Nanocomposite Magnet Technology for High Frequency MegaWatt Scale Power Converters

ARPA-E: Solar ADEPT Workshop
Electric Power Industry Conference
November 13th, 2012– Pittsburgh, Pennsylvania

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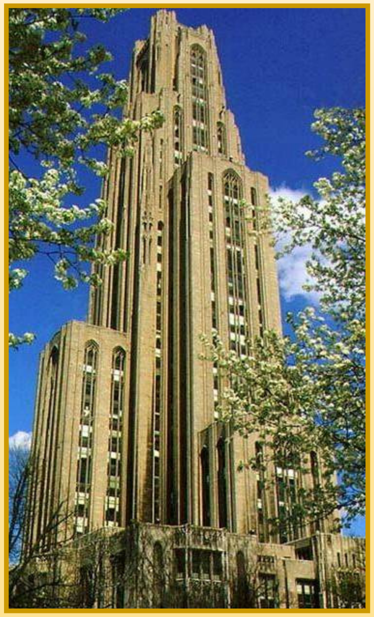
Graduate Student Researchers



Outline of Discussion

(1) Project Overview

(2) High Frequency Magnetics and Scaling

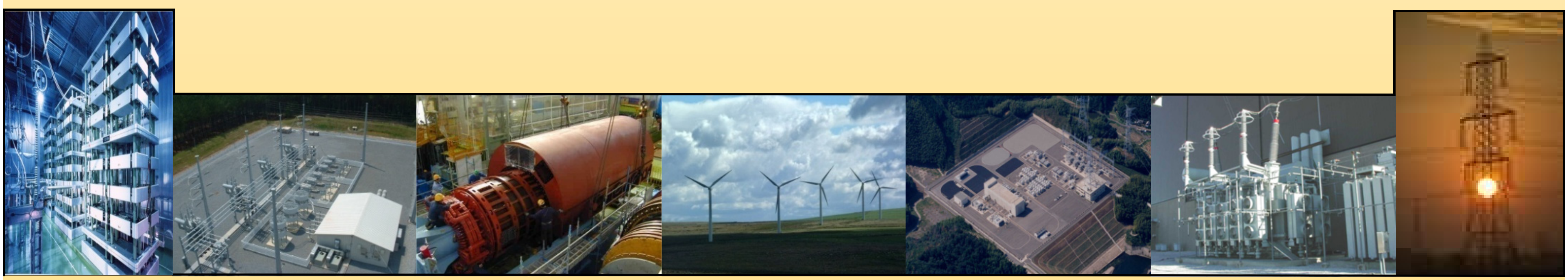
(3) General Pricing Guidelines for Utility Scale Photovoltaic Systems

(4) Future Development Needs to meet SunShot Target

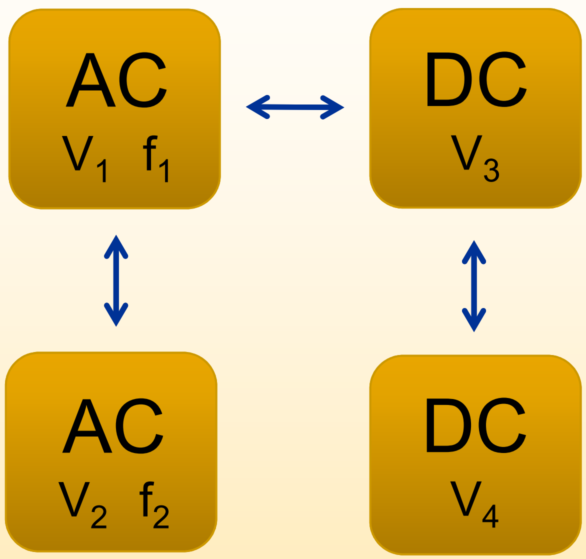
(5) Contributions and Impacts of this ARPA-E Program on DOE Targets

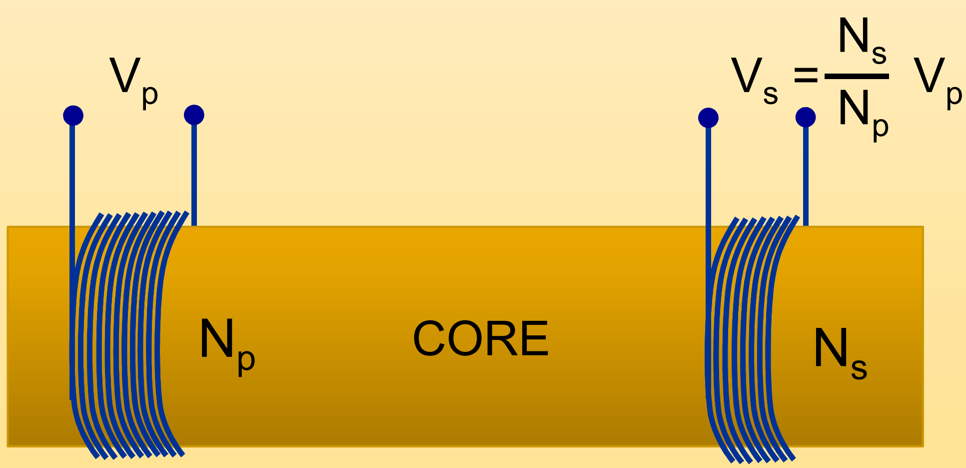
(6) Technology to Market Plan

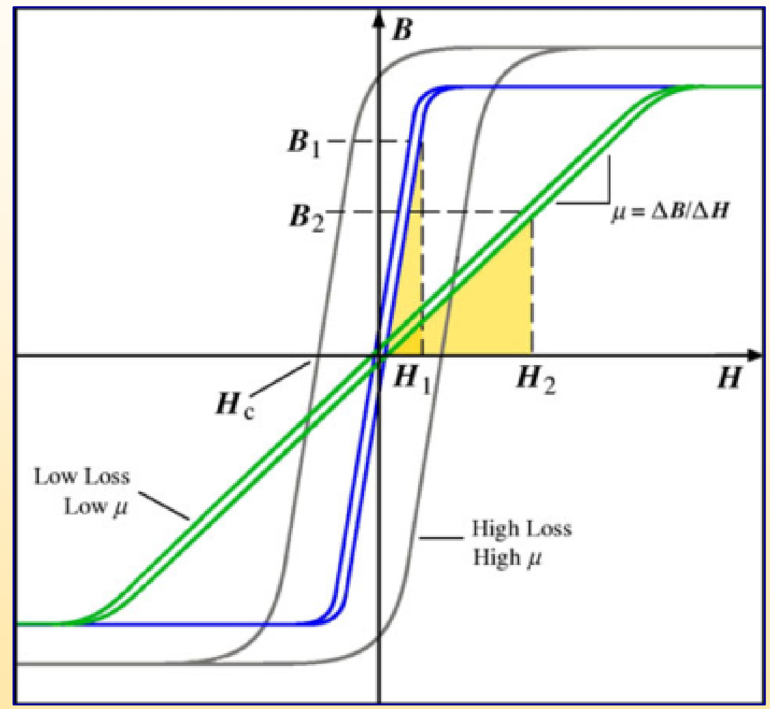
Project Overview



Magnetics in Power Conversion

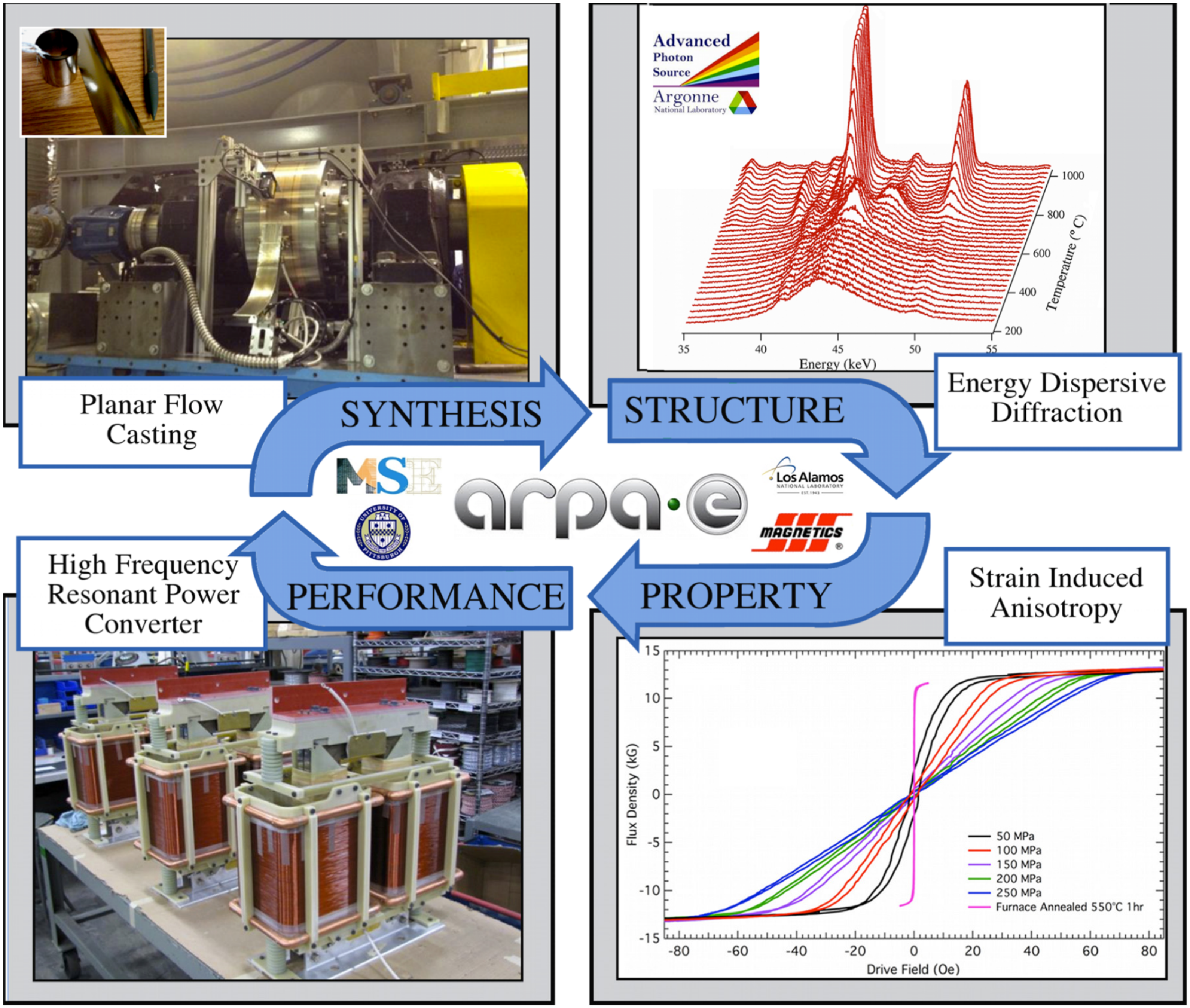






H = Magnetic Field

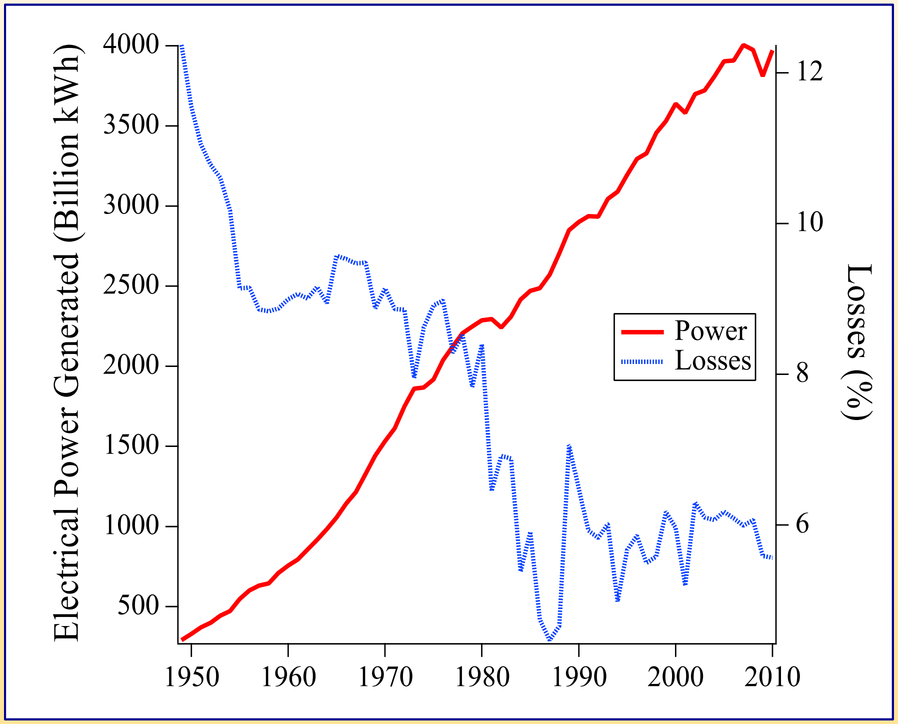
$B = \mu_0(H + M)$ = Induction


Planar Flow Casting
SYNTHESIS
Advanced Photon Source
Argonne National Laboratory
35
40
45
50
55
Energy (keV)
200
400
600
800
1000
Temperature (°C)
STRUCTURE
Energy Dispersive Diffraction
MSE
arpa·e
Los Alamos NATIONAL LABORATORY
MAGNETICS
High Frequency Resonant Power Converter
PERFORMANCE
PROPERTY
Strain Induced Anisotropy
Flux Density (kG)
15
10
5
0
-5
-10
-15
-80
-60
-40
-20
0
20
40
60
80
Drive Field (Oe)
50 MPa
100 MPa
150 MPa
200 MPa
250 MPa
Furnace Annealed 550°C 1hr

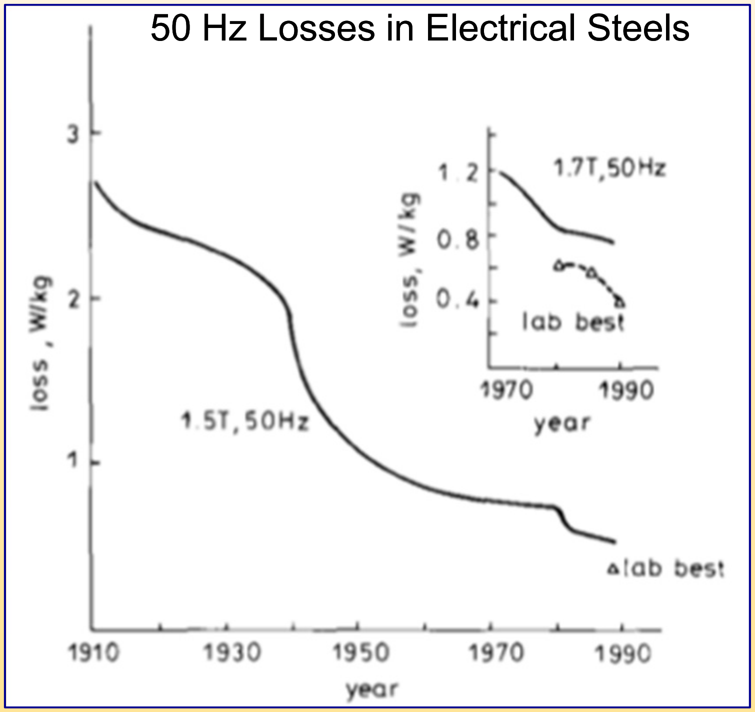
Project Goals

Goal: Develop medium voltage DC-DC power converter

- Power > 100 kW, Efficiency > 99%, mass < 25 kg
- Must be cost competitive with current technology

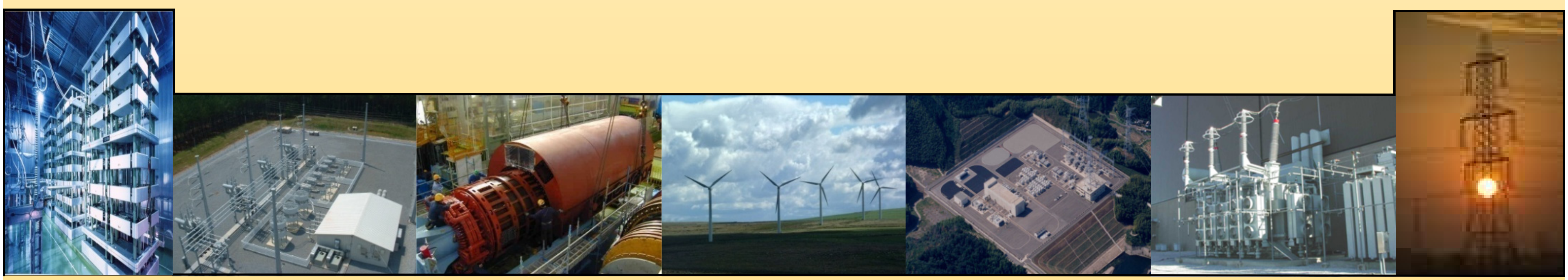


Data from DOE



A.J. Moses, Electrical steels: past, present and future developments, 1990

High Frequency Magnetics and Scaling



Magnetic Materials

	10 W	1000 W	100 kW	10 MW
50 kHz	N/A	Now: ferrites, amorphous	Now amorphous, ferrite, nanocomposite	Future: existing and new materials
500 kHz	Now: ferrite	Now: ferrite Future: new materials	Future: new materials	
5 MHz	Now: thin films	Future: new materials		
50 MHz	Future: thin film and air core			

ARPA-E Power Technologies Workshop (2010)

Si Steel

High B_s
Frequency limited

Ferrite

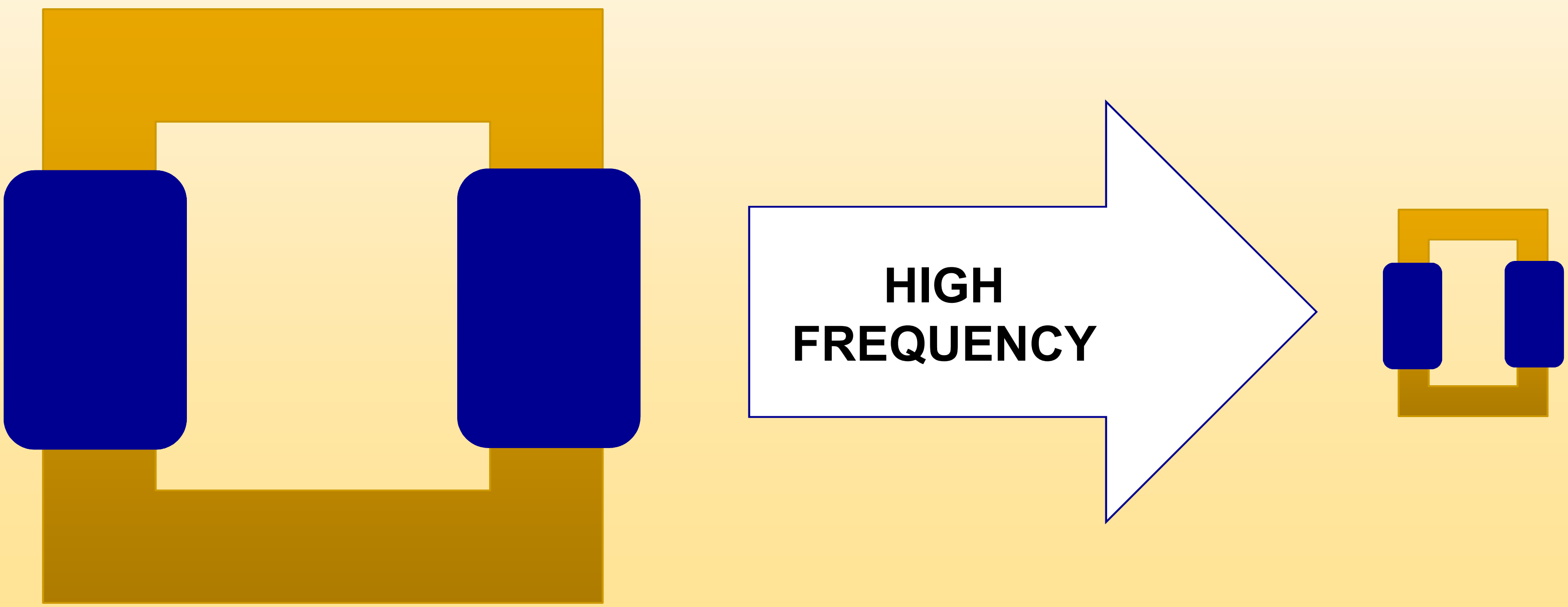
B_s limited
High frequency

Nanocomposite

High B_s
High frequency

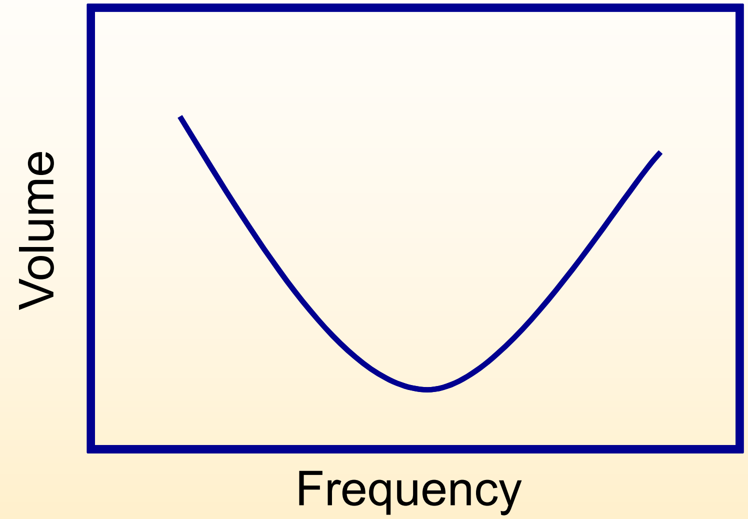
Faraday's Law

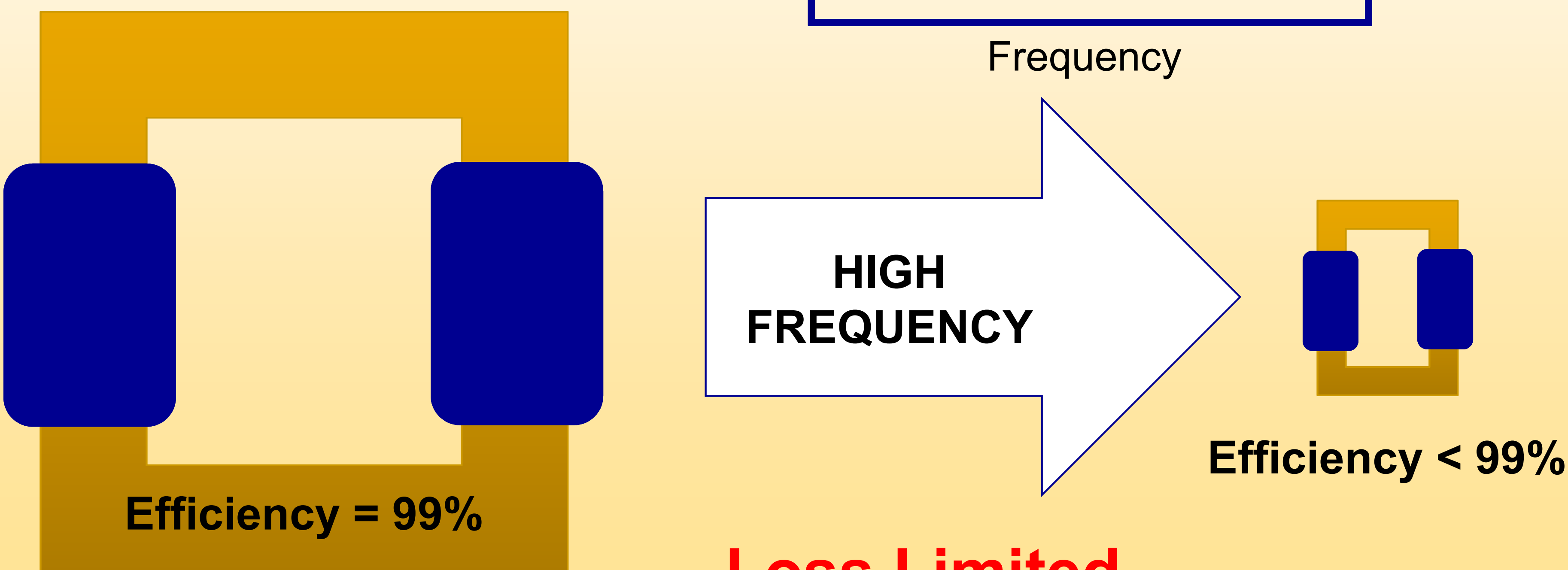
$$V = -NA\frac{\mathrm{d}B}{\mathrm{d}t} = -L\frac{\mathrm{d}I}{\mathrm{d}t} = -LI_0\omega\cos(\omega t)$$
$$= \frac{-\mu N^2 A}{l} I_0\omega\cos(\omega t)$$



Scaling: How small can we go?

Scaling relationships optimize for:
- **Efficiency**
- **Temperature rise**

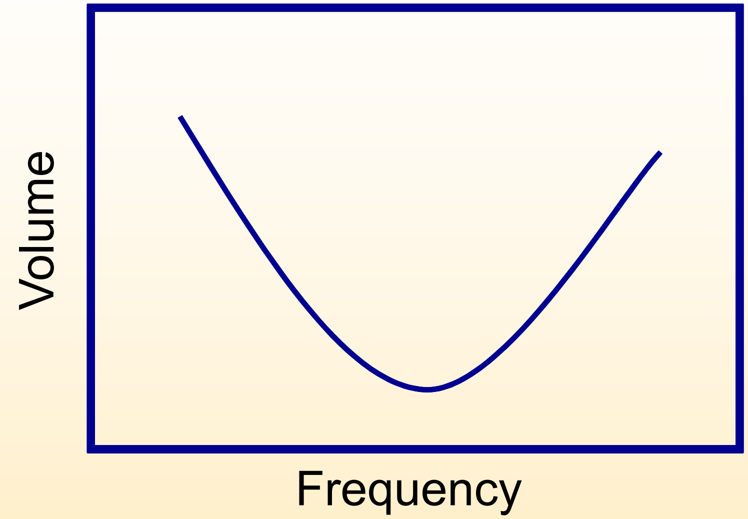


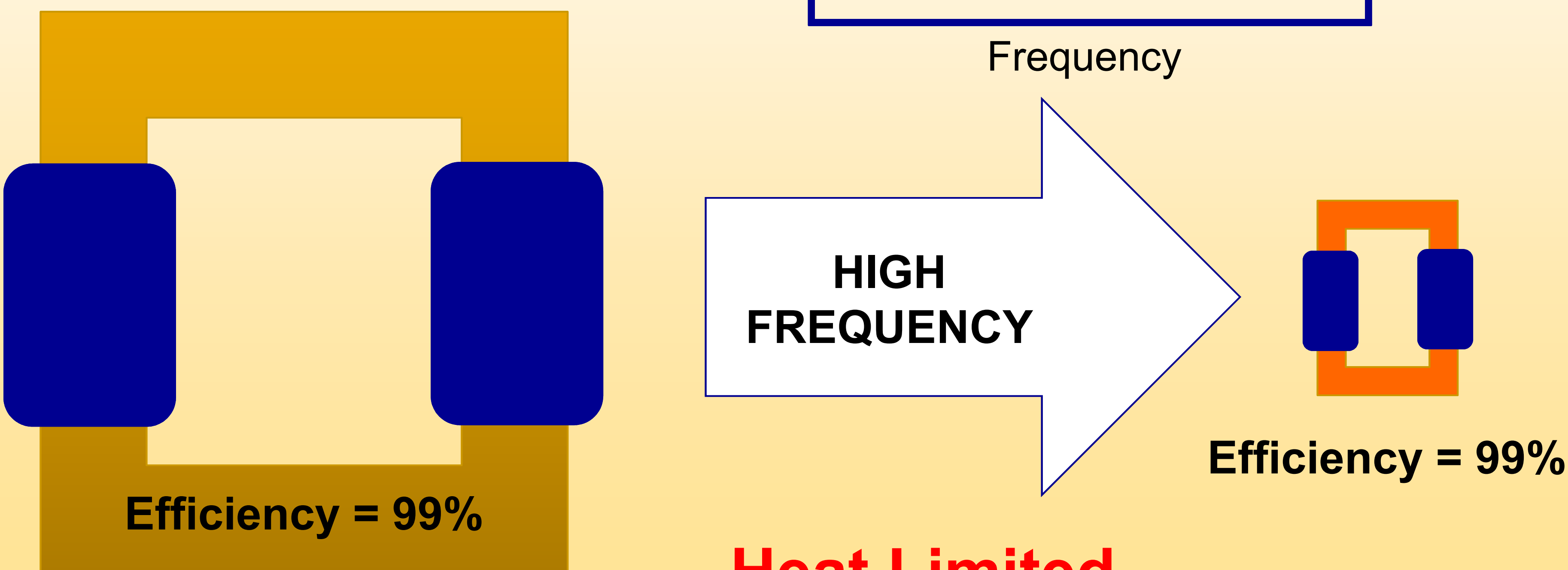


Loss Limited

Scaling: How small can we go?

Scaling relationships optimize for:
- **Efficiency**
- **Temperature rise**





Heat Limited

Inductor Modeling

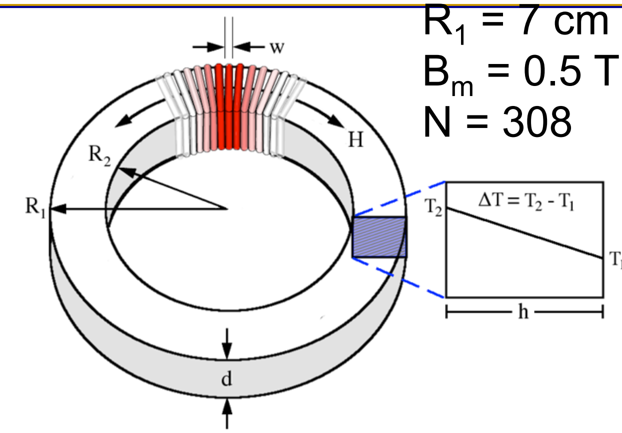
Core losses: FINEMET (k = 3.935, α = 1.585, β = 1.888)

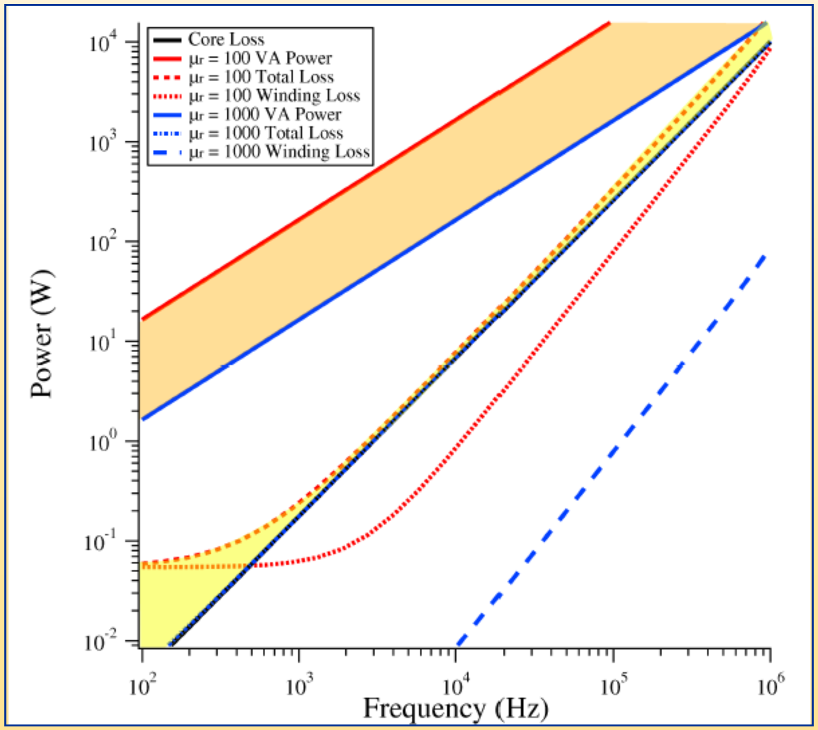
$$P_C = k f^{\alpha} B_m^{\beta}$$

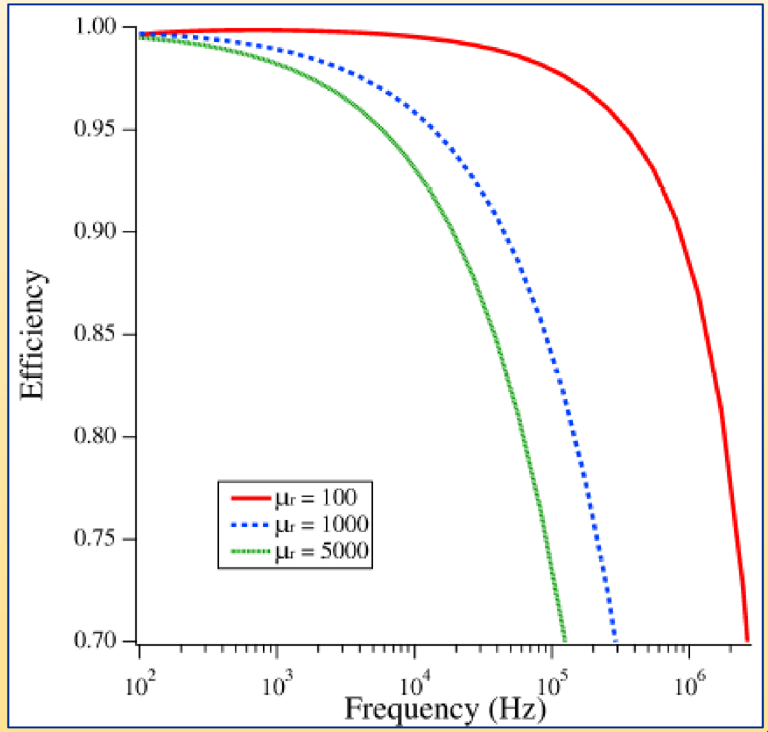
Winding losses: (Litz wire model)

$$P_W = I^2 R F_T \qquad \text{where} \qquad F_T = 1 + \frac{\pi^2 \omega^2 \mu_0^2 N^2 n^2 d_c^2 k}{768 \rho^2 b_c^2}$$

R_1 = 7 cm
B_m = 0.5 T
N = 308







Thermal Management

Random design:

f = 1 kHz ➔ 1 MHz

B_m = 0.5 ➔ 1.3 T

μ_r = 200 ➔ 5000

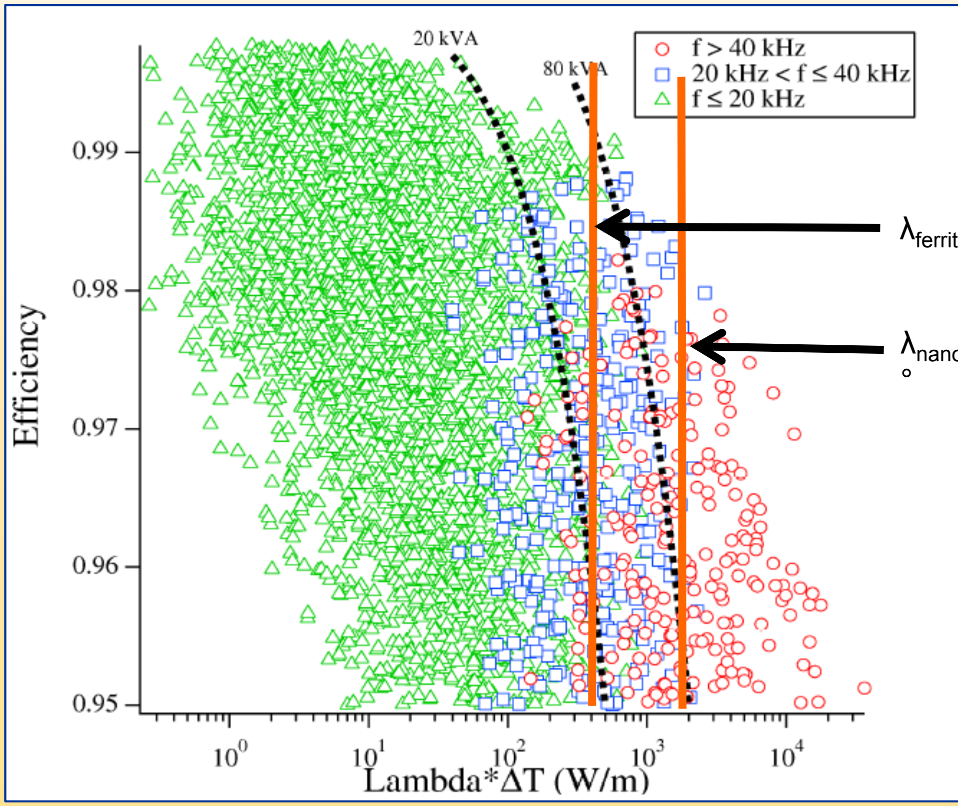
R_1 = 7 ➔ 20 cm

Thermal parameter:

$\lambda_{ferrite} \approx 4$ W/m-K

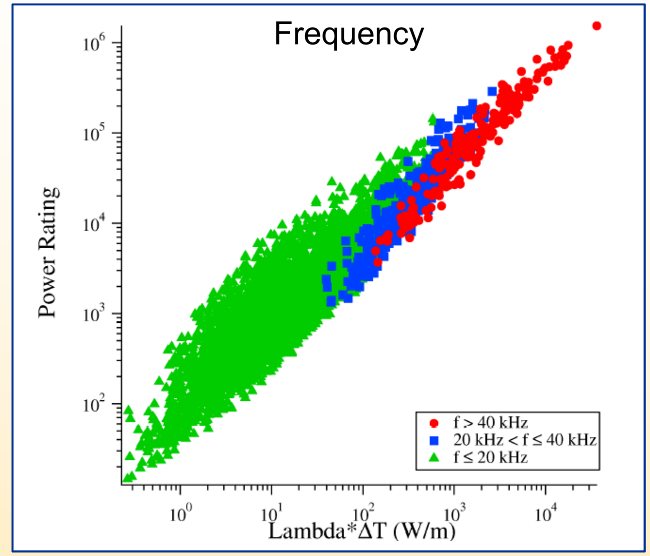
$\lambda_{nanocomp.} \approx 9$ W/m-K

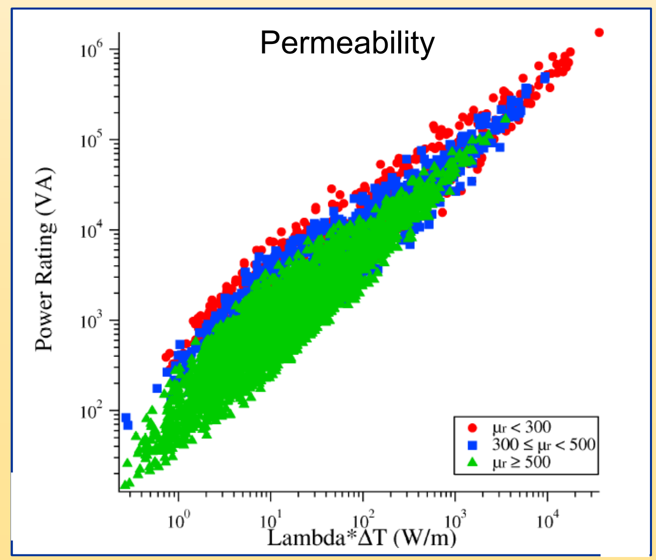
$$\lambda \Delta T = \frac{P_T h}{A}$$



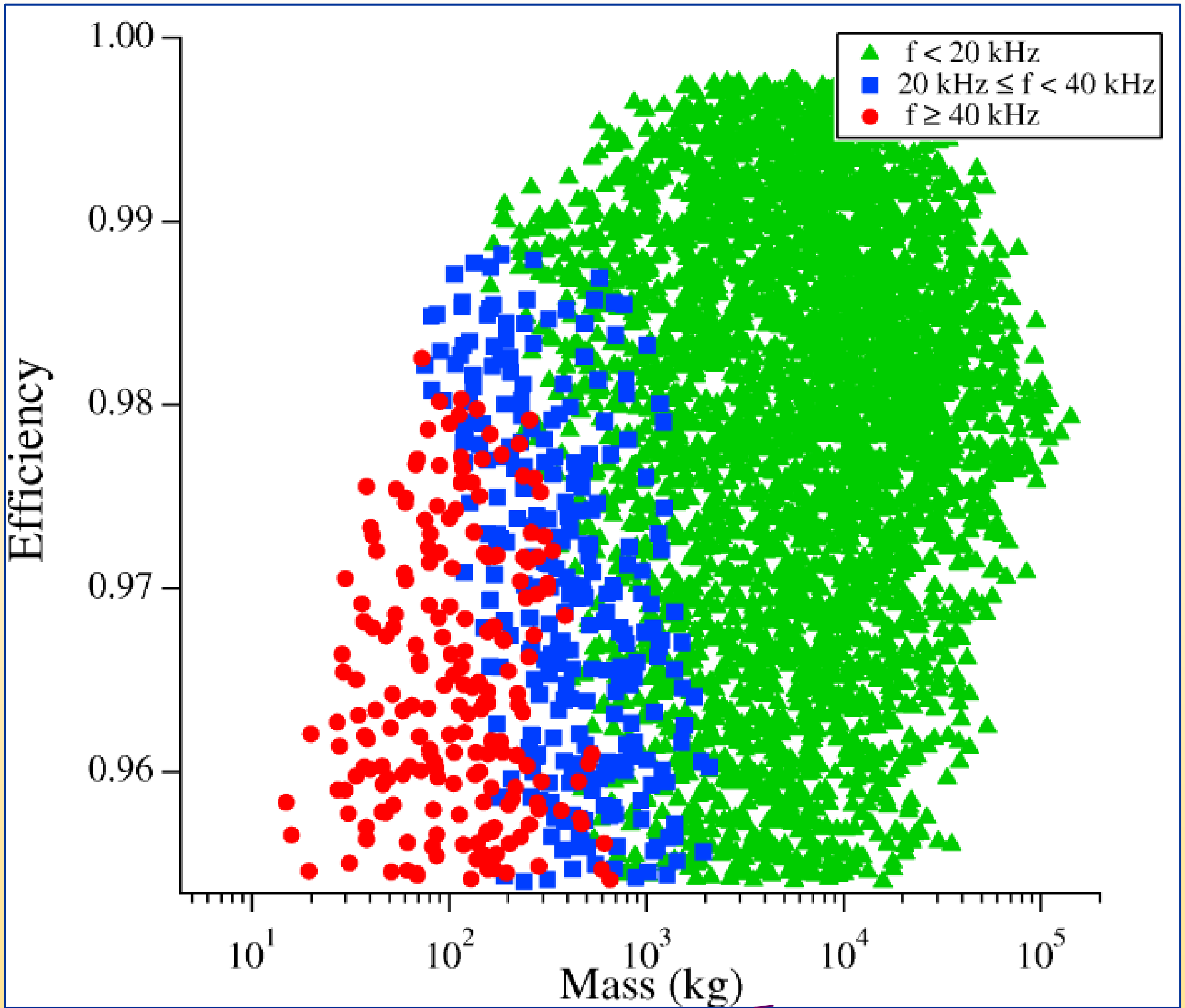
$\lambda_{ferrite}$*100°

$\lambda_{nanocomp.}$*200°





1 MW Flyback Scaling

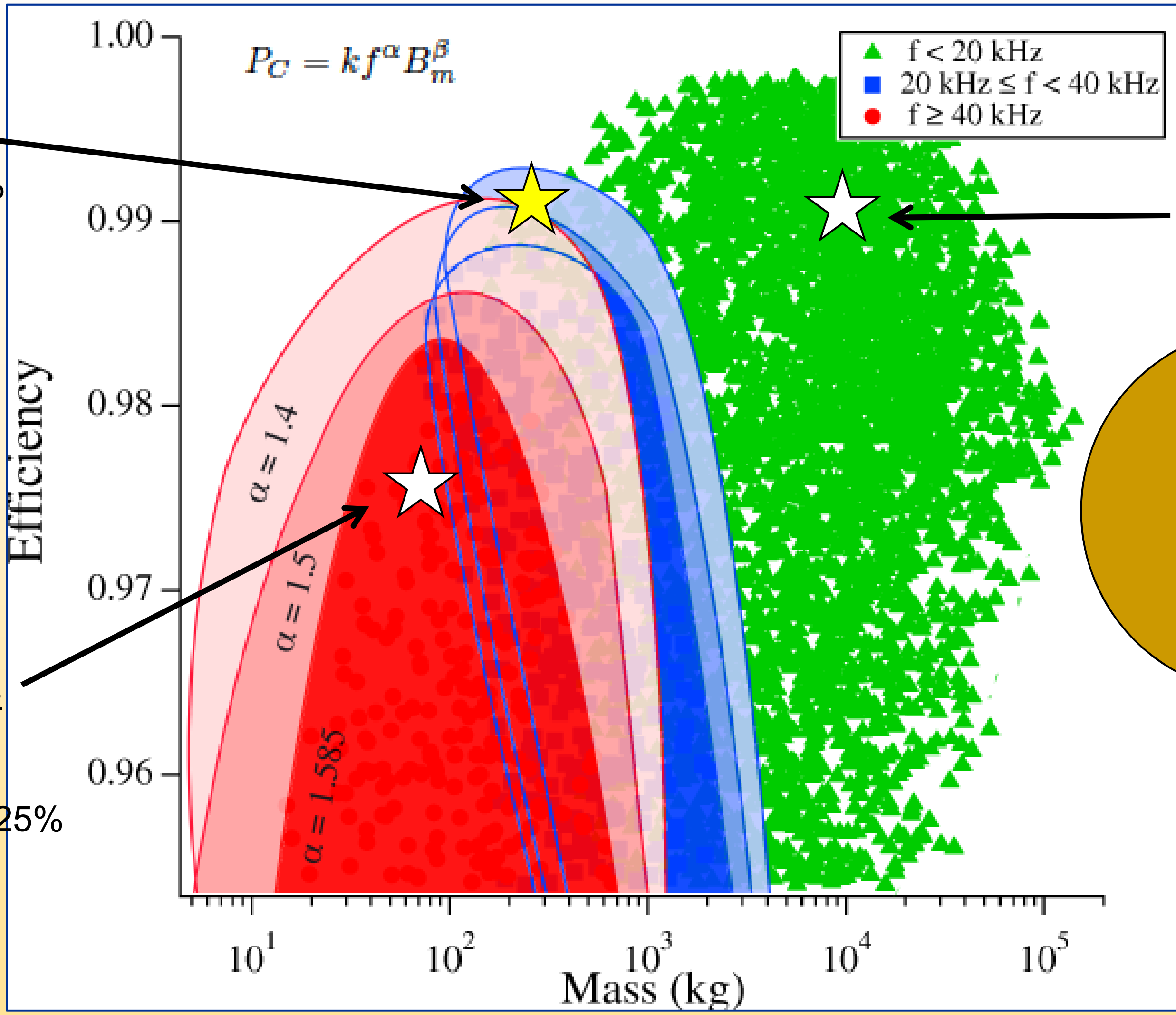


Mass required to achieve 1 MW

1 MW Flyback Scaling

<u>ARPA-E</u>
Transformer η = 99%
20 W/kg @10 kHz*T

250 kg



<u>Electrical Steel</u>
η = 99%
1 W/kg loss

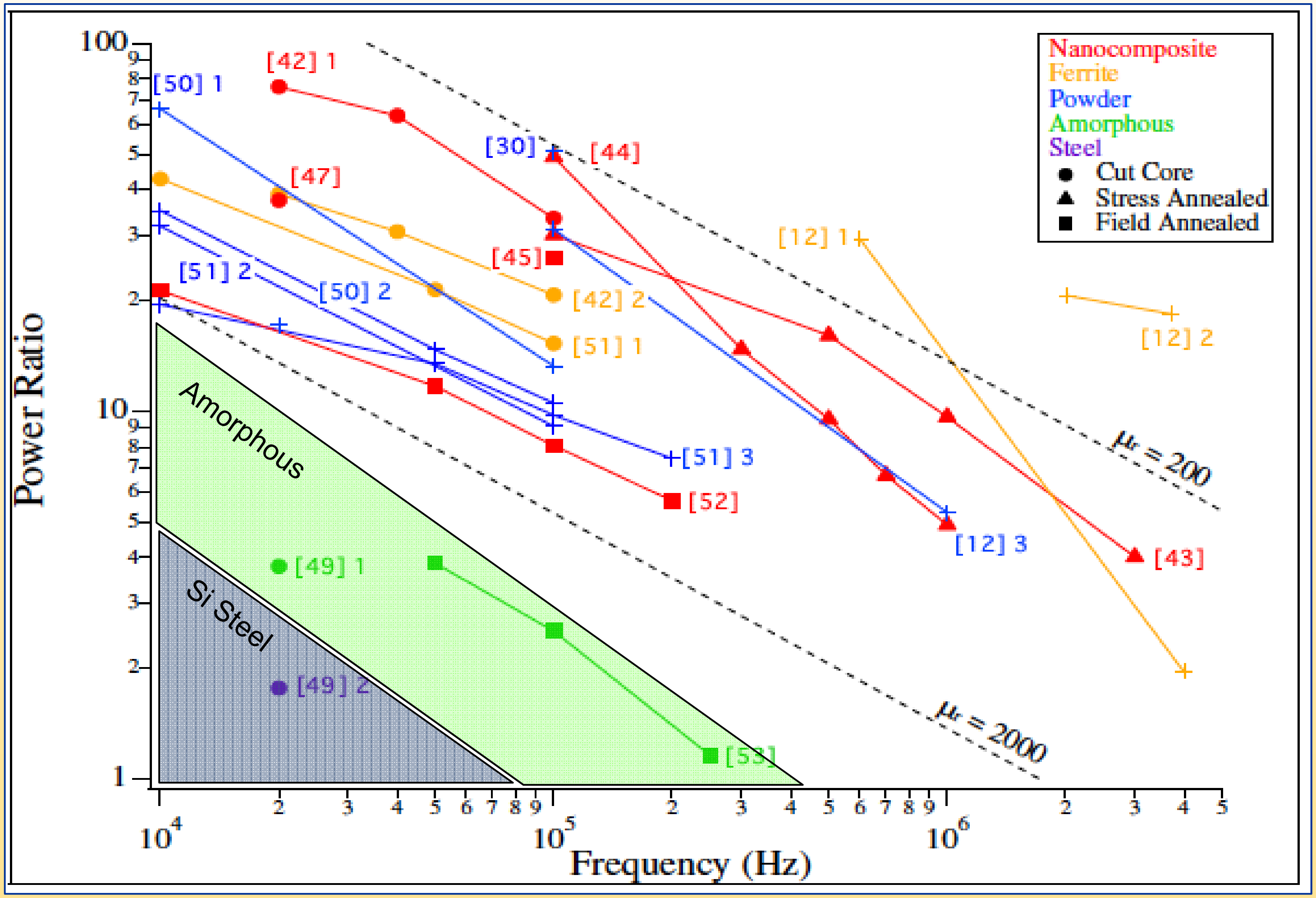
10000 kg

<u>Urciuoli, et al. 2008</u>
HTX002
20 kW, 15 kHz
Converter η = 97.625%

70 kg

High Frequency Magnetics

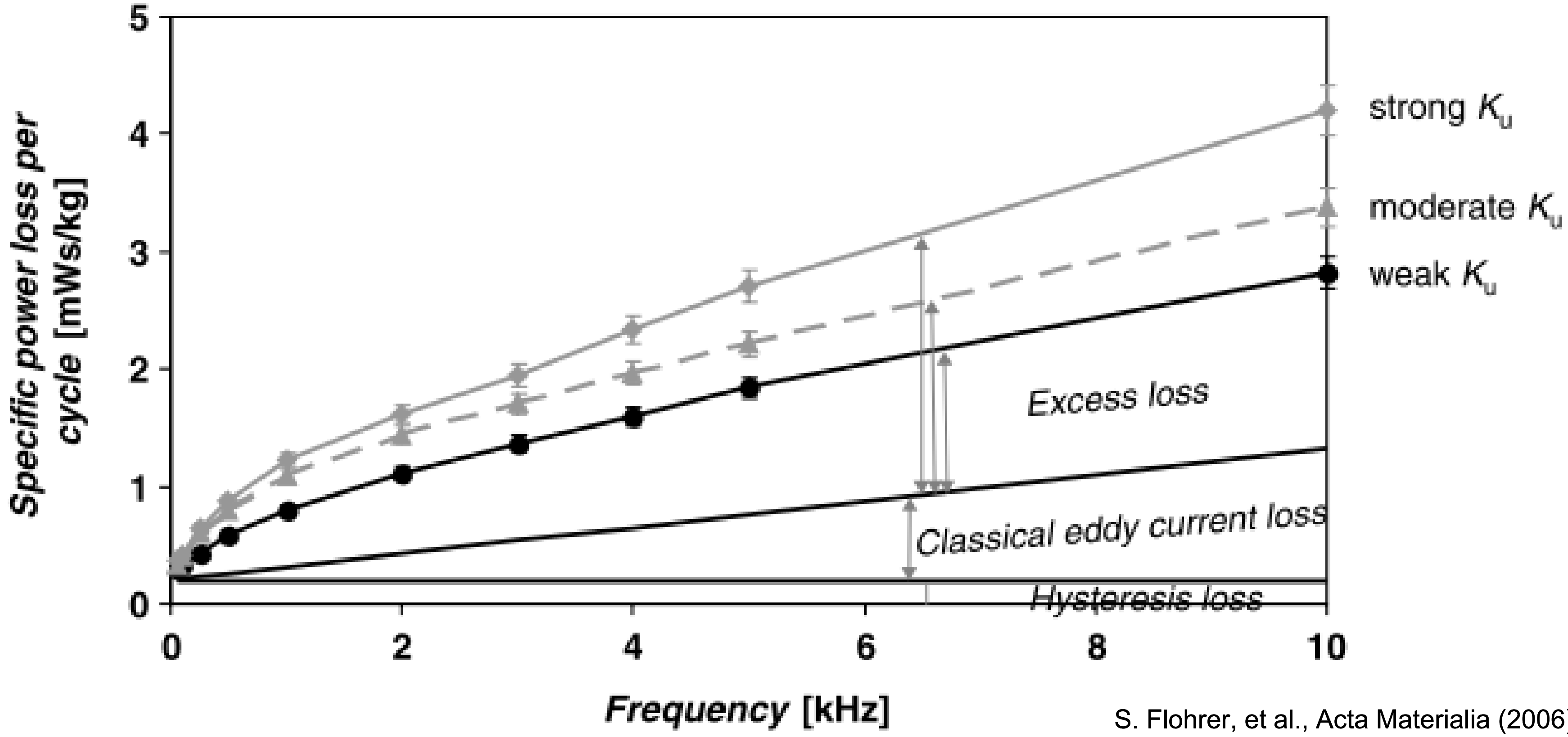
$$PowerRatio = \frac{Stored\ Power}{Power\ Loss} = \frac{\frac{1}{2}B_m H 2f}{1000k f_{kHz}^{\alpha} B_m^{\beta}}$$



High Frequency Magnetics

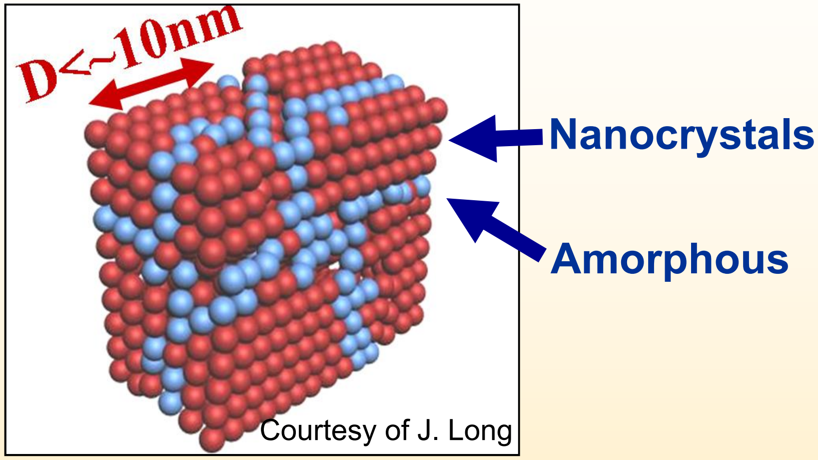
Hysteresis ~ f
Eddy current ~ f^2
Anomalous ~ $f^{3/2}$

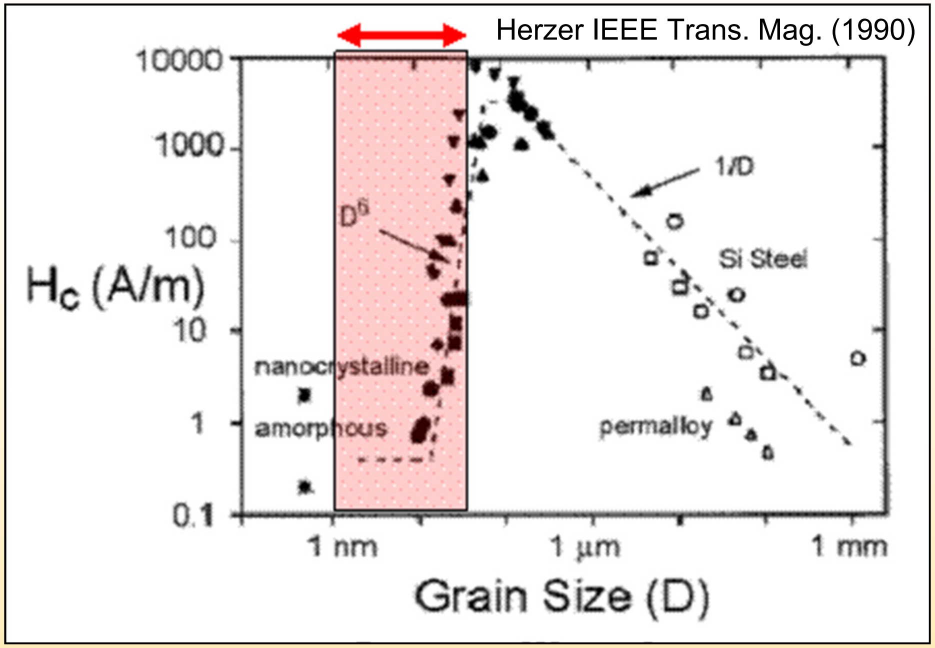
$$P_e \sim \frac{B^2 t^2 f^2}{\rho}$$

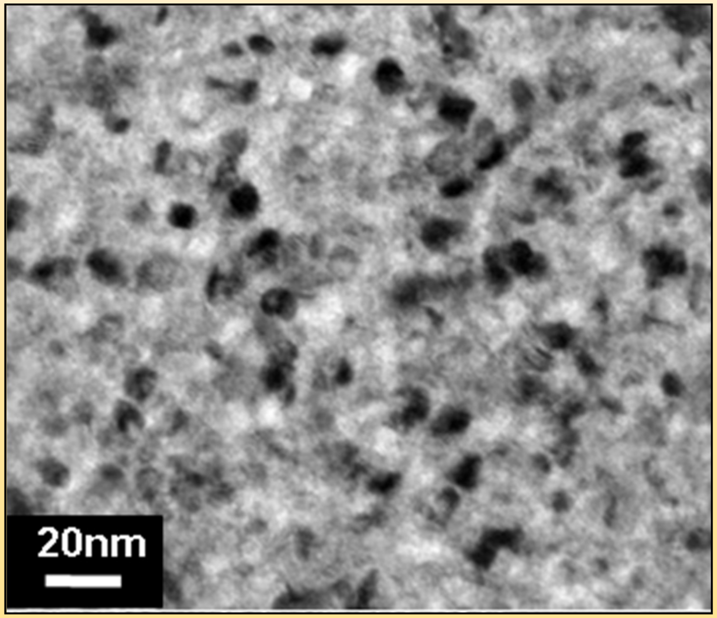


S. Flohrer, et al., Acta Materialia (2006)

What are Nanocomposites?







Small grain size = Low losses

High B_s

High resistivity

High temperature operation

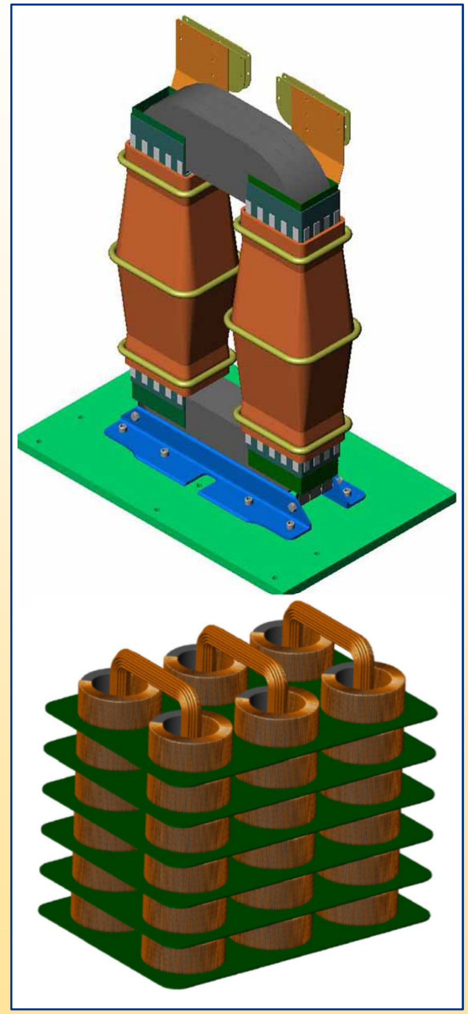
High Frequency Power Converter

•HVCM Transformer

- 150 kV, 20 KHz
- 20 Amp RMS
- 1 MW Average (3) Present Use
- <u>450 LBS for 3</u>
- 3 KW Loss At 2 MW
- “C” Core Design (Parallel Windings)

•Typical H.V. Transformers

- 100 kV, 60 Hz
- 20 Amp RMS
- 2 MW Average
- <u>35 Tons</u>
- ~30 KW Loss



Bill Reass
Los Alamos NATIONAL LABORATORY

Outline of Discussion

(3) General Pricing Guidelines for Utility Scale Photovoltaic Systems

a. Installation Costs for Utility Scale Applications

b. 2010 Benchmark Prices of Typical PV Installations

(4) Future Development Needs to meet SunShot Target

(5) Contributions and Impacts of this ARPA-E Program on DOE Targets

a. Update on Vendor Collaboration and Support

b. Internal Group Discussions to Drive Economic Studies

c. Initial Base Case Cost Structure

d. Technology-to-Market Plan Update

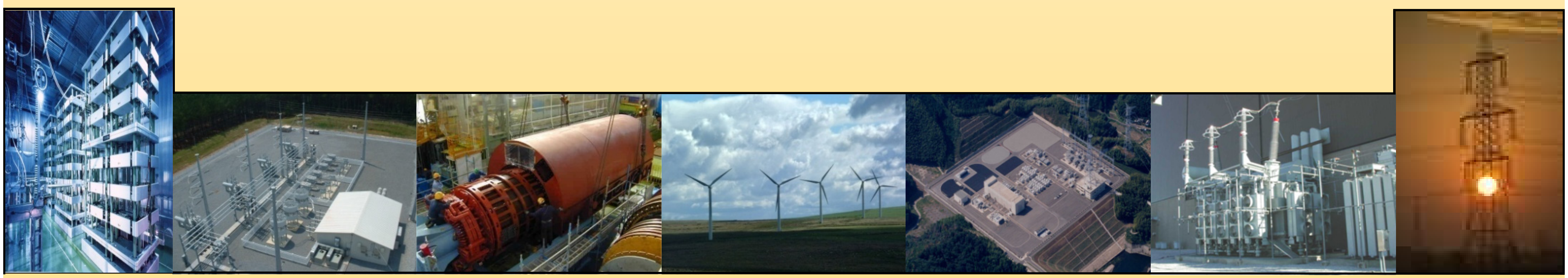
(6) Future Milestones and Goals for the University of Pittsburgh

a. Q4, 2012 and Q5, 2013

General Pricing Guidelines for Utility Scale Photovoltaic Systems

Installation Costs for Utility Scale Applications

2010 Benchmark Prices of Typical PV Installations



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Base-Case Cost Structure

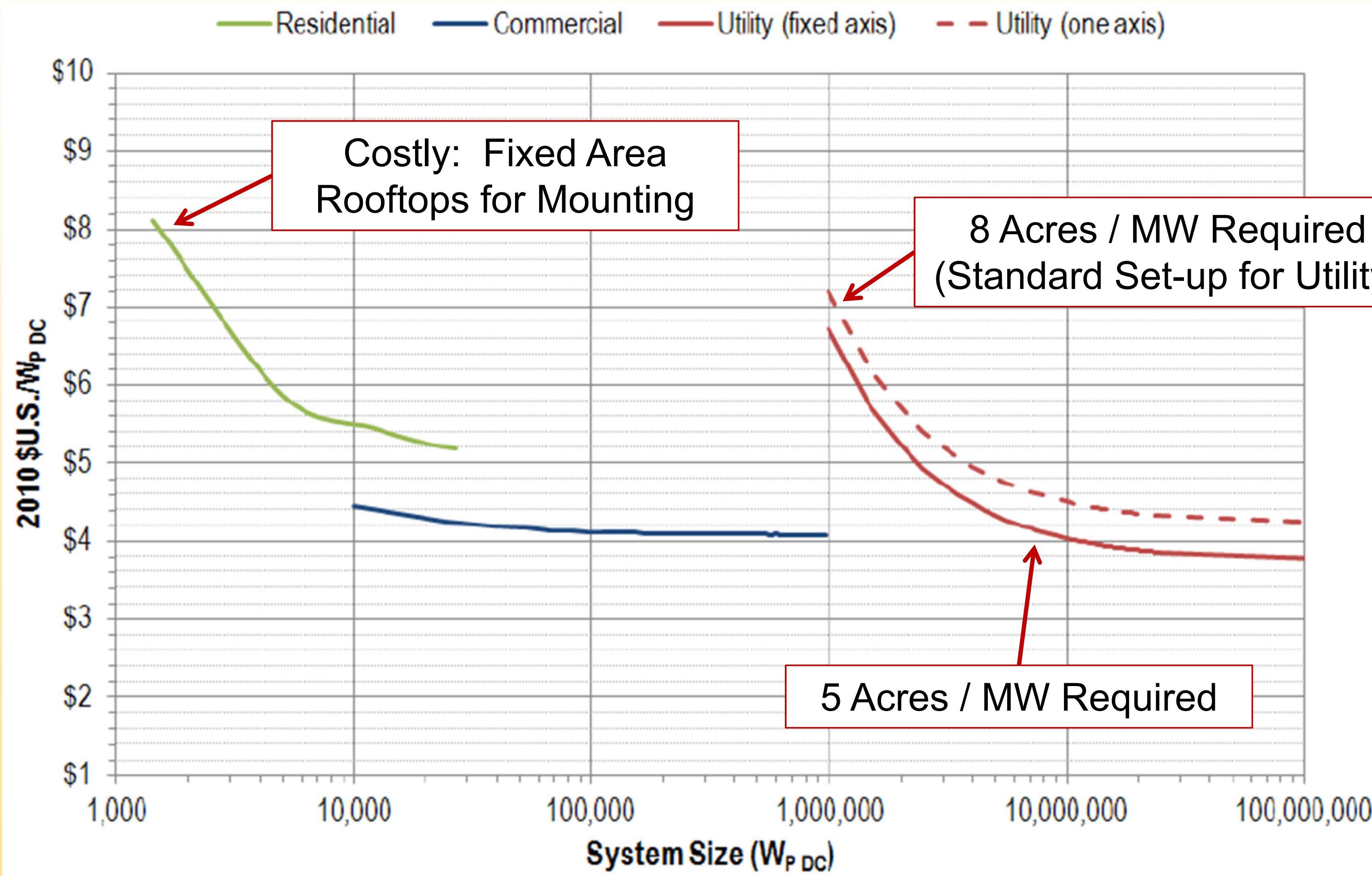
• Develop an initial 'base-case' cost structure for the full inverter system, including component costs for the new converter design, and major equipment/components required for full solar photovoltaic integration – both equipment costs and turnkey installation estimates will be established.

• Team is encouraged to proceed with a 'bottom-up' approach (detailed analysis) to determine PV system price drivers.

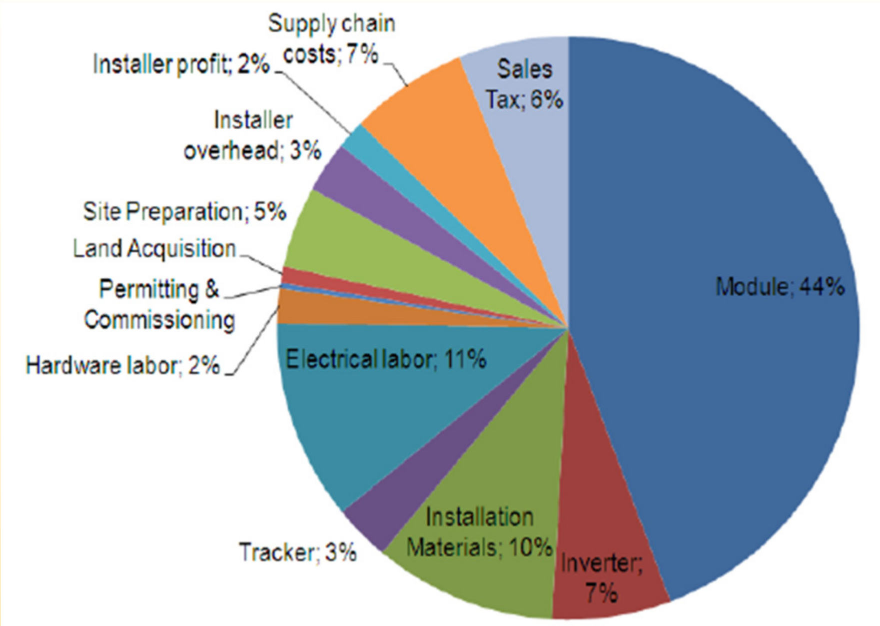
(A) **System Level**: Results deviate based on region, installer and installation specific details, which make price comparisons between systems challenging.

(B) **Bottom-Up Approach**: Includes all materials, labor, overhead and profit, land acquisition, and preparation costs all before the point of grid-tie.

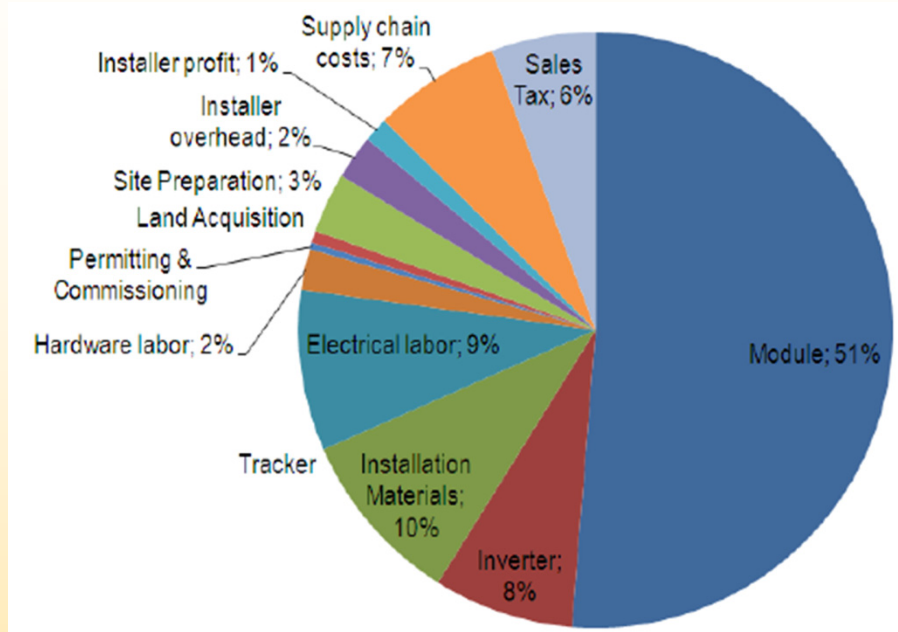
2010 Solar Photovoltaic System Price for Varying System Sizes [1]



Solar Photovoltaic System Price Breakdown by Element (% Basis)



Utility Scale (1-axis) Solar PV System Price Breakdown by Element [1] ($4.40/W)



Utility Scale (Fixed) Solar PV System Price Breakdown by Element [1] ($3.80/W)

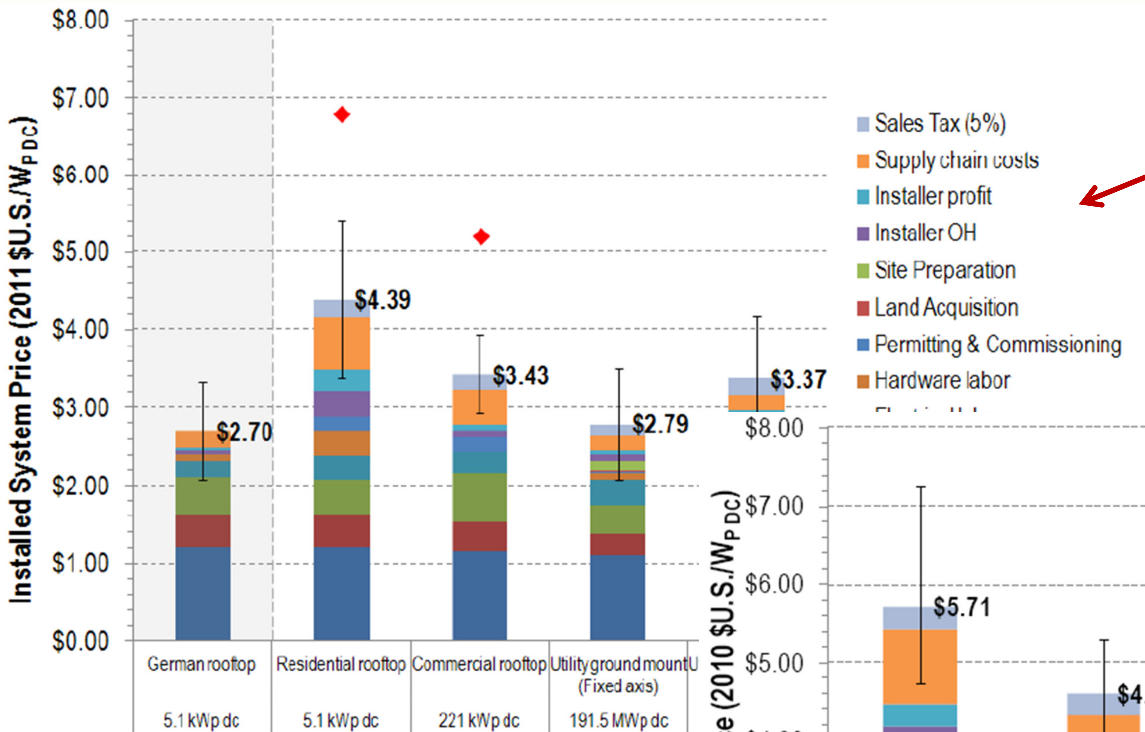
Fixed System

PV Modules (51%); Labor (14%); Installation Materials (17%)

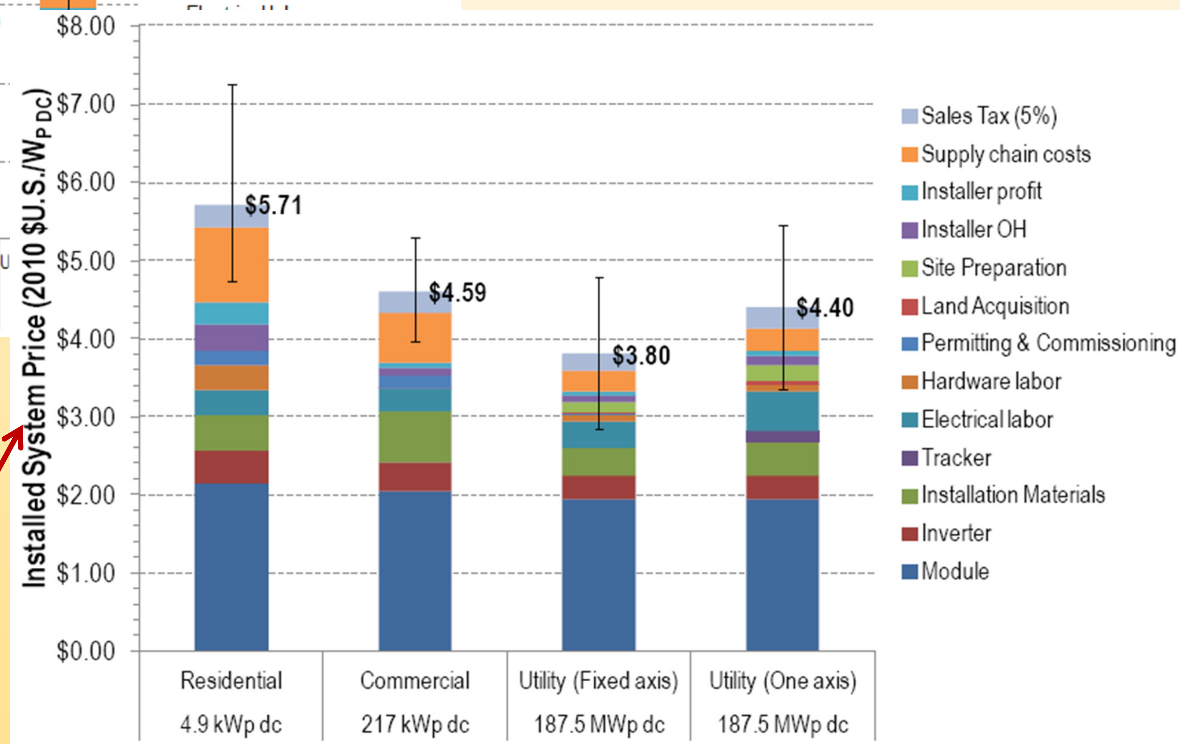
One-Axis Tracking

PV Modules (44%); Labor (18%); Installation Materials (17%)

Solar Photovoltaic System Price Breakdown by Element ($/W Basis)

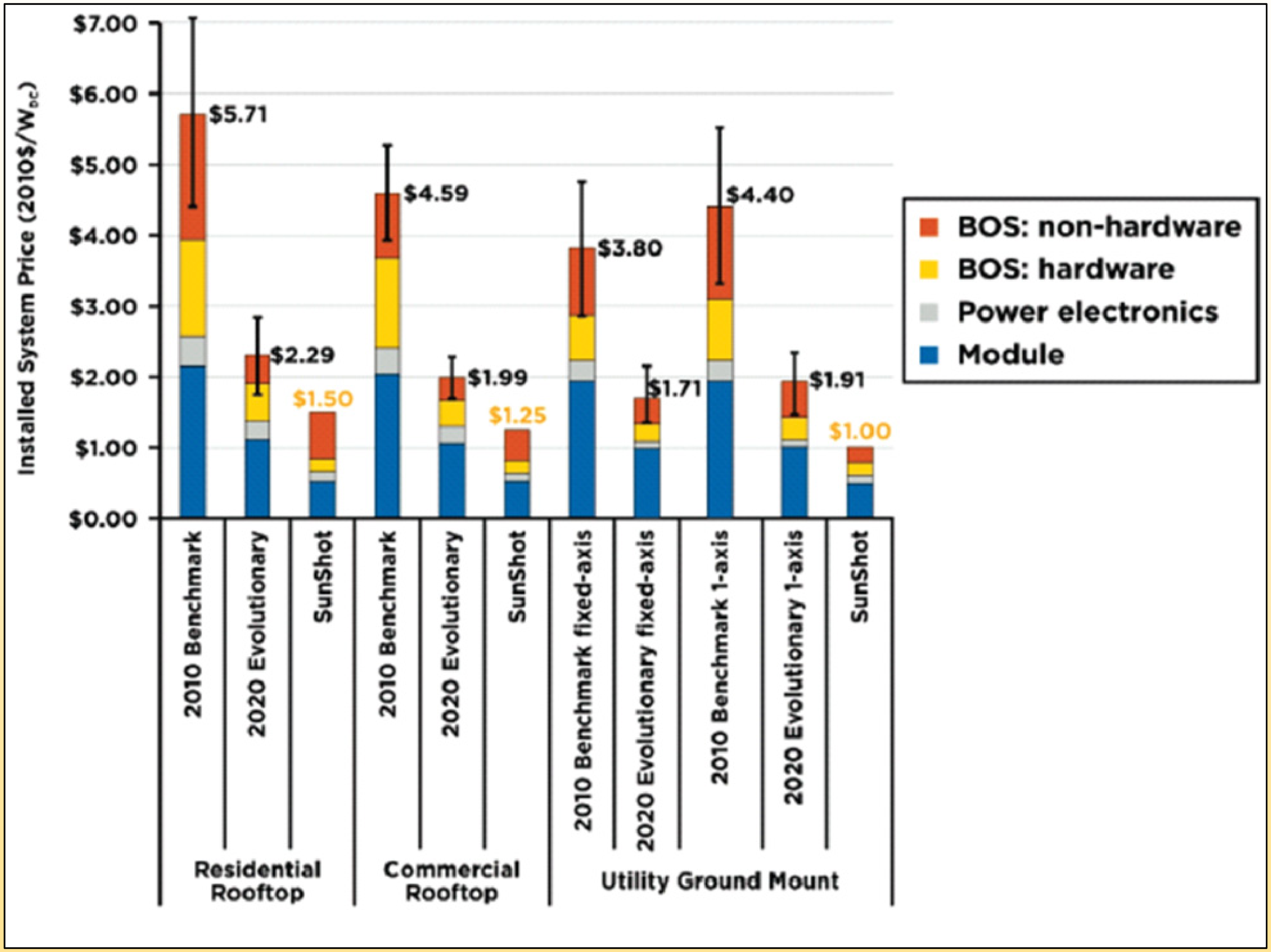


Solar PV System Price Breakdown by Element (2011), [1]

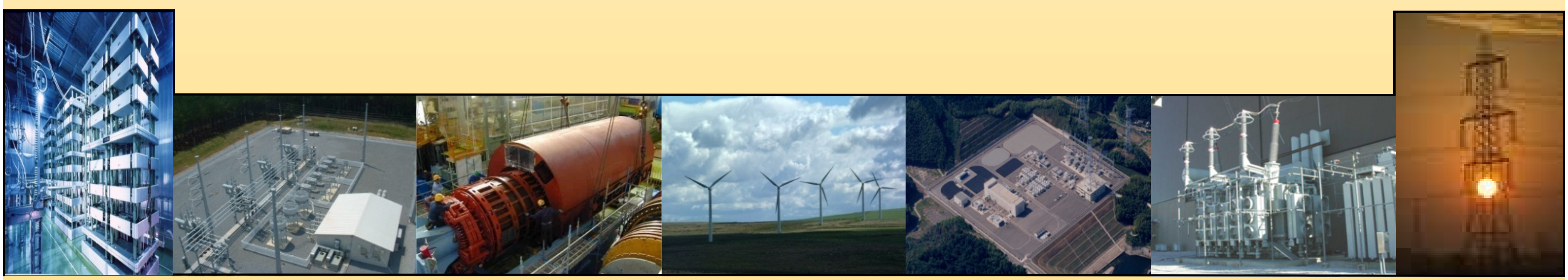


Solar PV System Price Breakdown by Element (2010), [1]

Solar PV Price Breakdown: Lumped Category Representation, [4]

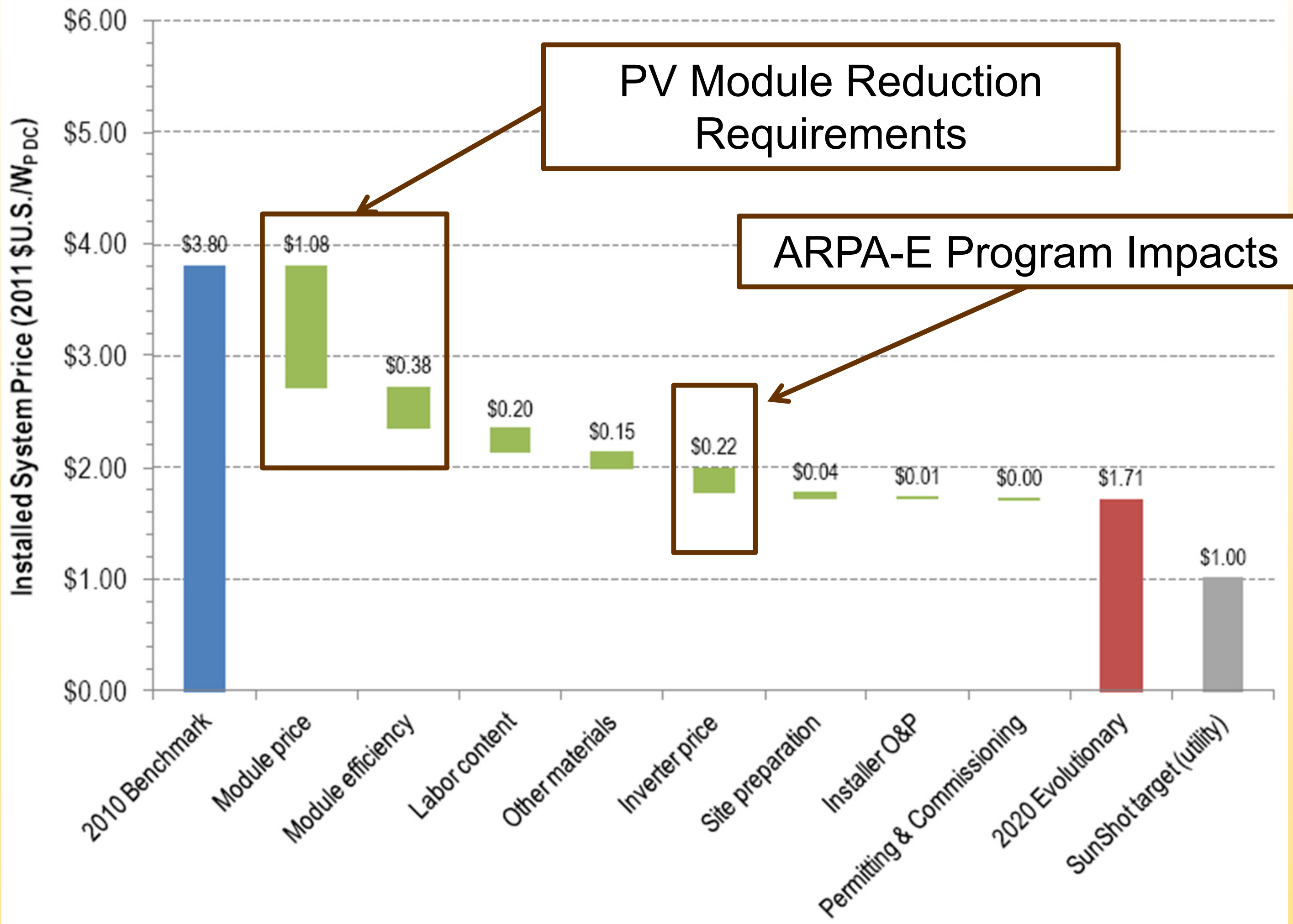


Future Development Needs to meet SunShot Target



DOE SunShot Target and Future Development Needs [1, 3, 4]

• The Department of Energy believes that achieving a target of $1/W (5 to 6 cents/kWh) would make solar more competitive as an energy option.



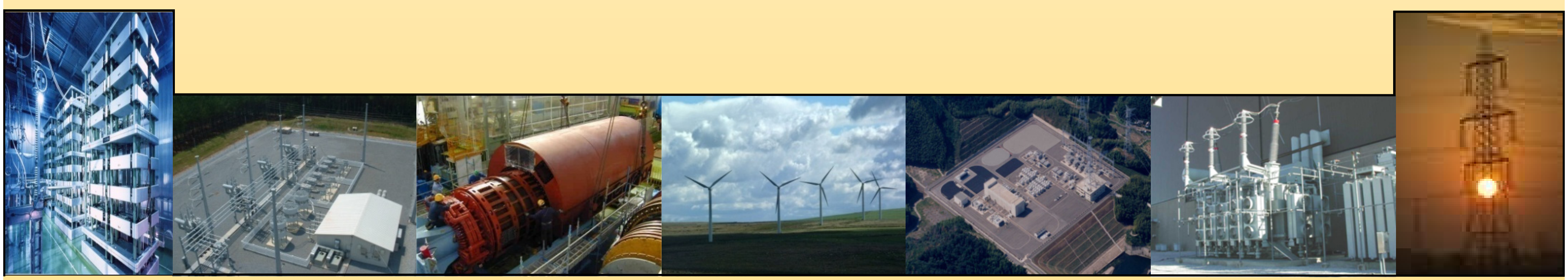
Contributions and Impacts of this ARPA-E Program on DOE Targets

Update on Vendor Collaboration and Support

Internal Group Discussions to Drive Economic Studies

Initial Base Case Cost Structure

Technology-to-Market Plan Update



Update: Vendor Collaboration & Support

- With the references cited, the importance of collaboration with industry stakeholders to quantify residential and commercial distributed and utility-scale PV installations was critical for metrics established.
- **General Discussion Points & Challenges:**
  - ❑ Companies are cautious with exchanging information (proprietary information, vendor sensitivity, IP, etc.)
  - ❑ Incentives to gain cooperation are important.

Update: Vendor Collaboration & Support

- During the summer, a few graduate students interned with Siemens Industrial (former Robicon) **application engineering group** where design-to-cost studies are performed to reduce the cost of the drives.
  - ❑ Contacted engineering design manager and R&D department and awaiting response.
- **Siemens Global Strategic Marketing Department**
  - ❑ Offers a global perspective on the inverter market and provides insight into economic and political factors that drive cost.
  - ❑ Reached out for potential support.

SIEMENS

Update: Vendor Collaboration & Support

Satcon Technology Corporation

- Utility-scale solar inverter supplier located in Boston, Mass.
- Involved with design and control modeling of the inverters and involved with the regulatory issues of connection to AC grid.
- Presently a support contractor for the DOE'S ARPA-E programs, where he is supporting many projects that aim to use HF power transformers to provide isolation and voltage matching in many grid applications.
- Currently in communication.

Satcon™

Update: Vendor Collaboration & Support

Eaton Corporation

- Supplier of commercial and utility scale photovoltaic inverters.
- Potentially providing lumped categories and cost data (ranges) where appropriate.
- Discussions focused on providing cost data for general subcategories of an Eaton inverter.
- Potentially providing list of vendors whom they seek for parts.
- Assisting with their first hand experience with entire PV installations at various power levels.

EATON
Powering Business Worldwide

Update: Vendor Collaboration & Support

General Electric Power Conversion

- Good relationship established with the University of Pittsburgh where GE has sponsored senior design projects and offered internships and CO-OP positions to students.
- GE power conversion has agreed to aid in the assessment.
- Next Phase: Setup meeting face-to-face to explore these opportunities.

Update: Vendor Collaboration & Support

Phipps Conservatory

- Local to the Oakland region, Phipps recently installed 125 kW worth of solar equipment.
- In the past, Phipps president has offered Pitt principal investigators access too solar installation for experimental purposes, etc.
- Pitt and CMU will be visiting their site on October 17th 2012. Since Phipps is neutral, this may provide opportunities to obtain installation costs, labor costs, bill of materials, etc.

Internal Group Discussions to Drive Economic Studies

Los Alamos National Laboratory

• ARPA-E one-line diagrams of system can be distributed that include ratings / sizes / weights of components on the drawings.

• Information on older high frequency designs gone to prototype can be provided. Beware that cost metrics will be higher compared to production.

Spang Magnetics

• Joe Huth can provide "rough" manufacturing costs for the ARPA-E design on a $/lb scale.

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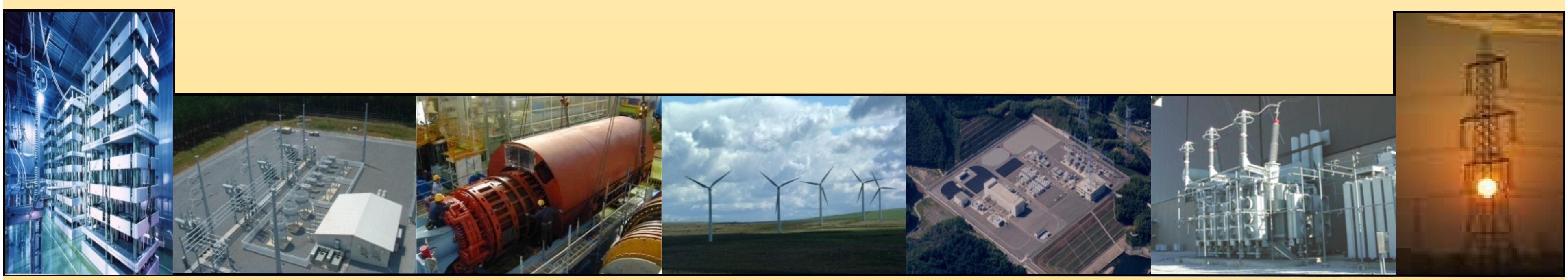
Initial Base Case Cost Structure

Component Contributing to Cost		Estimate ($/W)	
Photovoltaic Module			$1.94
Semiconductor		31.76%	$0.61
	Raw Materials	21.18%	$0.41
	Utilities, Maintainence, Labor	2.35%	$0.05
	Equipment, Tooling, Building, Cost of Capital	3.53%	$0.07
	Manufacturer's Margin	4.71%	$0.09
Cell		26.47%	$0.51
	Raw Materials (Dopant, Chemicals)	10.59%	$0.20
	Utilities, Maintainence, Labor	2.35%	$0.05
	Equipment, Tooling, Building, Cost of Capital	2.35%	$0.05
	Manufacturer's Margin	11.76%	$0.23
Module		41.18%	$0.80
	Raw Materials (Dopant, Chemicals)	15.29%	$0.30
	Utilities, Maintainence, Labor	0.59%	$0.01
	Equipment, Tooling, Building, Cost of Capital	0.59%	$0.01
	Manufacturer's Margin	4.71%	$0.09
	Shipping	20.00%	$0.39
Power Converter			$0.31
	Magnetics	13.64%	$0.04
	Manufacture	22.73%	$0.07
	Board and Electronics	31.82%	$0.10
	Enclosure	18.18%	$0.06
	Power Electronics	13.64%	$0.04
Installation			$2.18
	System Design, Management, Marketing	6.89%	$0.15
	Mounting and Racking Hardware	11.48%	$0.25
	Axis Tracker	6.06%	$0.13
	Wiring	6.43%	$0.14
	Permitting & Commissioning	0.46%	$0.01
	Site Preparation	10.10%	$0.22
	Land Acquisition	0.00%	$0.00
	Installer Overhead	6.06%	$0.13
	Hardware Labor	4.04%	$0.09
	Electrical Labor	22.22%	$0.48
	Other: Supply Chain Costs	14.14%	$0.31
	Sales Tax (5%)	12.12%	$0.26
		Total:	$4.42

Further Expanded as Time Progresses !!!

Internal ideas being established at Pitt too see how further detail/data can be obtained for this category, as required.

Very Basics of the Technology to Market Plan



Technology to Market Plan Update

- **Section I: Overall Transition Plan**
  - ❑ **Magnetics *has* facilitated the transition to market in two ways. (1) Manufacturing new alloys and providing them to a 3rd party for processing or (2) processing the material themselves and offering cores in specific configurations to meet customer needs.**

- **Section II: Intellectual Property**
  - ❑ **Patentable material design jointly shared between CMU/Magnetics is highly likely in near term.**
  - ❑ **Proprietary designs associated with ARPA-E work.**

- **Section III: Commercial Readiness**
  - ❑ **Commercial readiness level is still a 2 out of 9.**
  - ❑ **Commercial readiness level is expected to be a 5 by end of project. Beyond this, additional time and funding will be required.**

Technology to Market Plan Update

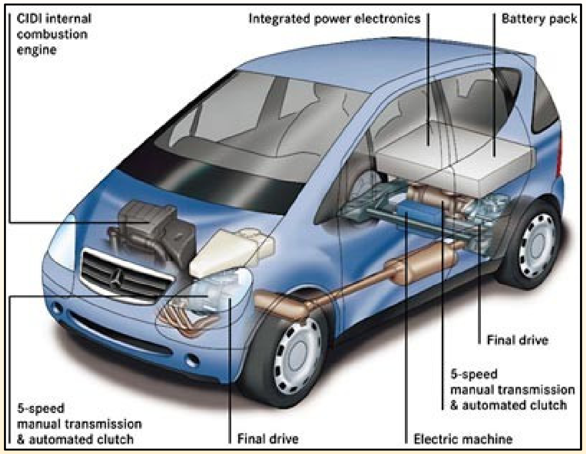
- **Section IV: Manufacturing and Scalability**
  - ❑ **Through ARRA funding, Magnetics built a 200 kg machines that combines vacuum induction melting (VIM) and spin casting into a single operation.**
  - ❑ **Magnetics has general knowledge of how to create tape wound cores of various geometries.**
  - ❑ **Nanocrystalline alloys present certain assembly challenges that are being addressed .**
  - ❑ **Goal has been to deliver wound tape cores, impregnated and cut to LANL's specification for winding and integration into a demonstration circuit (underway).**
- **Other Sections: Future Funding & Team Development**
  - ❑ **Facility upgrades, CMU labs mimicking Magnetics facility**

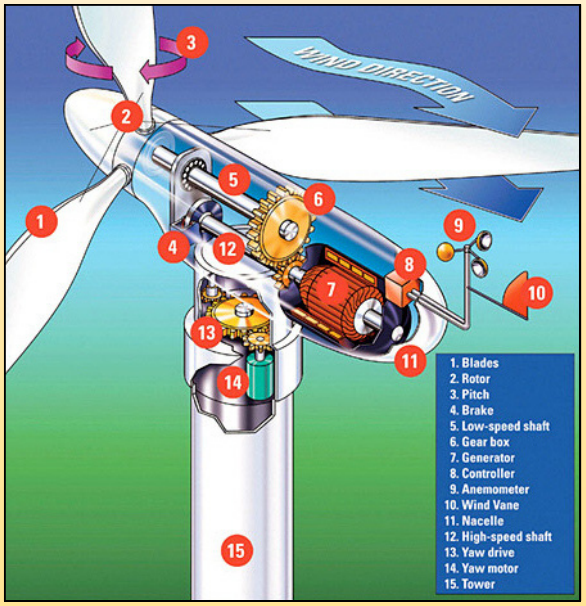
Potential Market Applications of Material Design

- Novel material promises to increase power density ratio.
  - Motor size reduction
    - E.V.s
    - wind turbines
    - military and naval applications.

- Optimize design with new material
  - reductions in Eddy current losses
  - improvements in torque vs. speed curves.

- Use this data to perform economic analysis and comparison against current technologies.





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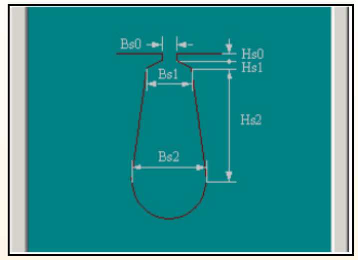
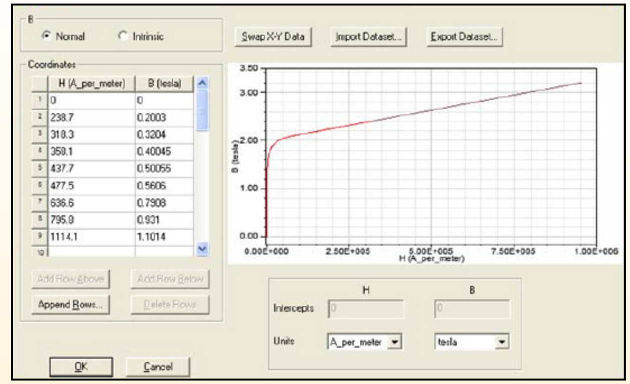
http://www.ansys.com/ansys-maxwell-brochure-14.0.pdf
RMxprt_onlinehelp.pdf
http://www.solarpowernotes.com
http://windmillsusa.com/windmills

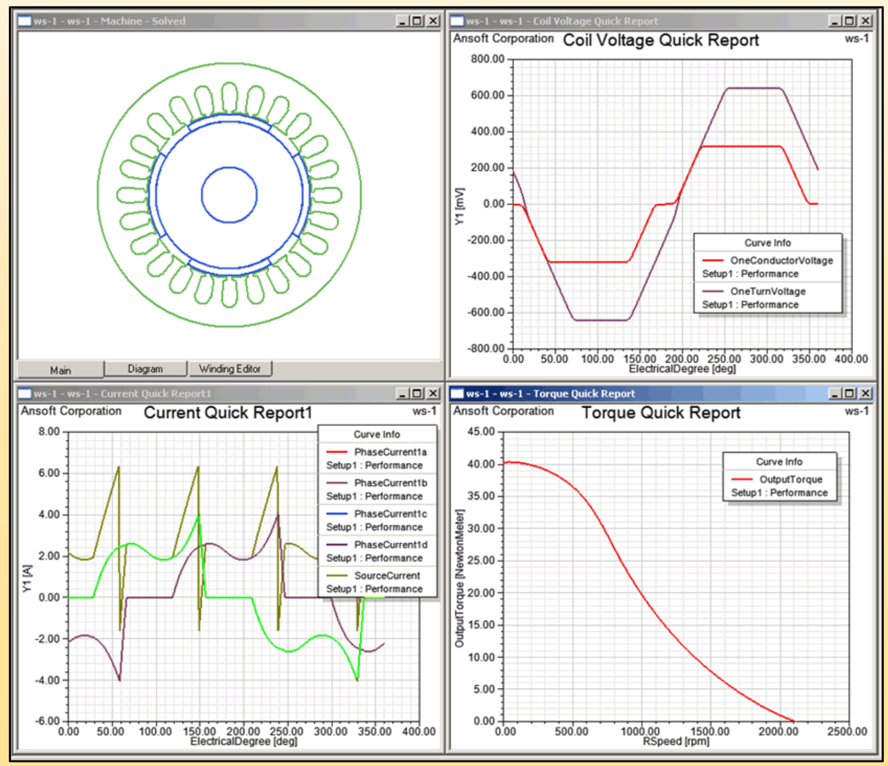
Capabilities of ANSYS Maxwell

- Inputs
  - Geometry
  - Material Properties
  - B-P & B-H Curves
  - Desired Outputs
  - Slot Size, Coil Turns, Wire Gage
  - Winding arrangement
  - Starting capacitance



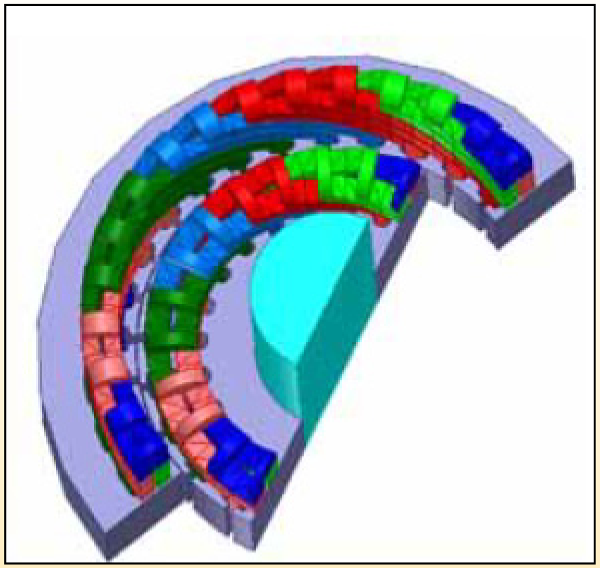


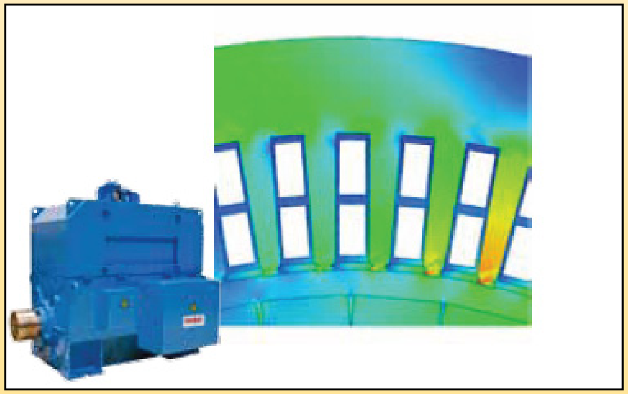
- Outputs
  - Solves AC electro magnetic, magnetostatic, DC conduction, and electric transients
  - Generates nonlinear equivalent circuits
  - Torque vs speed curves, power loss, flux in air gap, power factor, effeciency



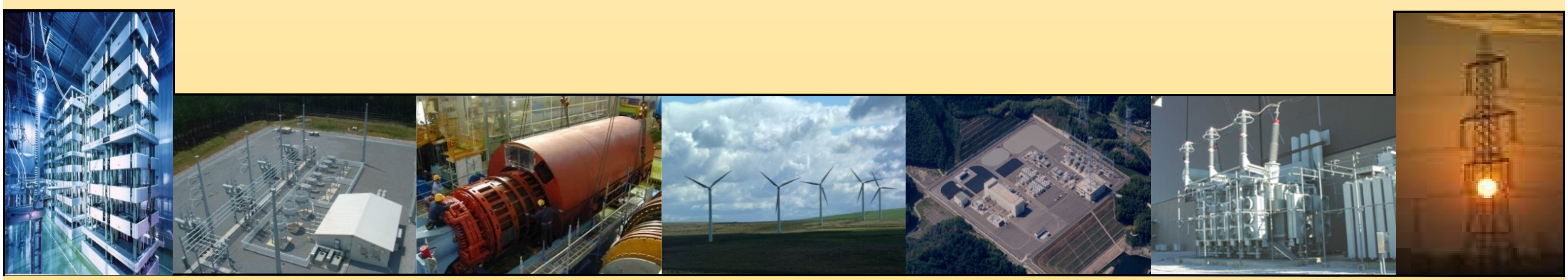
Objective of Using ANSYS Maxwell

- Set up simulation of induction motor and PM motor using state of the art materials for the core
- Compare performance of these with that of the novel material
  - At standard operation
  - At high frequency operation
- Continue analysis by varying core structure, slot dimensions, and winding configuration
- Pair motor designs and performance outputs with current applications for which they are best suited and create circuit models for more comprehensive system modeling.





Future Milestones and Goals for the University of Pittsburgh



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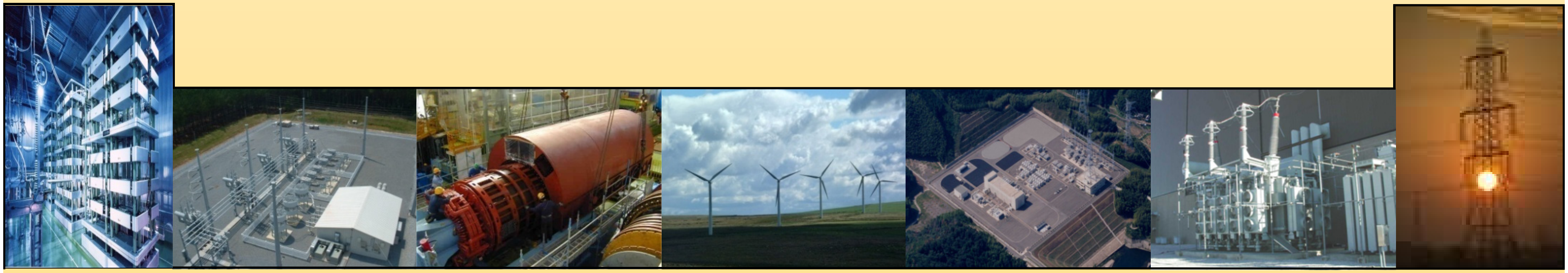
Future Milestones for the University of Pittsburgh

• **Quarter 4, 2012**: Develop the baseline for initial costs on a 'major component' basis, and build up a detailed cost analysis for the converter system that includes manufacturing/production costs in addition to materials. Once the base line is established, develop a method for **forecasting reduced** target costs for a production scale system -- including both equipment costs and turnkey installation estimates. ***(September 2012 to December 2012) – In Progress***

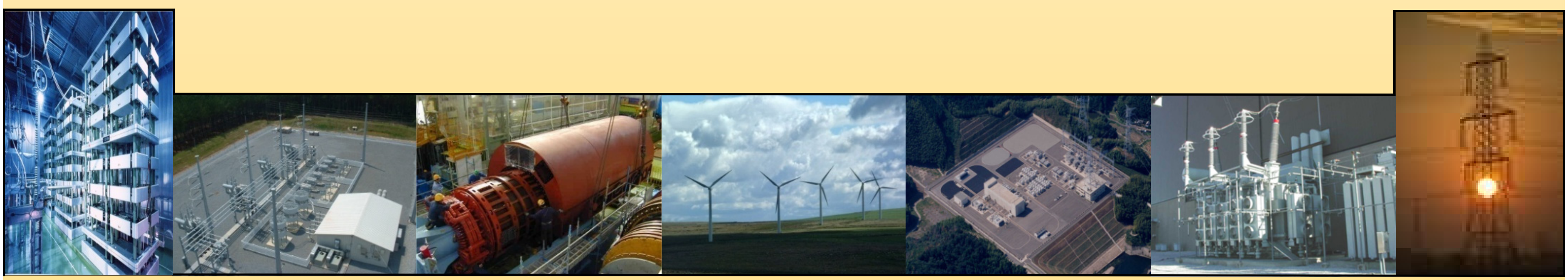
• **Quarter 5, 2013**: Based on a 'benchmark' for 60 Hz system operating costs, provide economic analysis comparisons and impact for operation at different frequencies based on application specific aspects. ***(January 2013 to March 2013)***

- ✓ **Direction Emmanuel Taylor is integrating into his dissertation direction.**

Conclusions



THANK YOU!



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[2] Woodhouse, M.; Goodrich, A; James, T.; et.al "An Economic Analysis of Photovoltaics versus Traditional Energy Sources: Where are We Now and Where Might We Be in the Near Future?" *IEEE Photovoltaic Specialist Conference*. June 19-24, 2011.

[3] (2011). "$1/W Photovoltaic Systems: White Paper to Explore A Grand Challenge for Electricity from Solar." Advanced Research Projects Agency-Energy (ARPA-E).

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[5] Goodrich, A; Woodhouse, M.; James. T (2011).; "Solar PV Manufacturing Cost Model Group: Installed Solar PV System Prices."