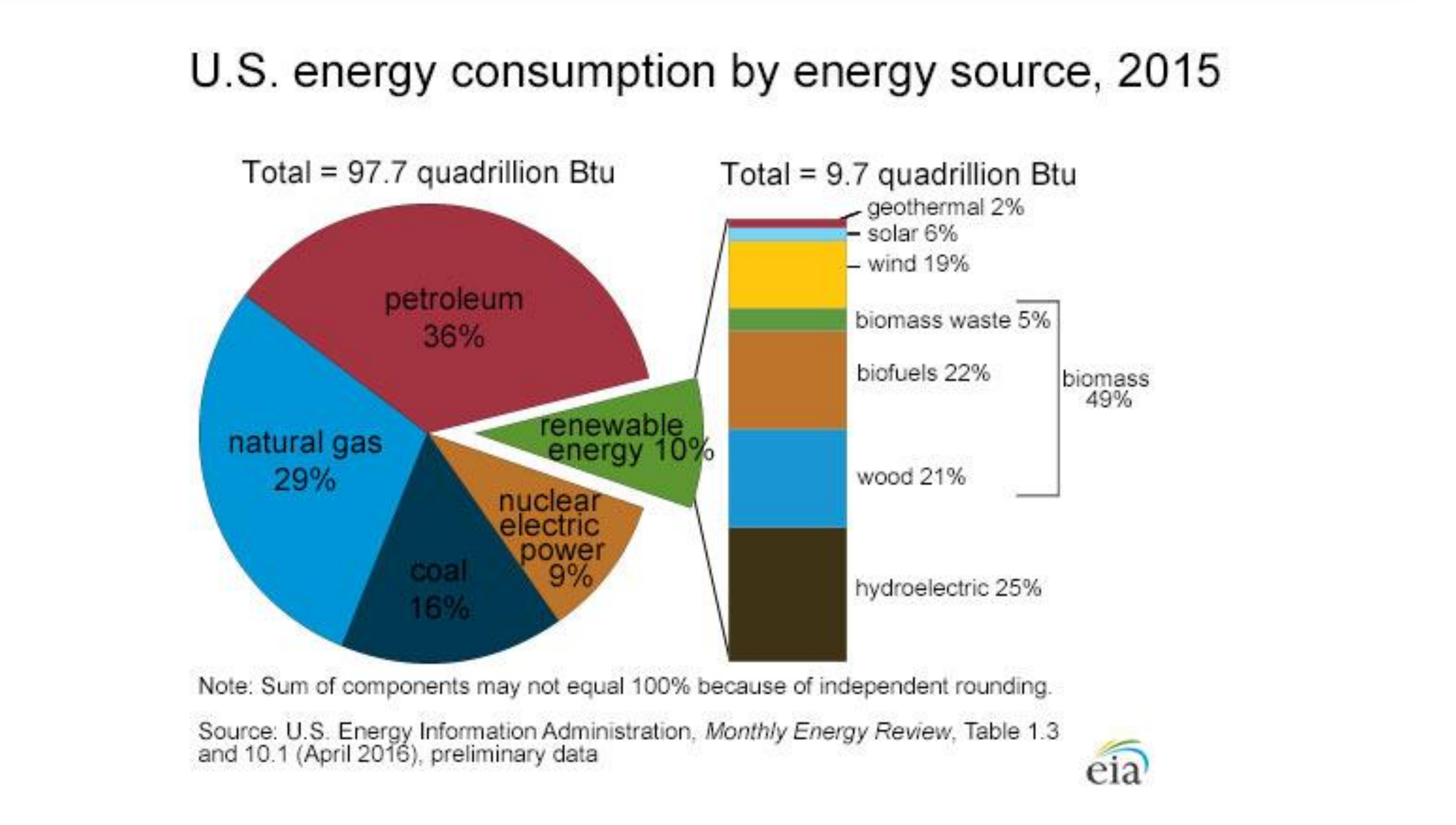
World Energy Consumption by Region



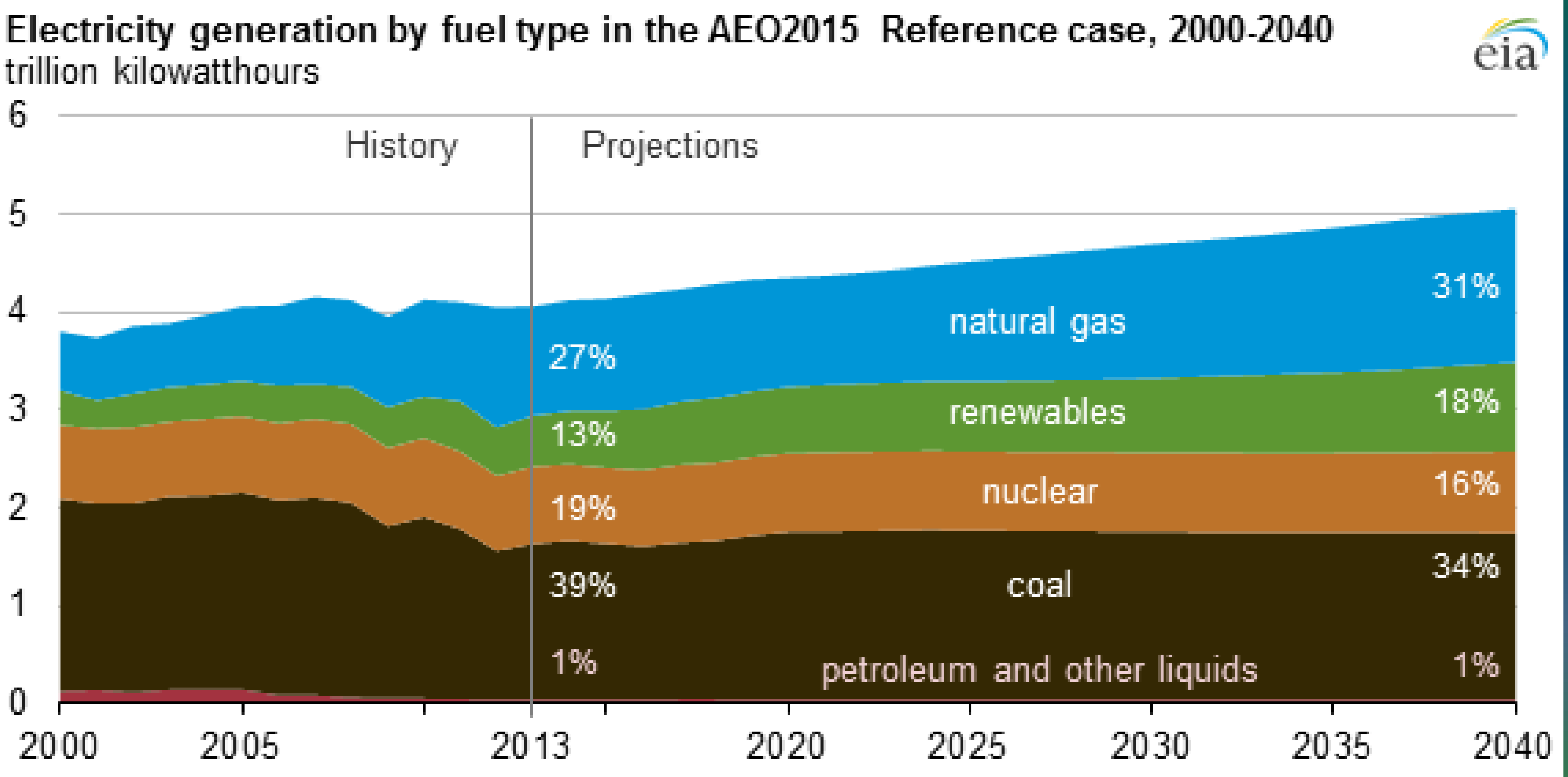
World Projected Electrical Energy Needs



U.S. Total Energy Consumption by Source



U.S. Electrical Energy Production



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U.S. Electrical Energy Uses

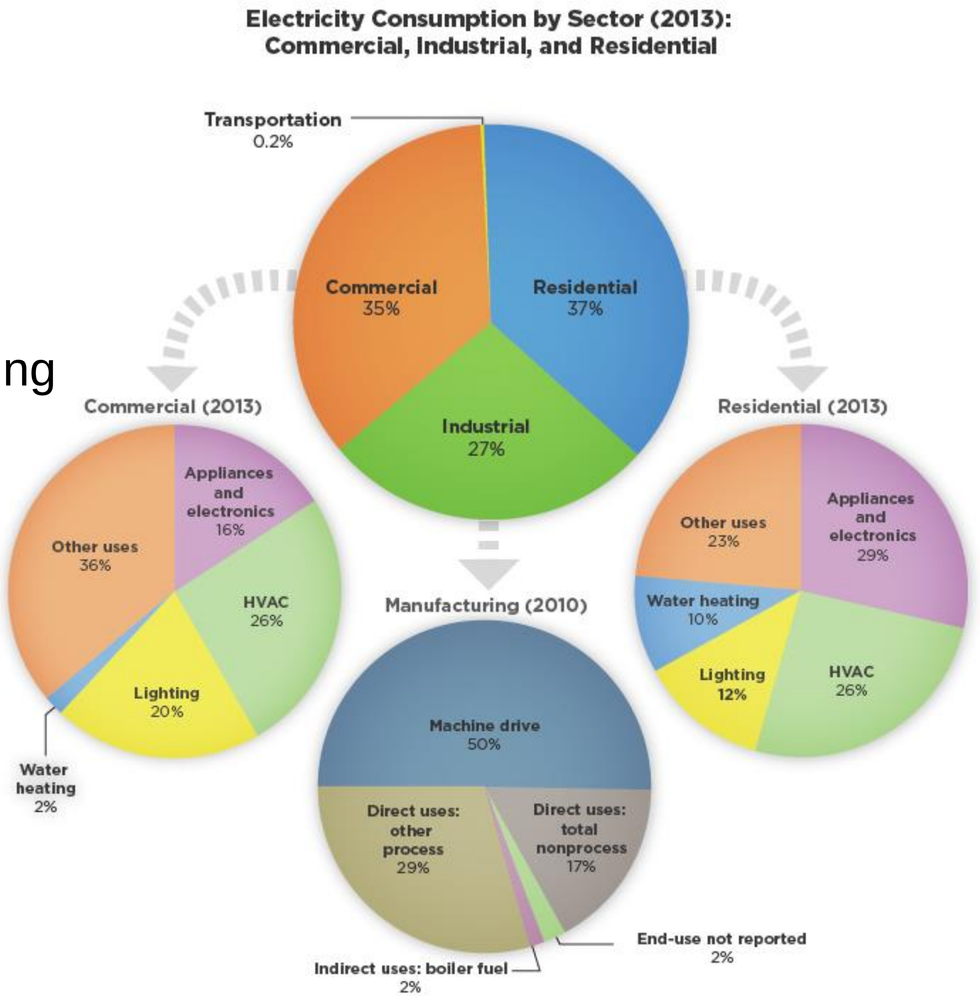
Motors ~ 45-55% and increasing

Lighting ~15-20% and decreasing

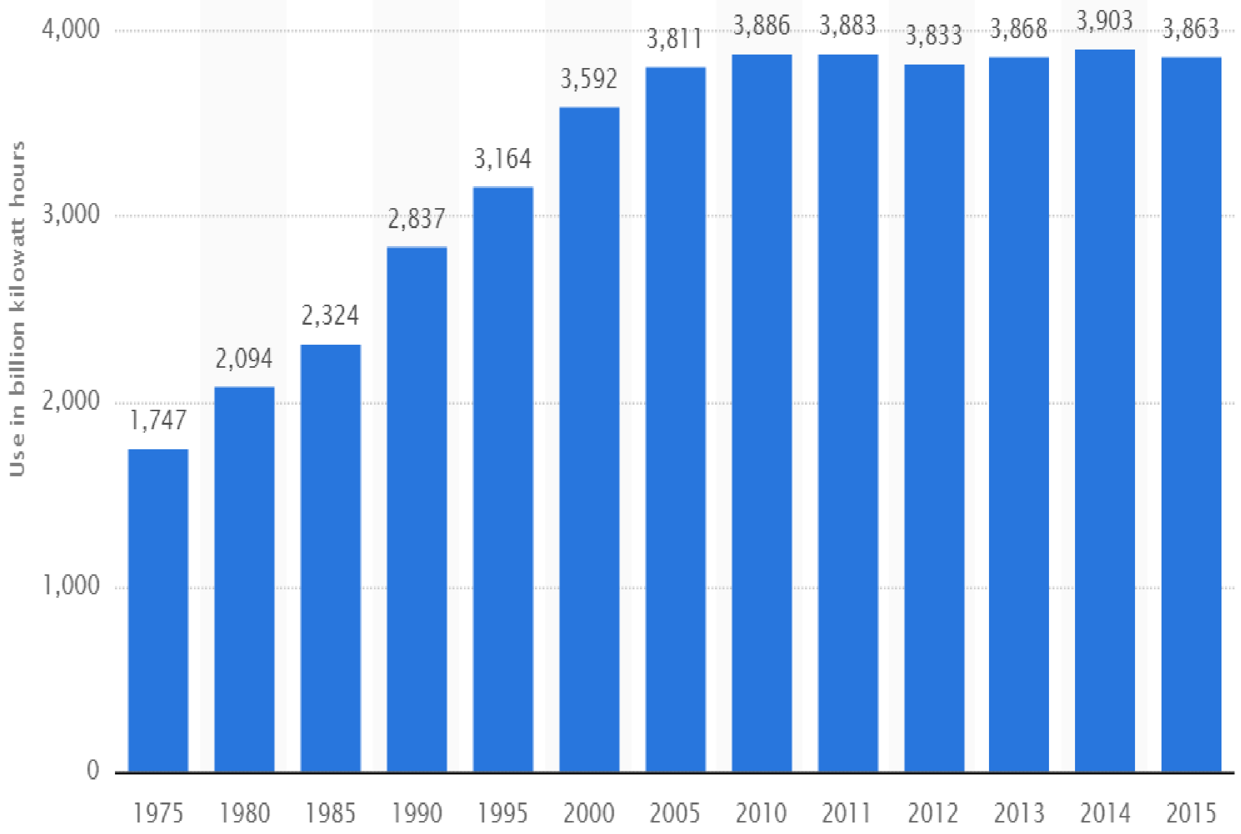
Electronics ~ 10-15% and decreasing

Heating ~ 8-15% may increase

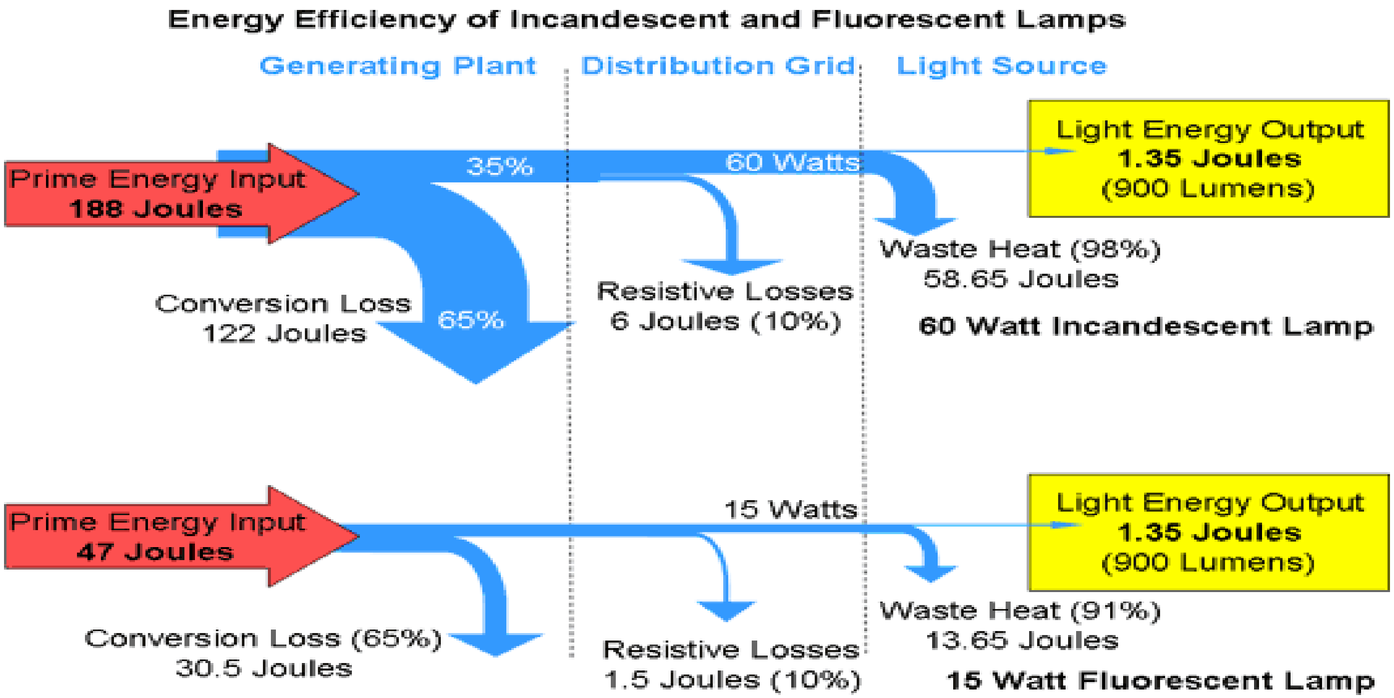
Other ~ 5-8%



U.S. Total Electrical Consumption by Year



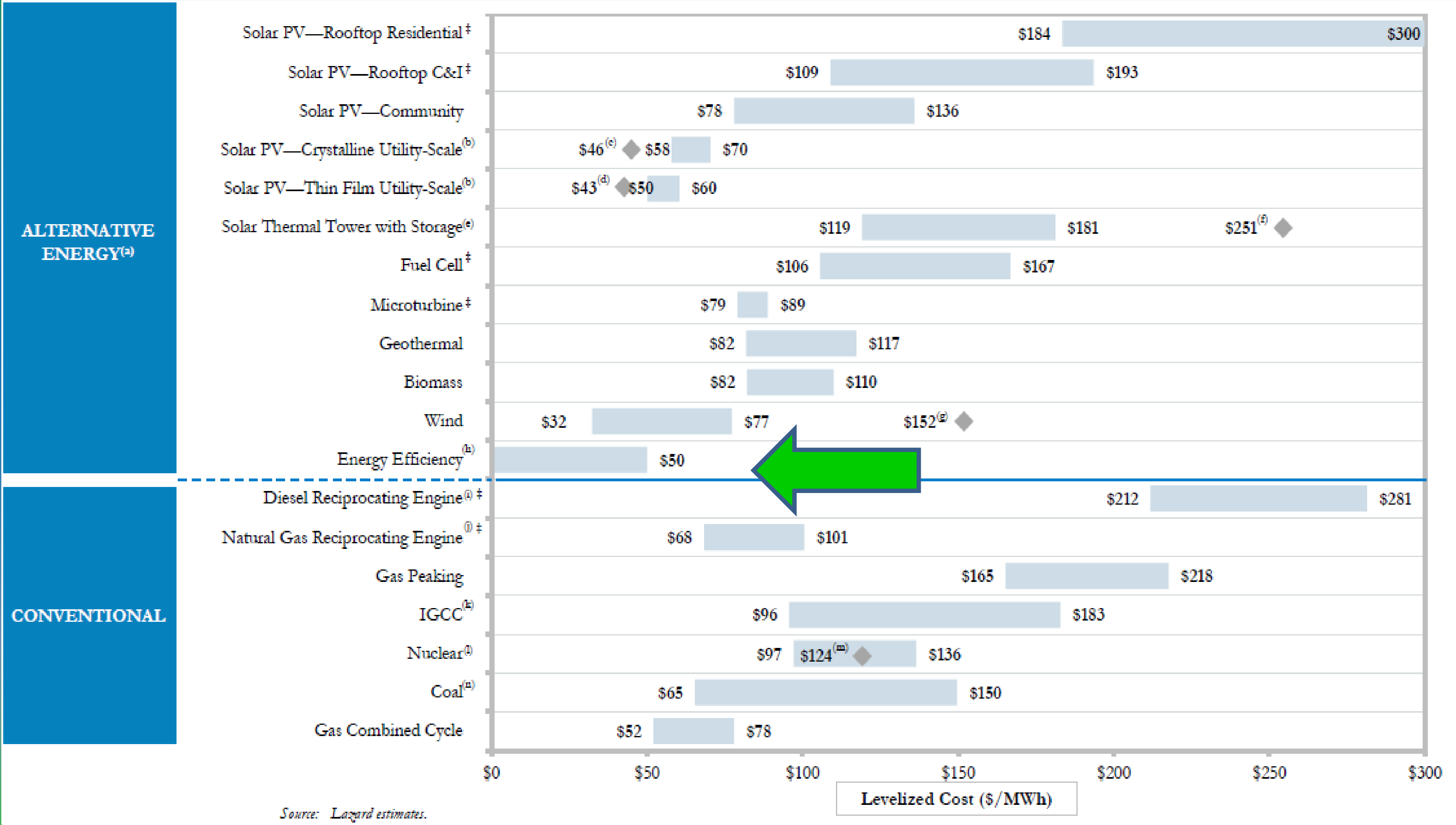
Extended Benefits of Energy Efficiency



32 Joules Input

9 to 10 Watts
with LED’ss

Energy Efficiency Cheaper than Generation



Changes Coming, Some May be Rapid

- **Electrification of Transportation**
  - Electric cars – required by some locations after 2025
  - Electric and hybrid trucks
- **Drones**
  - Delivery – Amazon testing now
  - Personal transportation
- **Electric Aircraft**
  - Auto-piloted delivery trucks
  - Short hop direct routes

How Changes may Affect Electric Use

- ~75% of U.S. Oil is Used for Transportation
  - Energy will now need to supplied by electric power
- Could Double Electricity Demand
  - Need for generation capacity
  - Need for electrical storage
    - Batteries – Fixed and Flow Cells
    - Flywheels
    - Compressed gas
    - Other ???
  - Need for higher efficiency – Tonight’s Focus

Magnetics: Key to Energy Conversion

- Soft Magnetic materials - Inductive Components
  - Transformers
  - Motors
  - Power supplies

- Hard Magnetic materials – Permanent Magnets
  - Motors

Paths to Higher Electrical Efficiency

- What are the Main Loss Sources
  - Ohmic and other losses in power lines
    - Reduce with HVDC transmission – requires magnetics
  - Losses in Inductive Components
    - Transformers
    - Motors
      - Fans and pumps
      - Mobility
    - Power supplies
      - Office equipment – computers, copiers, lighting
      - Chargers – connected and wireless
      - Lighting – LED and florescent



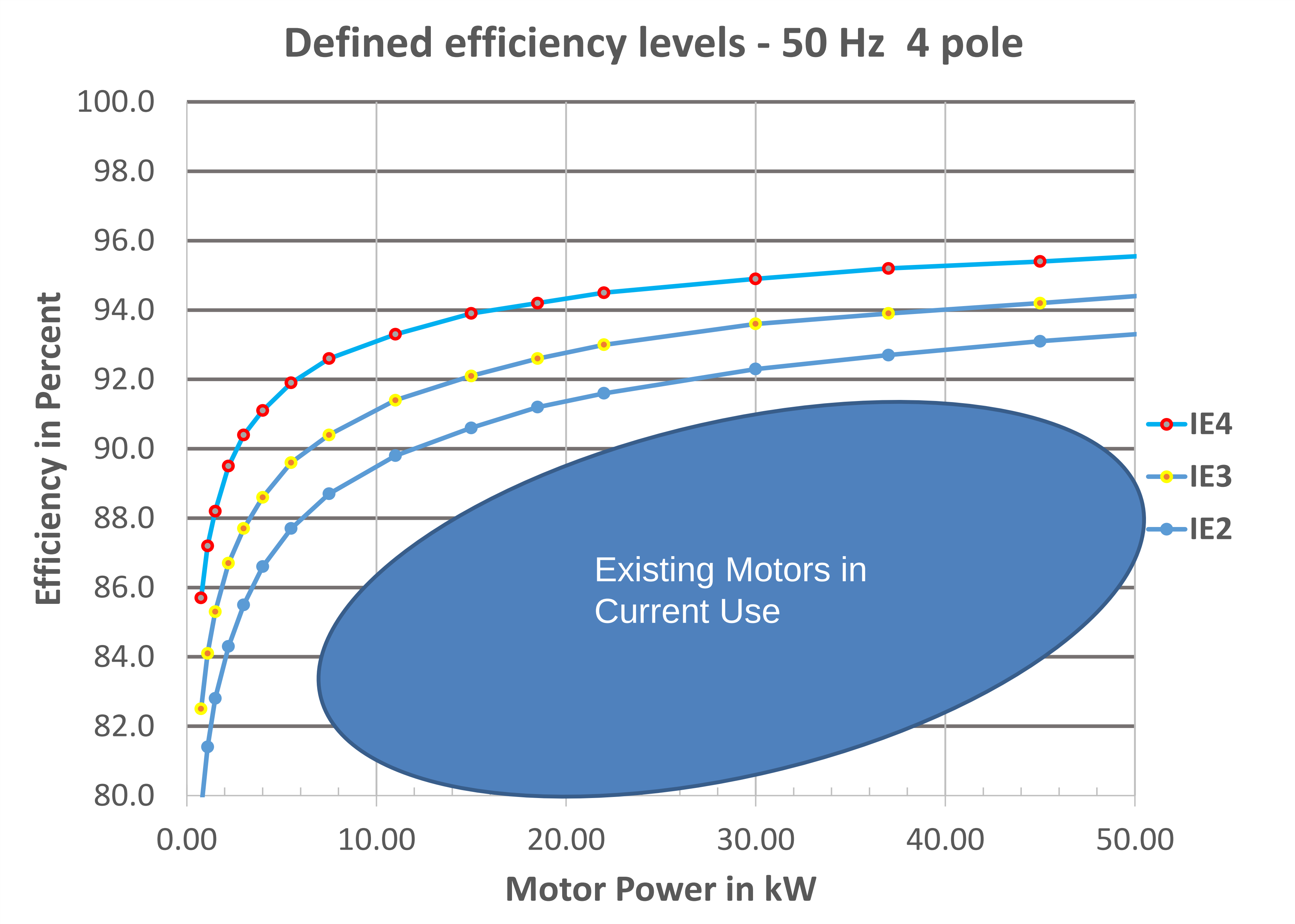
Aren't Motors Already Highly Efficient?

- Currently motors are over 90% efficient

- But a 1% improvement saves 125 Billion kilowatt-hours per year
- This is over 14 Gigawatts running continuously

- The cost of this improvement is less than building new generation plants

- There is room for improvement
  - 2-3% over best motors today
  - 10 to 15 or more over existing motor stock



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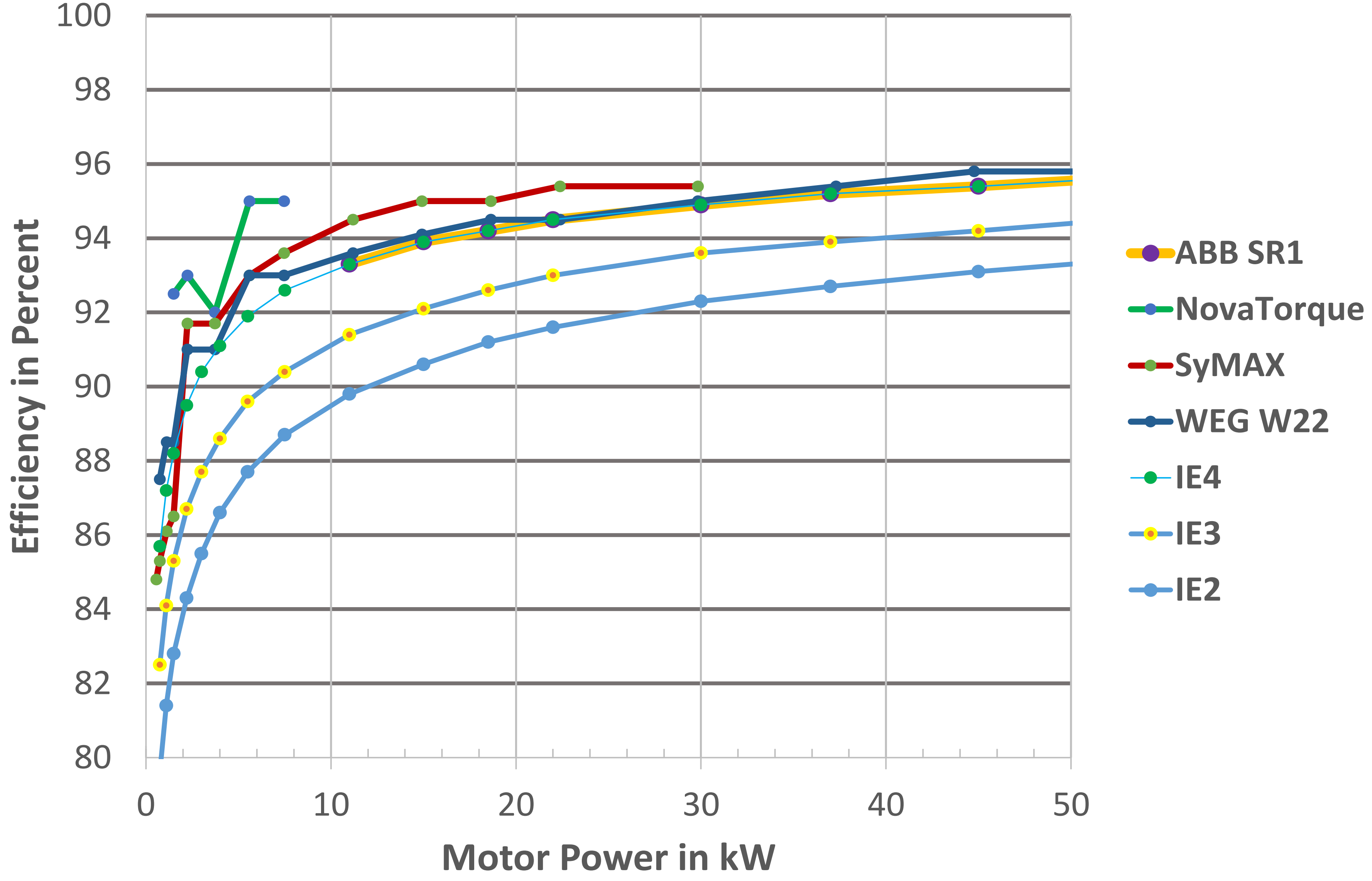
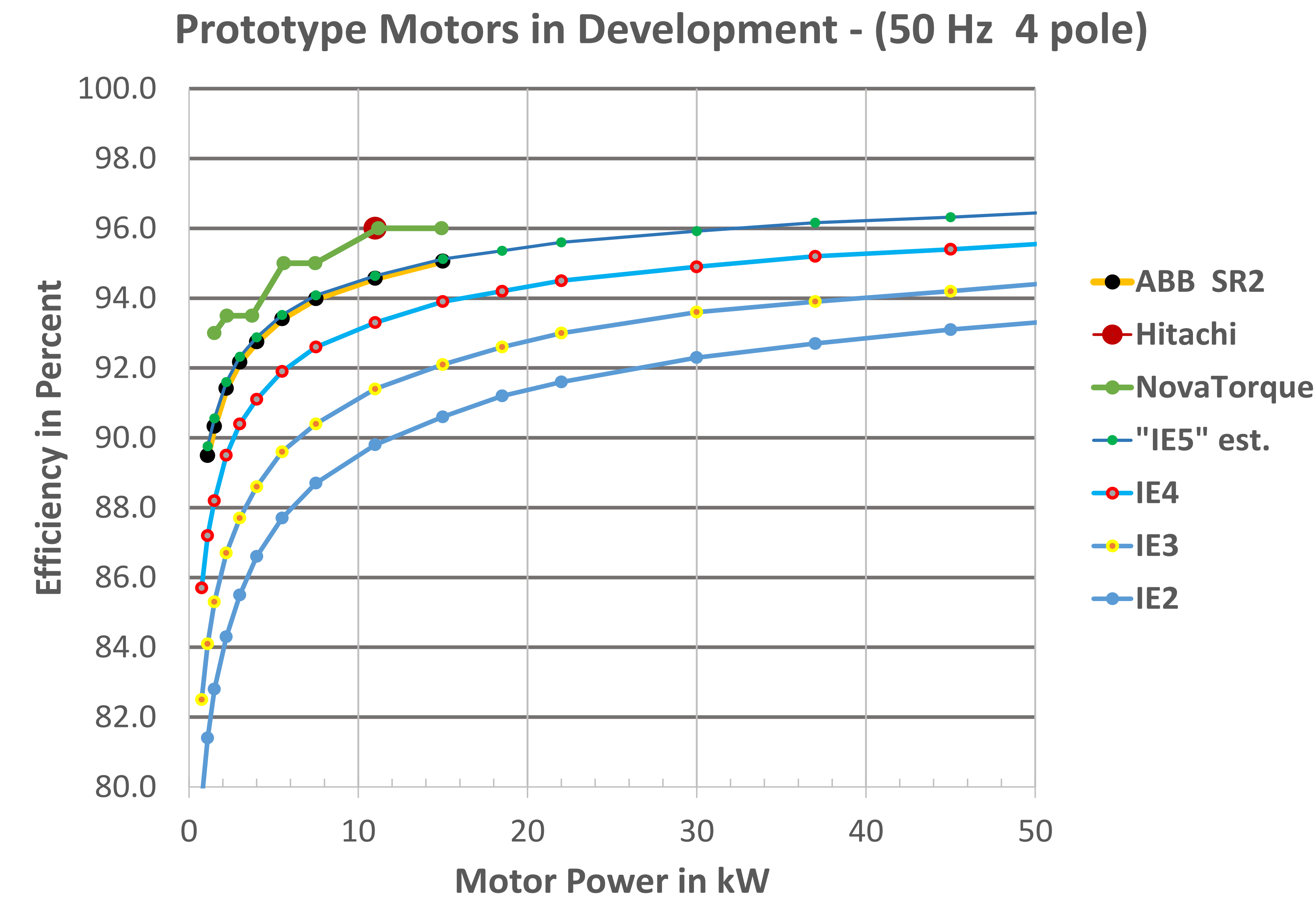
Available Motors Today - (50 Hz 4 pole)





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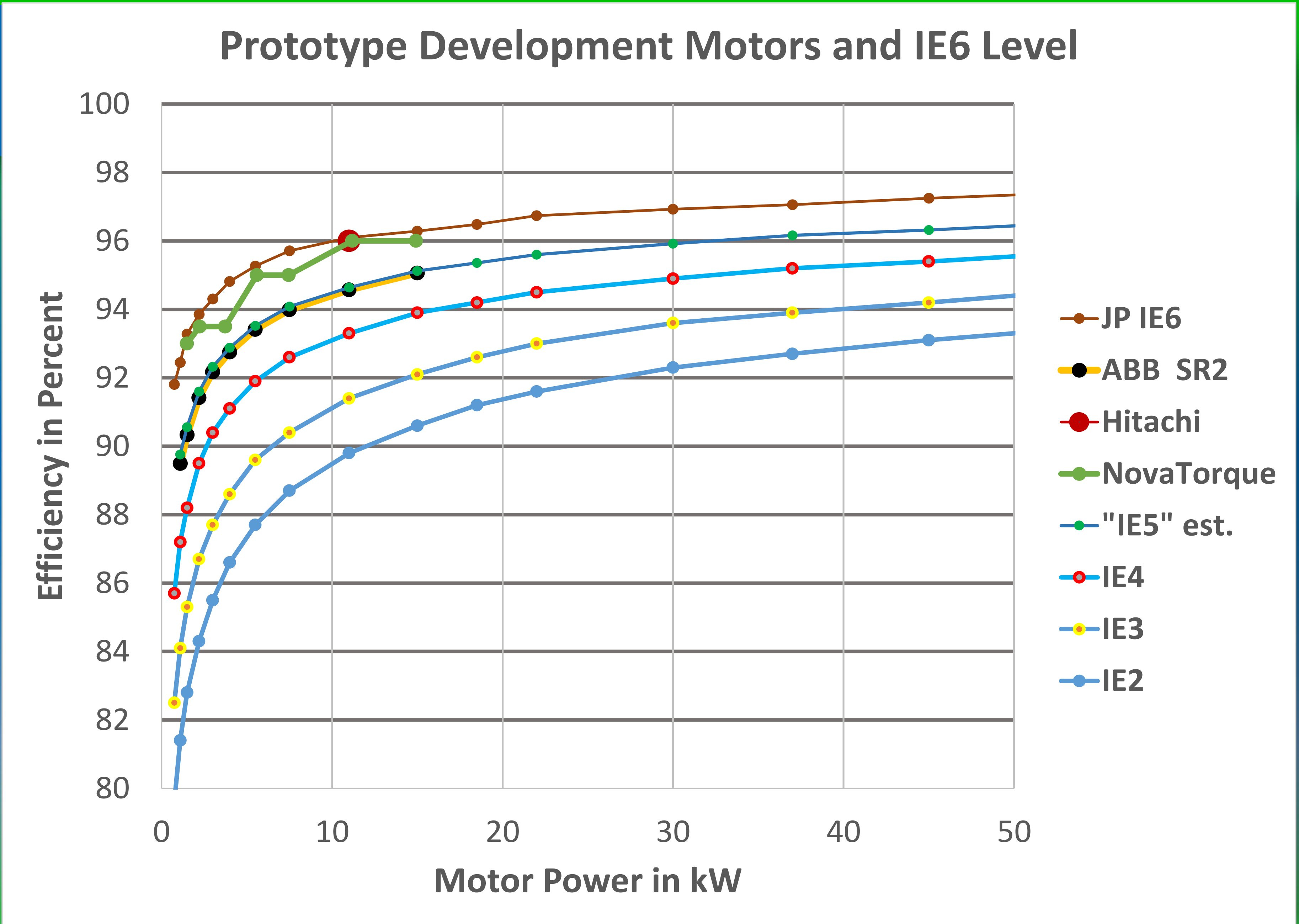
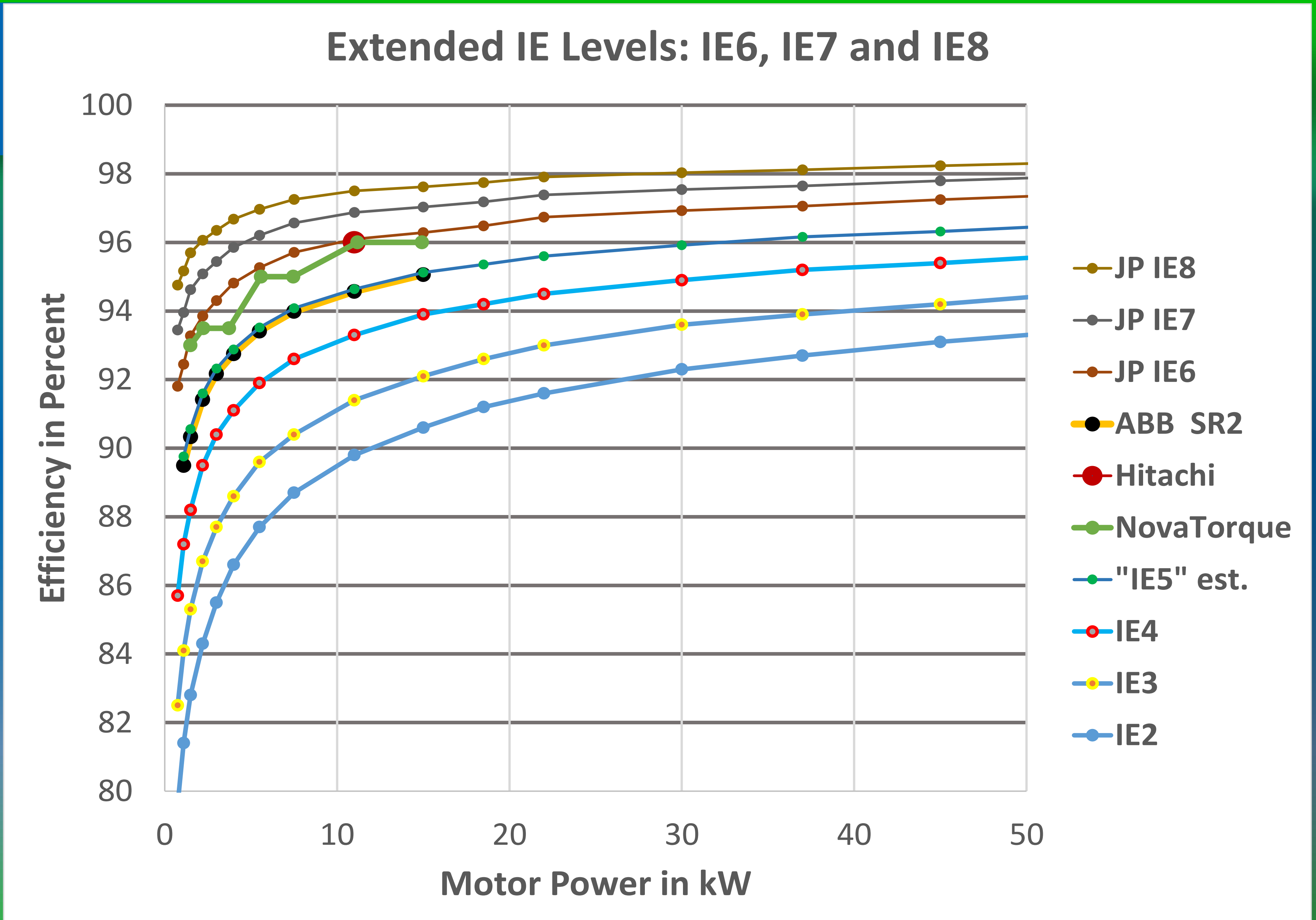

Prototype Development Motors and IE6 Level
Efficiency in Percent
100
98
96
94
92
90
88
86
84
82
80
0
10
20
30
40
50
Motor Power in kW
JP IE6
ABB SR2
Hitachi
NovaTorque
"IE5" est.
IE4
IE3
IE2



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Motor Innovation is Moving Fast

- While IE3 levels are just starting to be required,
- IE4 and even IE5 motors are already available
- Motors beyond IE5 are in development
- Cost reduction of these motors is the ultimate goal

- Result is:

<u>Technological improvements are leading policy initiatives</u>

BUT --- Adoption is NOT very fast

- Higher efficiency motor cost more initially to purchase
- Motors have a long lifetime
- Production does not want to replace working machines
- Life cycle costs are not taken into consideration
- Motor installer often does not pay electricity bill
- Accounting wants quick payback (1 to 3 years)
- Motor industry resistant to change

- This means: Cost reduction of efficient motors needs to be the goal

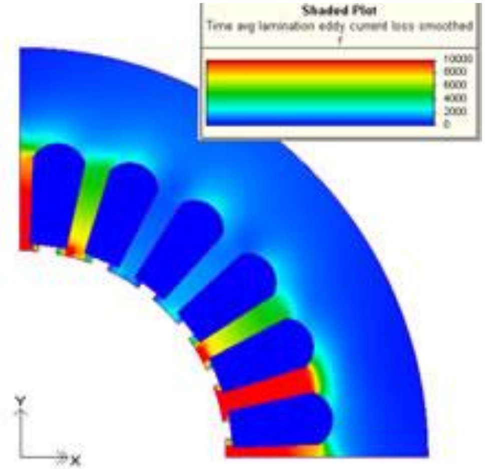
Approach to Making More Efficient Motors

- Use lower loss materials in cost effective manner
- Better windings design – less wasted copper
  - Better conductor fill
  - Concentrated winding designs
  - Segmented core windings
  - Hair pin windings

- Reduce rotor loss - copper rotor induction motors
- Optimized with FEA analysis
- Higher quality lamination steels available

Iron Losses Limit Higher Motor Efficiency

- As improvements have been made in
  - Reducing rotor loss
  - Copper loss has been reduced with better windings
- This leaves iron loss as the largest unaddressed area
- Iron losses include both
  - Hysteresis loss
  - Eddy current losses

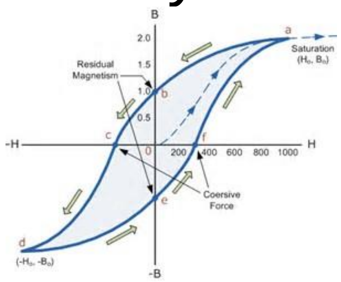


As motor efficiency has increased,

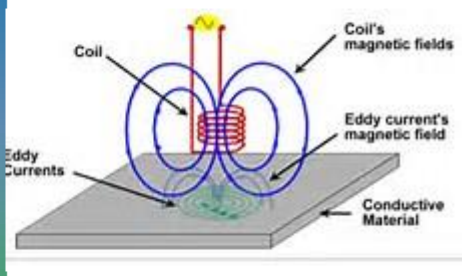
Iron losses take on a dominant role

Magnetic Material Losses

- What are the Main Loss Sources
  - Hysteresis: All magnetically permeable materials



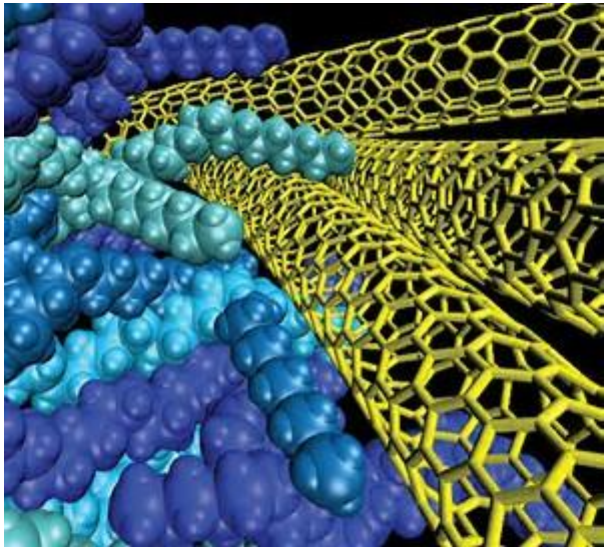
    - Magnitude of change in flux level to a power
    - Frequency
    - Material characteristic
  - Eddy currents: All conductive materials

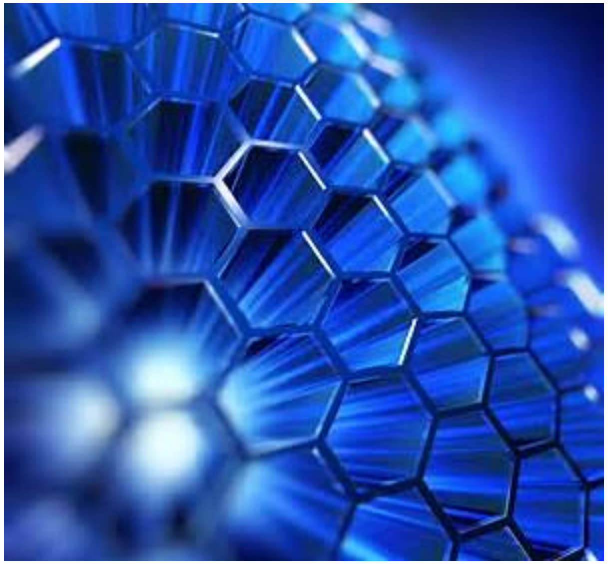


    - Magnitude of change in flux level
    - Frequency squared
    - Material resistivity
    - Material volume where current flows

Need for Better Soft Magnetic Materials

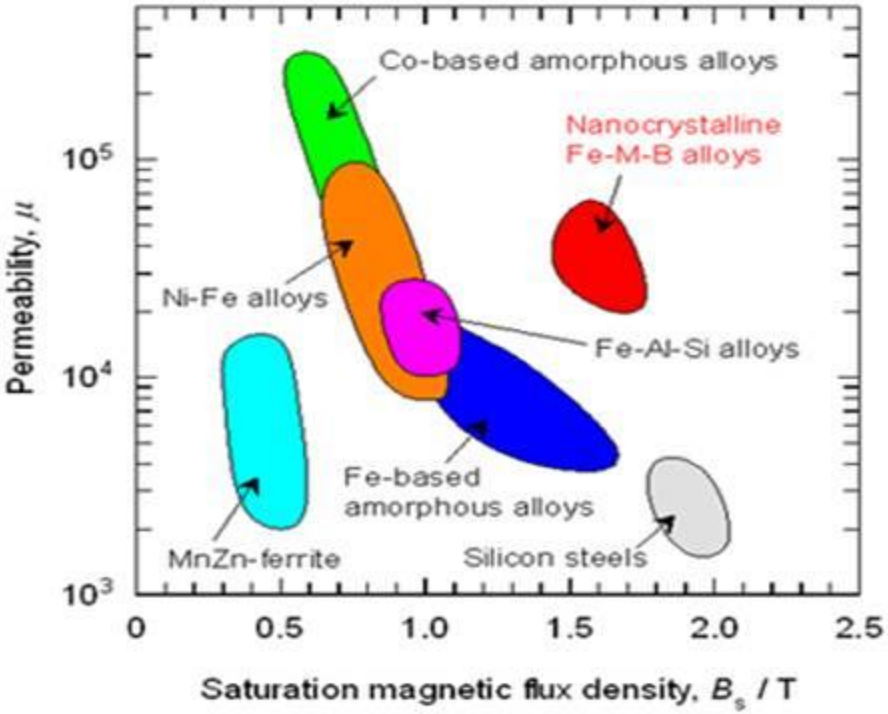
- What are Ideal Material Properties
  - Very small hysteresis loop
  - Square loop characteristic
  - High resistivity – non-conducting is ideal
  - Easy to fabricate – thin laminations
  - Low cost!!





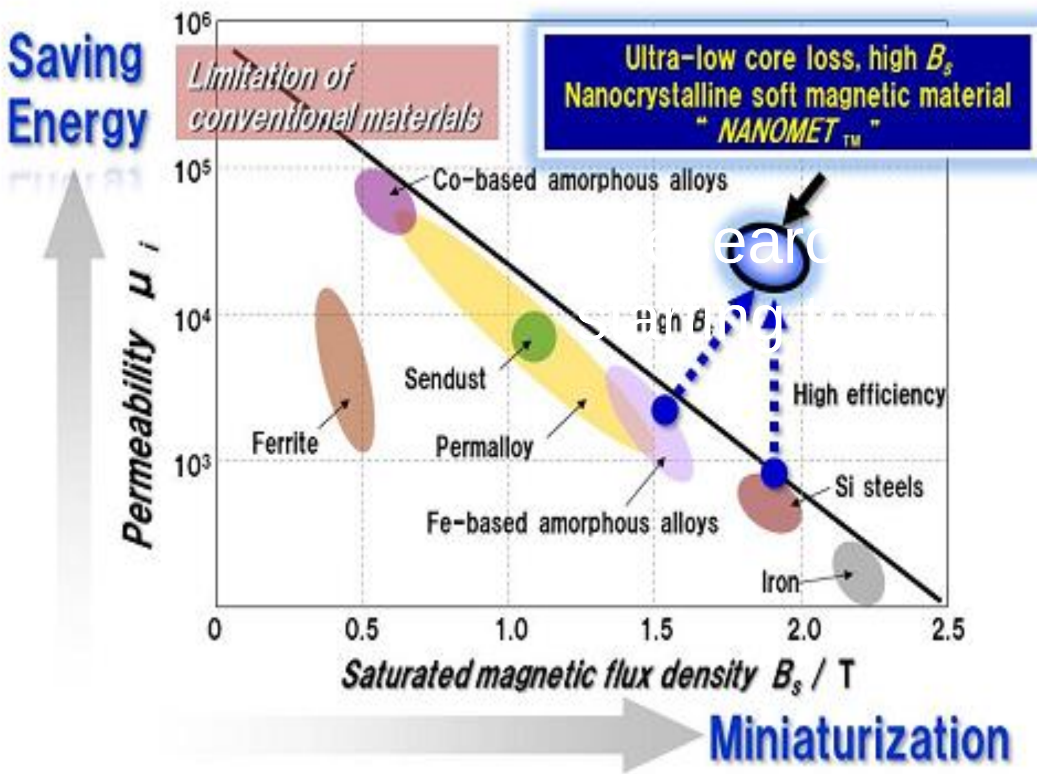
Options for Reducing Iron Losses

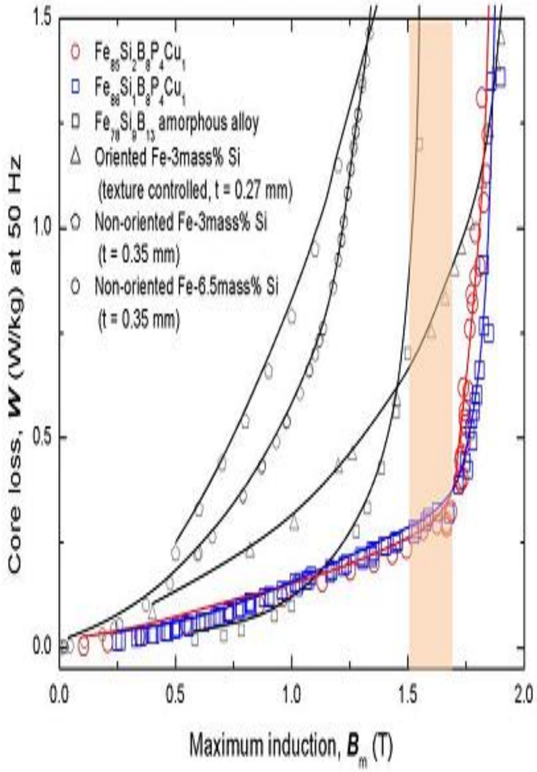
- Thinner laminations
- Laser processing and annealing
- Higher resistivity
  - Higher silicon content
  - Other alloying elements
  - Soft magnetic composites
- Lower loss materials
  - Nickel Irons
  - Cobalt Irons
  - Amorphous iron-based materials
  - Nanocrystaline materials
  - Iron nitride (FeN)



Soft Magnetic Material Improvements

Better materials are under development





Graphics from Japanese Publication – A. Makino

Advanced Soft Magnetic Material in Motors

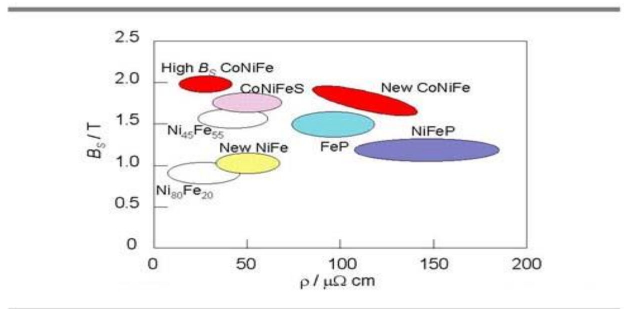
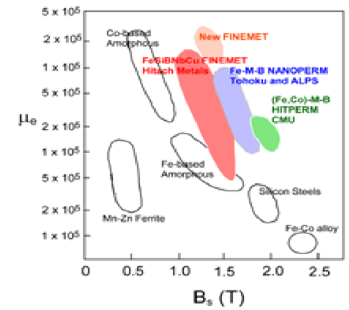


Fig.1 Soft magnetic materials with high *Bs* and high *ρ* mainly developed by waseda group.

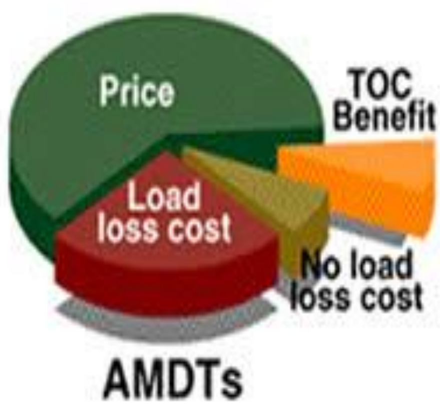


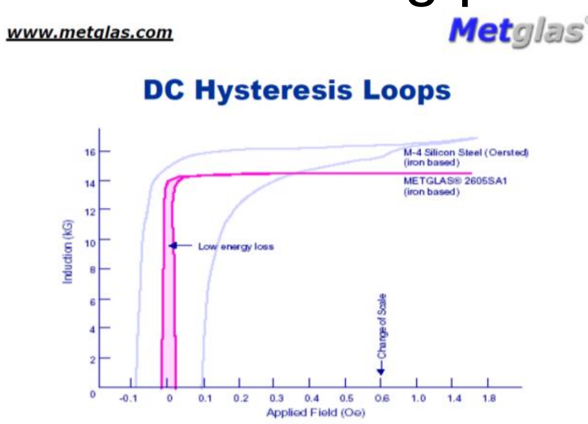
Alloy name	Typical composition	Primary phase	Bs(T)	Tc(° C)
FINEMET	$Fe_{73.5}Si_{13.5}B_{9}Nb_{3}Cu_{1}$	FeSi(D03)	1.0 - 1.2	<770
FINEMET2	$Fe_{76.9}Si_{11}B_{9}Nb_{2.5}Cu_{0.6}$	FeSi(D03)	1.45	<770
NANOPERM	$Fe_{88}Zr_{7}B_{4}Cu_{1}$	α-Fe	1.5 - 1.8	770
HITPERM	$Fe_{44}Co_{44}Zr_{7}B_{4}Cu_{1}$	α'-FeCo(B2)	1.6-2.1	>965

- Next big increase in motor efficiency will come from using amorphous and nanocrystalline materials
- Motors with these materials are being developed
- New manufacturing methods are being attempted
- Commercial introduction is just starting, but will accelerate
- Initially will address smaller motors (less than 10 kW)

Why Choose Amorphous for Motors?

- Already in volume production and use
- Proven in power transformers to reduce core loss
- Reasonable cost for the material
- Extremely low hysteresis loss
- Very thin laminations – low eddy current loss
- Insulation layer created as part of manufacturing process





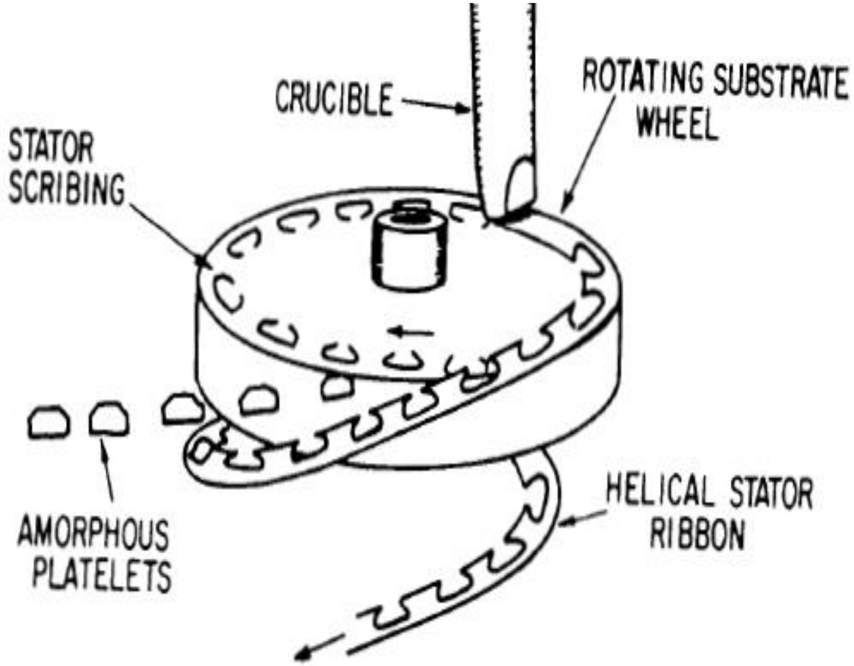
Issues with Amorphous Materials for Motors

- Material is only produced in thin strip material - 25 micron
- Very high hardness
- Difficult to stamp and assemble stacks
- Insulation layer is thin, less than 1 micron
- Typical maximum flux density of 1.6 Tesla
- Cut edges are not insulated
- Difficult to get superior packing factors

- Result is that it is difficult to construct motor components from amorphous material

Manufacturing Techniques for Amorphous

- GE worked on continuous casting technique in late 1980s
- Cast a continuous ribbon with pole shoes
- Assembled motor stator with helical winding



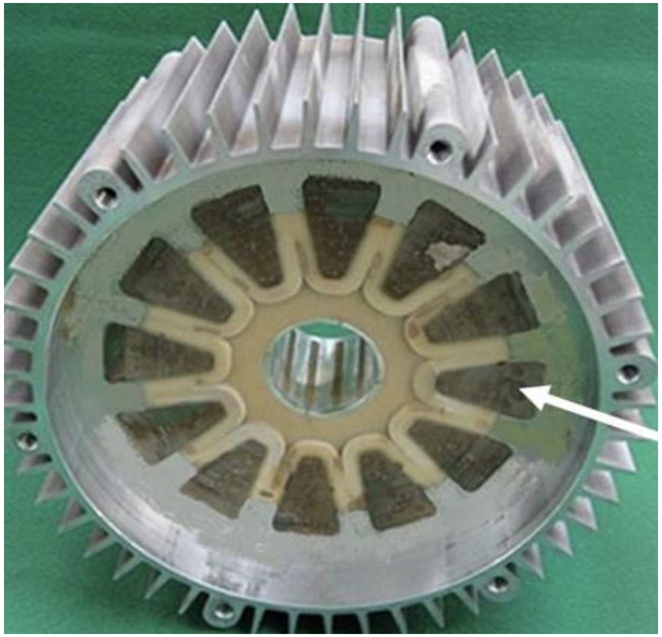
Manufacturing Techniques for Amorphous

- Adelaide Group produced stators with water jet cutting
- Wind conical shape from stock ribbon
- Cut slots with water jet cutters
- Can make stators with pole shoes and other shapes

a b

Manufacturing Techniques for Amorphous

- Hitachi has not revealed production method
- Early prototypes show cut and stacked field poles
- Poles assembled and potted into stator structure



Manufacturing Techniques for Amorphous

- RADAM has worked on segmented core radial motors
- Cut and stack individual pieces
- Wind coil on individual pole shoes
- Assemble stacks into radial stator

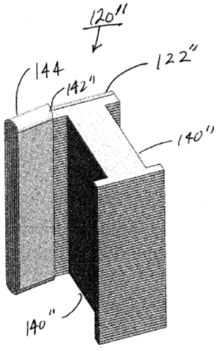
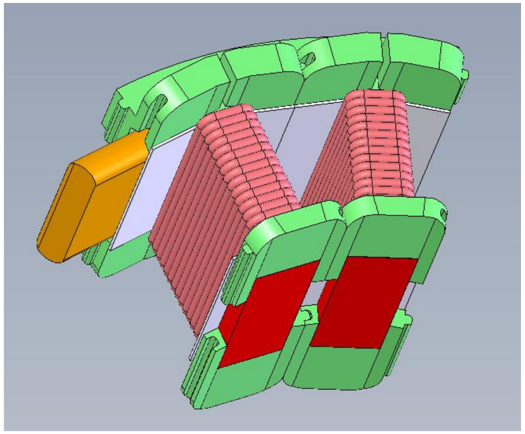


Fig 19



Manufacturing Motors with Amorphous

- Many techniques have been attempted for both radial and axial motors
  - Traditional stamping – radial motors
  - Cut individual pieces and then stacking – axial motors
    - Mechanical cutting
    - Chemical etching
  - Wrap structure and then cut slots – axial motors
    - Water jet cutting
    - Laser cutting
  - Segmented core radial motor configurations – radial motors
  - Continuous wrap while cutting slots – axial motors
  - Cast stator shape directly with helical wind – radial motor
- Unfortunately, none have been commercially successful

Attempts at Commercial Sales

- Light Engineering (now owned by XEMC)
  - Sales throughout the 1990's and 2000's
  - Product still listed as available, but few details
  - Investigated for automotive traction motors
- Hitachi
  - Has 11 kW motor developed, using for internal products
- RADAM
  - Developed techniques for making radial motors and built prototypes
- Adelaide Group
  - Built numerous prototypes and preparing production version
  - Initial market motor in 1 kW range

Low Cost Approach to Make Efficient Motors

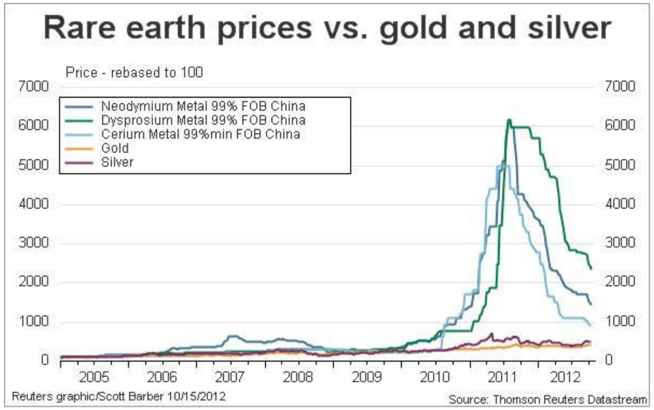
- Another approach is though design changes
- >90 percent of motors in industrial use are induction motors
- New designs have started to gain traction
  - Permanent magnet motors (surface magnets and interior magnets)
  - Synchronous reluctance motors (with PM assist)
  - Switched reluctance motors
  - Transverse flux designs (PM design)
  - Axial designs and outer rotor radial designs
- All of these currently require drive electronics which puts them at a disadvantage compared to induction motors
- New approach for direct-on-line operation are coming

Low & High Speed Applications are Expanding

- Industry is still very focused on 1800 rpm (induction)
- Motors are being used at both lower and higher speeds
- Many processes are more efficient at lower speeds
- Air handling fan speeds of 500 to 900 rpm are desirable
- At these speeds, direct drive PM motors are fantastic
  - **5 to 25** percent efficiency improvement
  - Lighter weight **75 kg** versus 120 kg
  - Smaller package **210 frame** versus 250 frame
  - Reduced VA requirements allows smaller VFD
  - Elimination of gearing and belt speed reducers

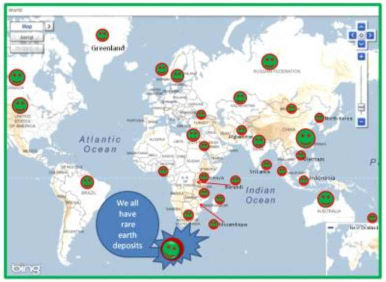
Current Permanent Magnet Status

- Magnet Choices
  - Ferrite – Low cost, Low energy product (MGO)
  - Neodymium Iron Boron – High cost, High MGO
  - Samarium Cobalt – Highest cost, Medium MGO
  - Samarium Iron Nitride – Medium cost, fair MGO
  - Alnico – Not used anymore
- Need for better cost / performance ratio
- Significant research due to price spike in Neo

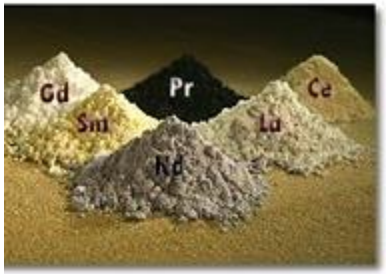


Recent Permanent Magnet Progress

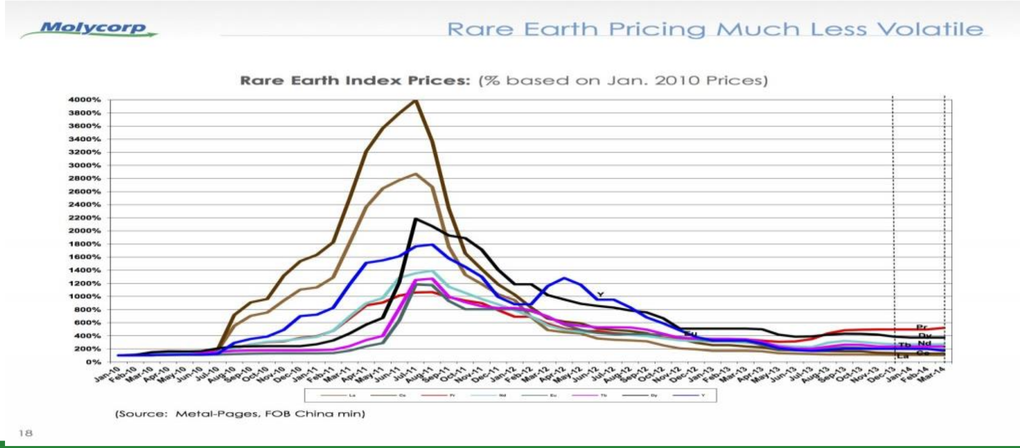
- Major diversification of rare earth sources
  - US, Australia and Canada are opening mines
  - Projects in Brazil, India, Russia and others



- Magnet production still concentrated in China
  - China more aware of possibility of spoiling the market



- Rare earth pricing spike has subsided



Future Permanent Magnet Improvements

- Research projects on Permanent Magnets
  - Japan – MagHEM, ESICMM
  - US – REACT, Strategic and Critical Material Program
  - Europe – REFREEPERMAG, NANOPYME, MAG-DRIVE, ROMEO, PerEMot
  - China, Russia, India, Brazil and others involved too
- Ongoing research on many possible PM alternatives
  - Cobalt compounds produced with wet chemical process
  - MnBi, MnAl, MnFe, and others
  - Exchange Spring mechanisms
  - $Fe_{16}N_2$
  - And others

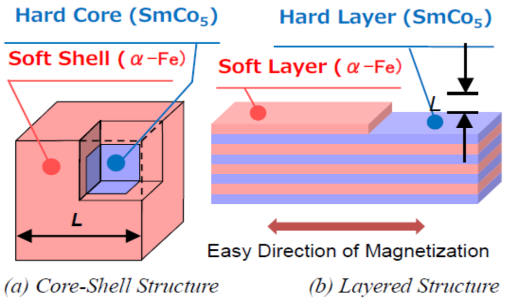
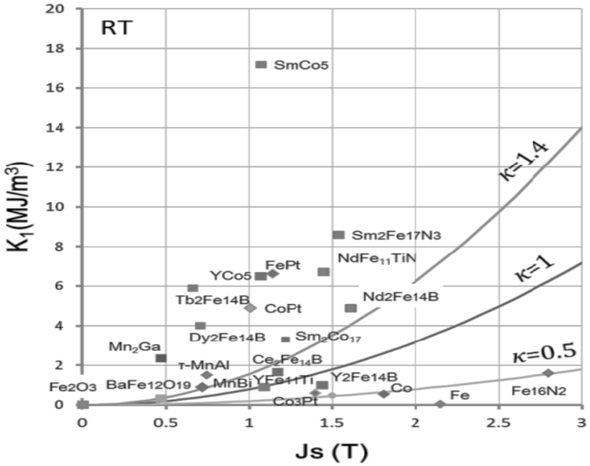


Fig.1 Simulation Models.



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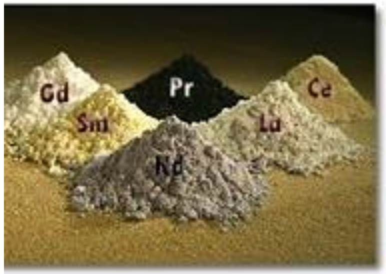
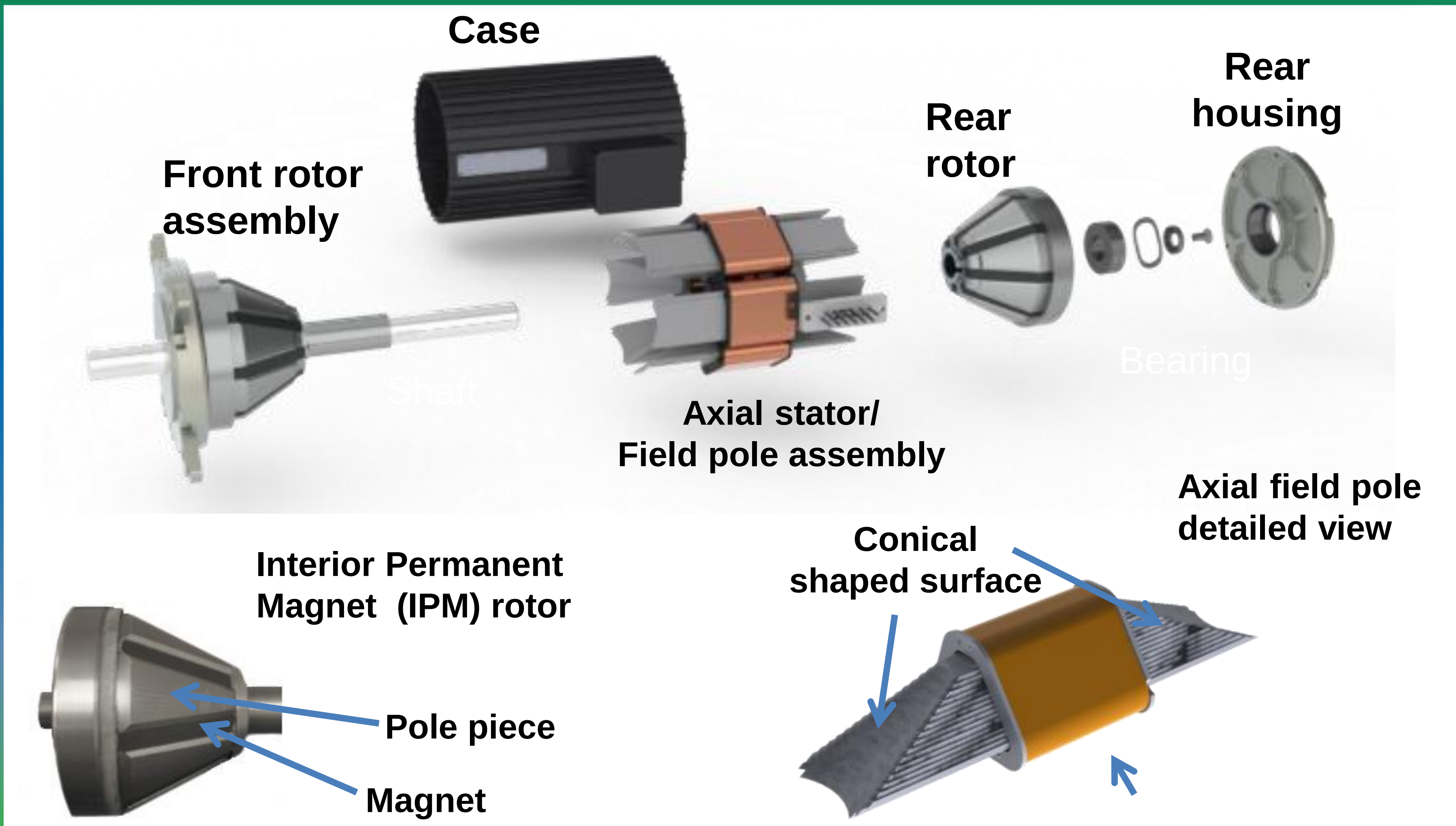
Recent Permanent Magnet Progress

- Magnet research programs starting to deliver
  - Low dysprosium rare earth magnets are in use
    - Grain boundary enhancement techniques
  - Dysprosium-free rare earth magnets on horizon
  - Anisotropic bonded magnets are improving
    - MagFine products to 21 MGO as processing improves
  - More use of SmFeN and Cobalt compounds
  - Improved ferrite magnets - grade 15 and higher



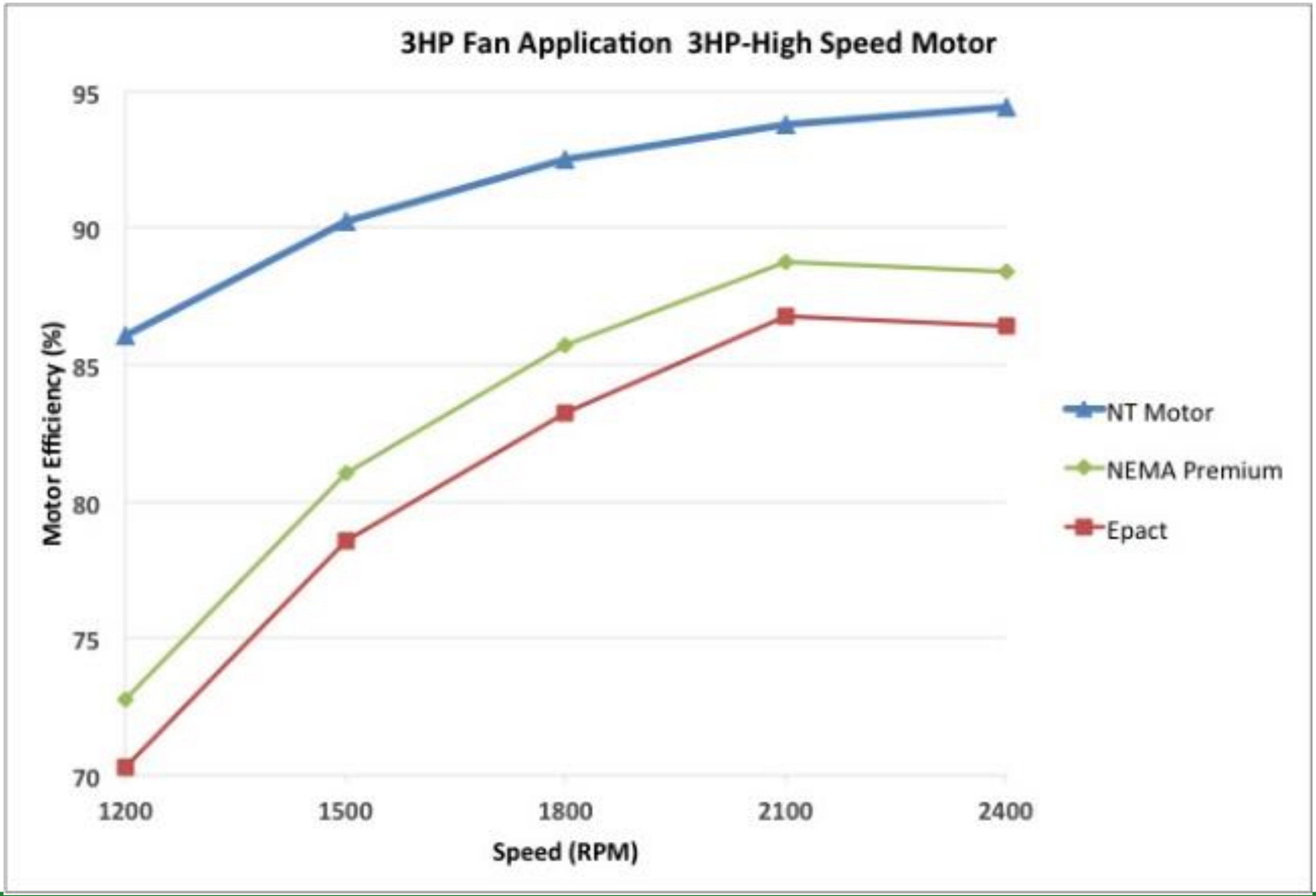
- Ongoing research on many possible PM alternatives

NovaTorque Axial Motor with Conical Air Gap



Completed Motor

PM Motor Efficiency versus Speed

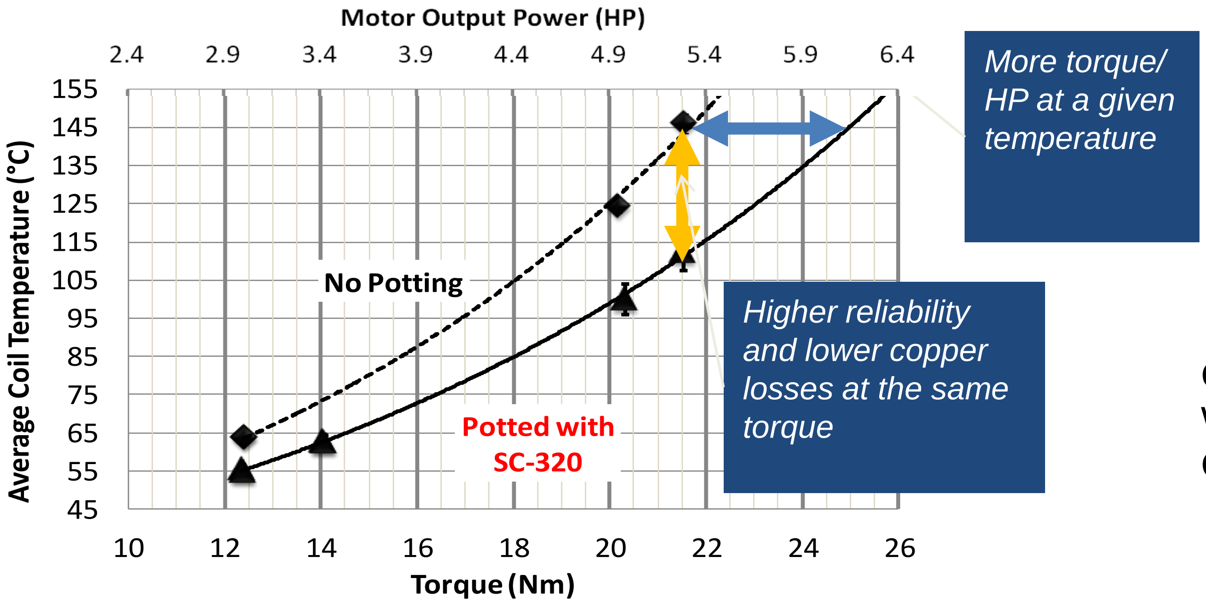


Other Improvements Are in Development

- Better motor thermal design and materials
- Superior variable speed drives
- Enhanced bearings and lubrications
- Magnetic gearing

Thermal Design and Materials

- Thermal design considerations are now a high priority
  - Better design leads to cooler, more efficient motors
- Thermal materials are improving
  - High thermal conductivity potting compounds
  - Potting improves motor performance

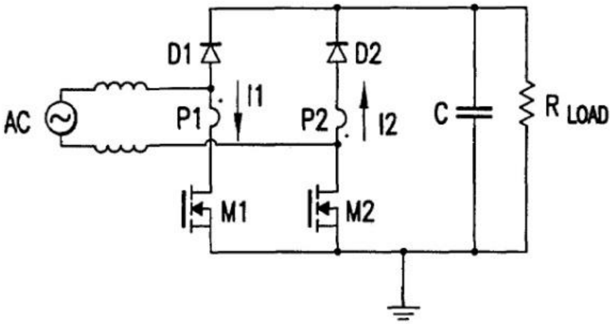


Graphic from IEEE Webinar by LORD Corporation

Motor Drive Improvements

- Components for drives improving
  - Power semiconductors
  - Passive components – inductors and capacitors
  - Control components and software algorithms

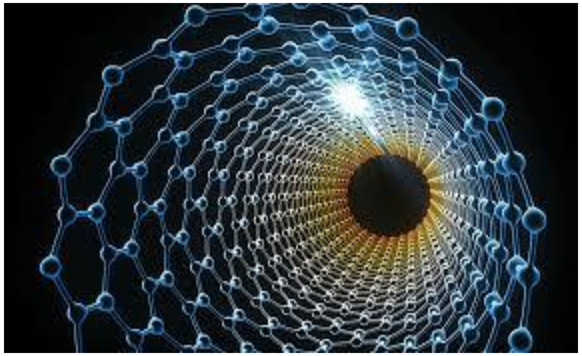
- Improved designs
  - Bridgeless input stages
  - Power factor correction
  - Improved control schemes



- Costs will decrease
  - Component volume increasing with automotive and solar usage
  - Standard semiconductor cost reduction over time

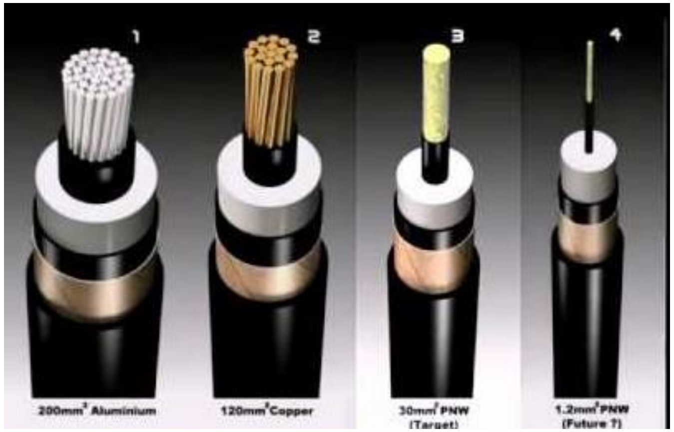
Other Motor Material Improvements

- Conductors
  - Improved shapes –rectangular
  - Better insulations – thin, high temp
  - Aluminum foils – low cost bobbin wind
  - Carbon nanotube wire



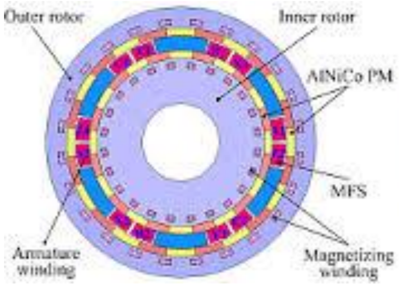
- Bearings
  - Ceramic bearings
  - Better lubrications

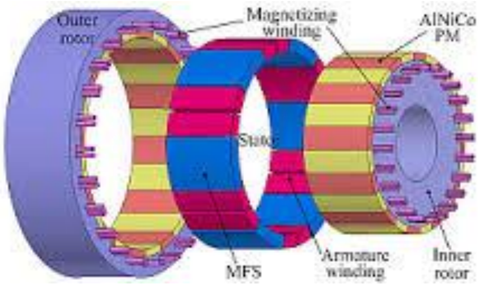
- Casing Materials
  - Higher thermal conductivity potting
  - Better motor thermal designs



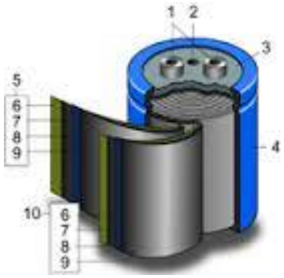
Other Improvements

- Magnetic gearing
  - Very low loss
  - Excellent ratios
  - Integrated into motor
  - Overload and impact load tolerant





- Super capacitors
  - Graphene super capacitor at 60 WHr/L in lab
  - Enables storage and capacitive coupled designs



Conclusions

- Improvements in magnetic materials will help improve electrical energy efficiency
- Better soft magnetic materials help in many applications
- Better magnets would help with improved motors
- The key is to improve magnetic performance per dollar of material application cost

Path Forward

- 98% efficient motors and drives can be built today, but the marketplace does not accept the added cost
- It is not possible to predict when new cost reduced efficient materials will be available in the marketplace
- Focus for now is how to reduce the cost of higher efficiency motors without new materials
- New motor designs offer possible path forward

The End

Thank you !!!

Questions?

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