Renewable Energy – Technology Needs, Policy Drivers, and Business Opportunities

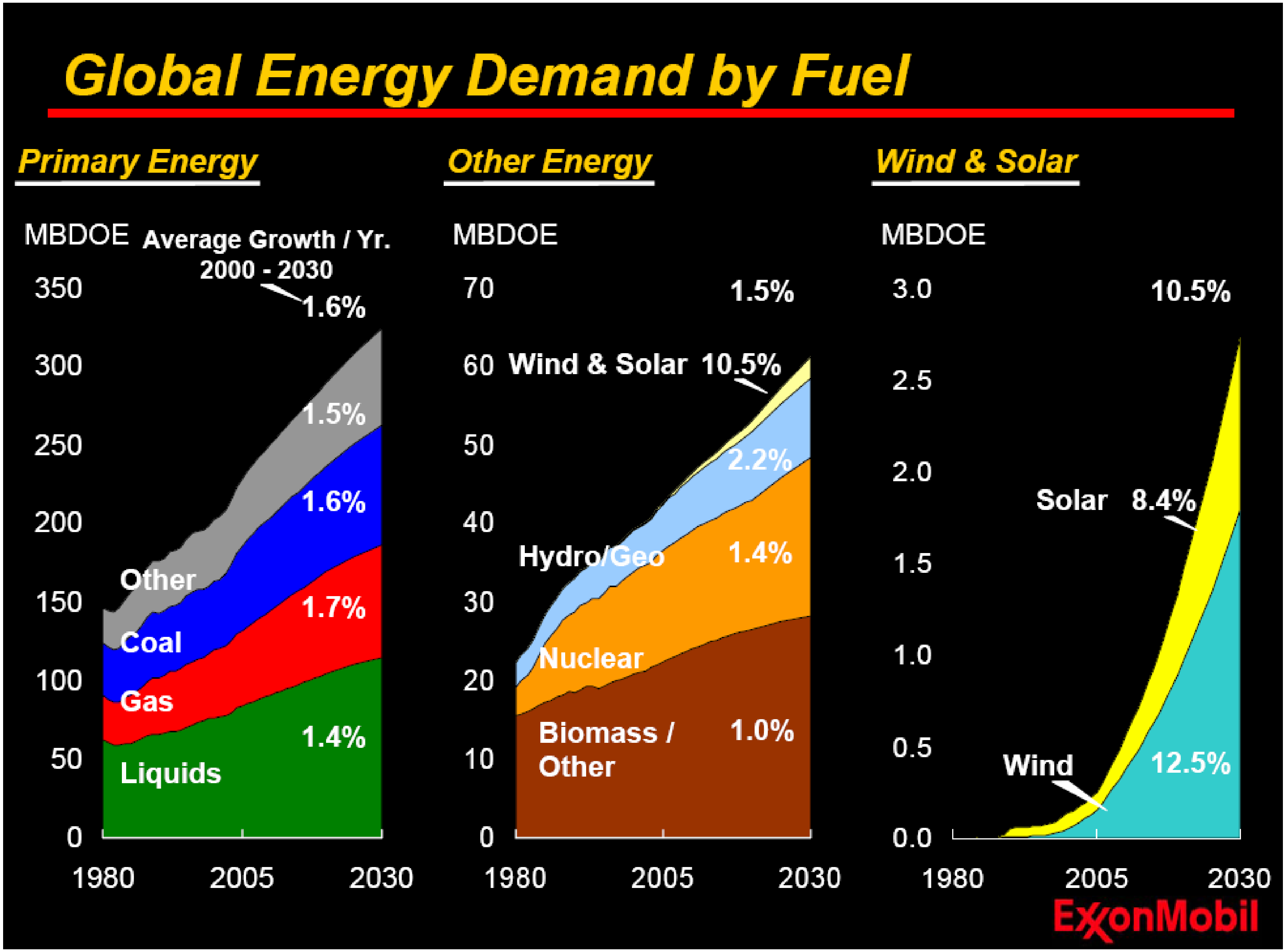
Nag Patibandla
Center for Future Energy Systems
Rensselaer Polytechnic Institute
Troy, NY 12180

ICAER 2007
IIT Mumbai, India

Energy Units and Conversions

- Gasoline /Oil Related
  - 1 mbdoe (365 million barrels per year) = 2.13 quads = 624 TWh
  - One barrel of oil = 42 gallons (US) = 5.85 mmBtu
  - 1 US gal of gasoline = 125,000 Btu = 37 kWh = 44 MJ/Kg
  - 1 litre of gasoline = 10 kWh (approx)
- Natural gas
  - 1 mcf (1000 cu.ft.) = 1 mmBtu
  - Megawatt-hour = 3.33 mcf = 3.40 decatherm
- Coal
  - 1 pound of coal = 10,000 Btu
- Power
  - Kilowatt-hour electricity = 3413 Btu
- Heat energy (Megawatt equivalents)
  - Megawatt-hour (thermal) = 3.41 mmBtu = 3.21 klb steam (100 psi saturated)
- Refrigeration capacity
  - Megawatt cooling = 284.34 tons cooling

World Energy Consumption (2000 – 2030)



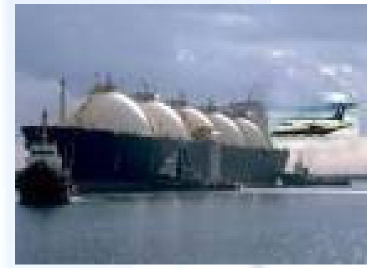
The Drivers

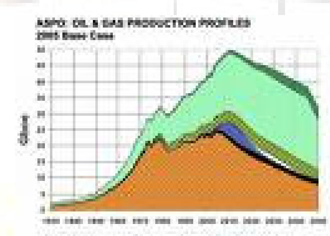
Fuels

- Energy Insecurity, Price Volatility, Peak Oil, Environmental Awareness, etc.
- Federal Policy
  - Ethanol blend, RFS, MTBE

Electricity

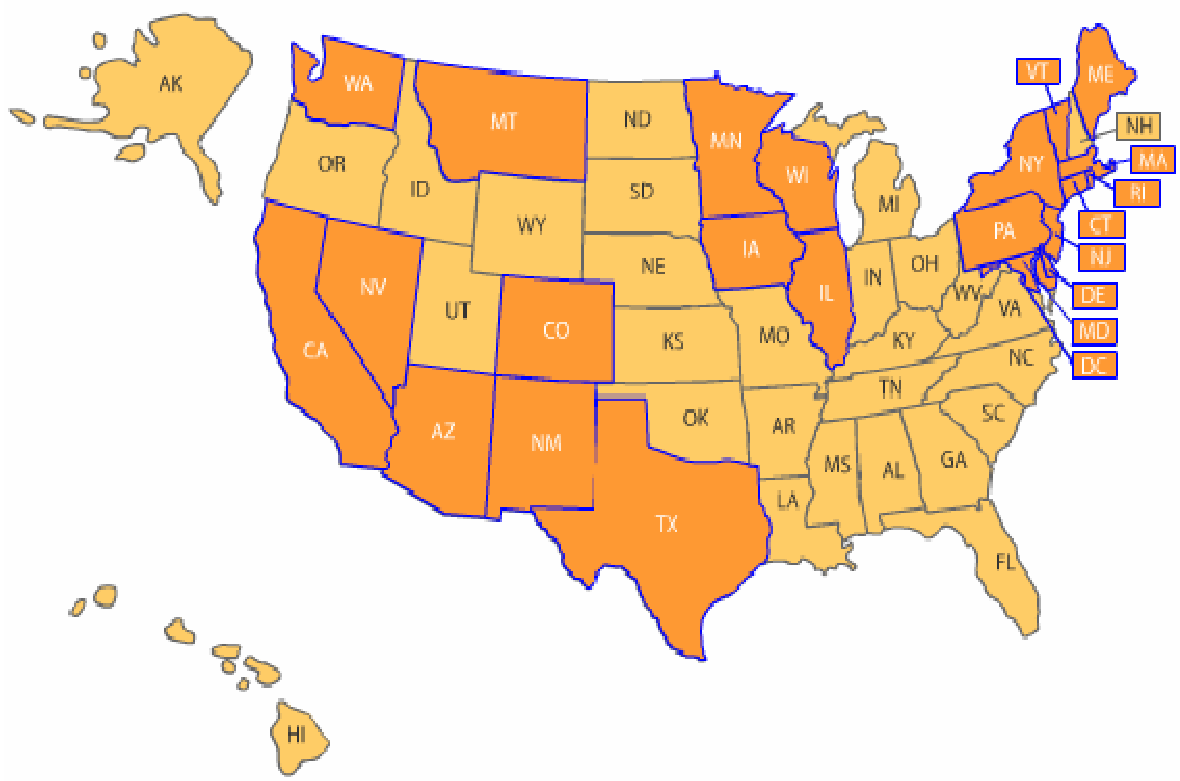
- Renewable Portfolio Standards, Electric Utility Deregulation, Aging T&D Infrastructure, Demand and Supply, End-Use Efficiency, Pollution
- State & regional regulation
  - Net metering, decoupling, RGGI, Western Climate Initiative





CENTER FOR FUTURE ENERGY SYSTEMS
FUEL CELLS AND HYDROGEN • ENERGY EFFICIENCY • RENEWABLE ENERGY
Rensselaer FUTURE ENERGY SYSTEMS

States with Renewable Portfolio Standard



Ex: New York’s PSC adopted RPS in Sept 2004

Main Tier

- 3,583 MW @ 0.38 CF 11,988,888 MWh/yr
- Wind, Biomass, Biofuel, etc
- Total Funds: $762 million (2006-’13)

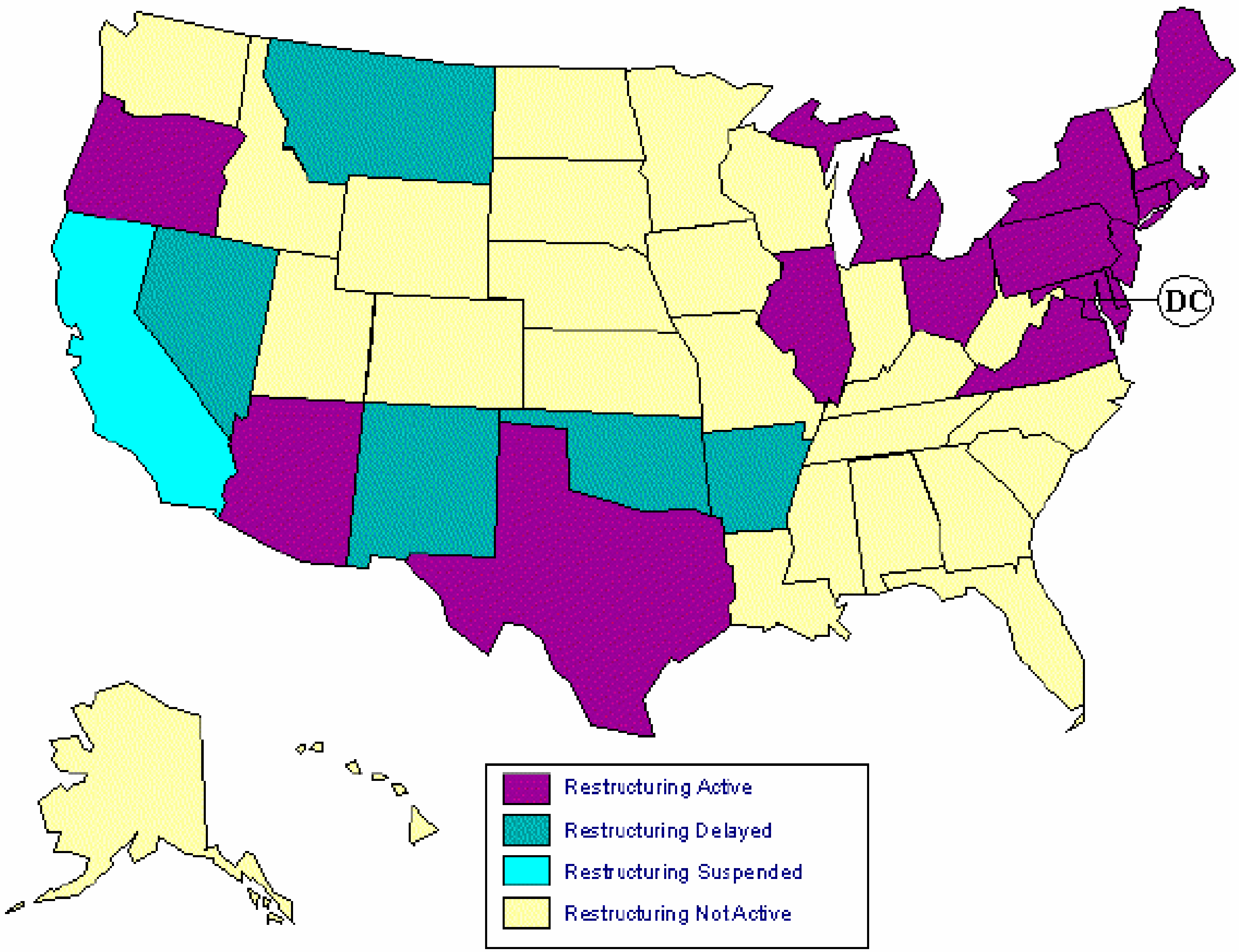
Customer Tier

- 44 MW @ 0.61 CF 239,778 MWh/yr
- Solar PV, Small wind, Fuel Cells, and Farm ADG
- Total Funds: $130 million (2006-’13)

State	Amount	Year
Arizona	15%	2025
California	20%	2017
Colorado	10%	2015
Connecticut	10%	2010
District of Columbia	11%	2022
Delaware	10%	2019
Hawaii	20%	2020
Iowa	105 MW	
Illinois	25%	2017
Mass	4%	2009
Maryland	7.5%	2019
Maine	10%	2017
Minnesota	1,125 MW	2010
Montana	15%	2015
New Jersey	6.5%	2008
New Mexico	10%	2011
Nevada	20%	2015
New York	25%	2013
Pennsylvania	18%	2020
Rhode Island	15%	2020
Texas	5,880 MW	2015
Vermont*	10%	2013
Washington	15%	2020
Wisconsin	2.2%	2011

CENTER FOR FUTURE ENERGY SYSTEMS
FUEL CELLS AND HYDROGEN • ENERGY EFFICIENCY • RENEWABLE ENERGY
Rensselaer
FUTURE ENERGY SYSTEMS

Status of Electric Utility Deregulation

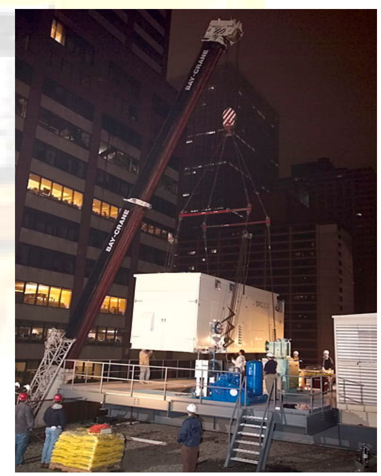


Clean/Green Technologies

- **Wind**
  - Both as large wind farms (utility scale/wholesale) and small wind turbines (customer sited/retail)

- **Photovoltaic**
  - Primarily customer sited (behind the meter) serving a load – often enjoys net-metering

- **Fuel Cells**
  - Both large (200 – 1000 KW) and small (5 – 25 KW) are typically sited behind the meter

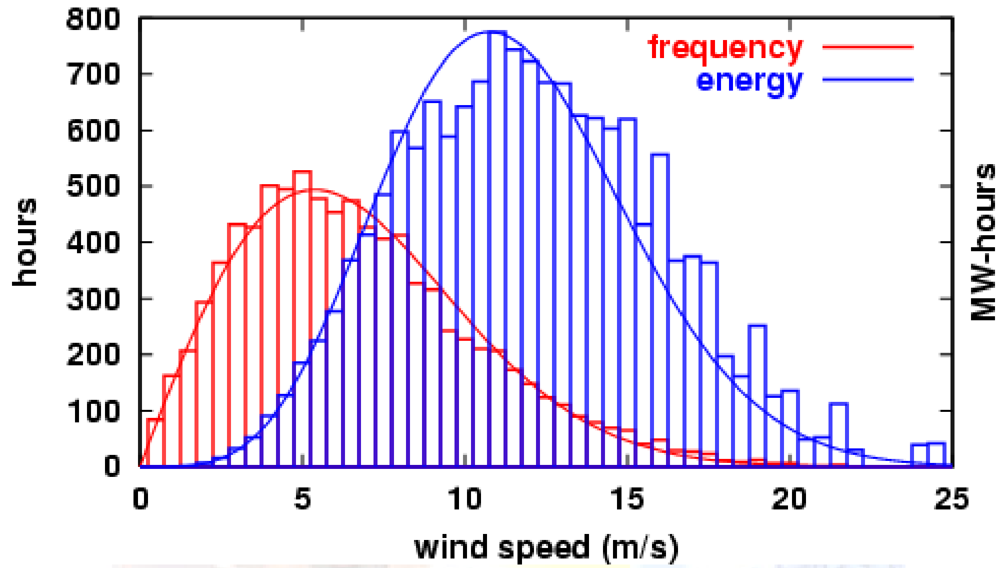


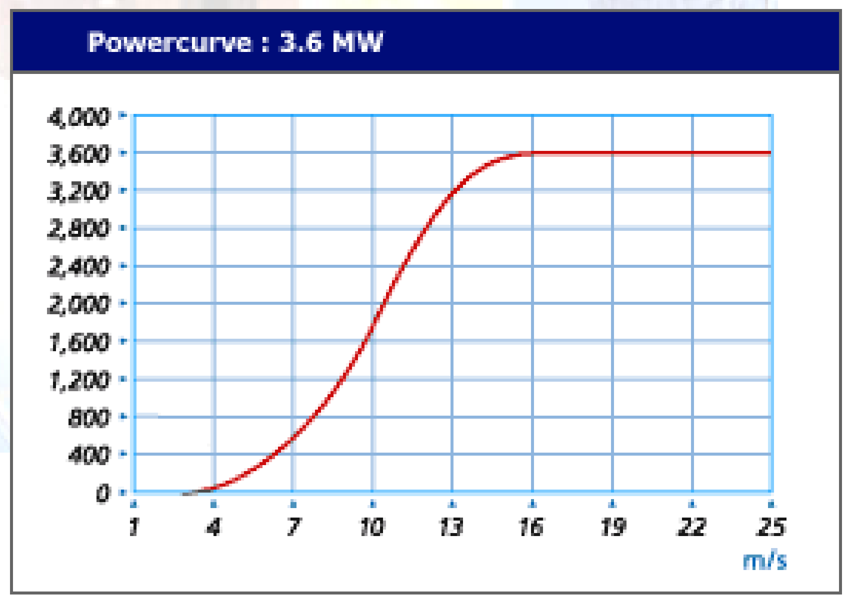
Wind, PV vs. Fuel Cells

	Wind	Photovoltaic	Fuel Cells
Primary Application	Supply Side	Behind the Meter with Net-metering	Behind the Meter
Available Size Range	1000 to 3500 kW	1 to 100s kW	200 – 1000 kW
Tariff/Potential Revenue	\$0.05 - \$0.08 /kWh	\$0.10 - \$0.15 /kWh	\$0.10 - \$0.15 /kWh
Fuel Costs	None	None	\$0.04 - \$0.06 /kWh (w. O&M)
Co-Products (value)	None	None	Heat (\$0.02 /kWh±)
Market Readiness	Commercially Available	Si-based: Commercial CIGS, others – Early Stages	PAFC, MCFC – Commercial PEM, SOFC – Emerging
Major Technological Challenges (/R&D needs)	Efficiency, capacity factor, storage (generally applied)	Efficiency, Process Optimization, manufacturing scale-up	Membranes, catalyst, system engineering, BOP
Cost target	\$1000 /kW	\$1000 - \$1500 /kW	\$500 - \$1000 /kW
Emissions	None	None	CO_2 at fuel source
Capacity Factors	20 – 30%	10 – 20%	90% +

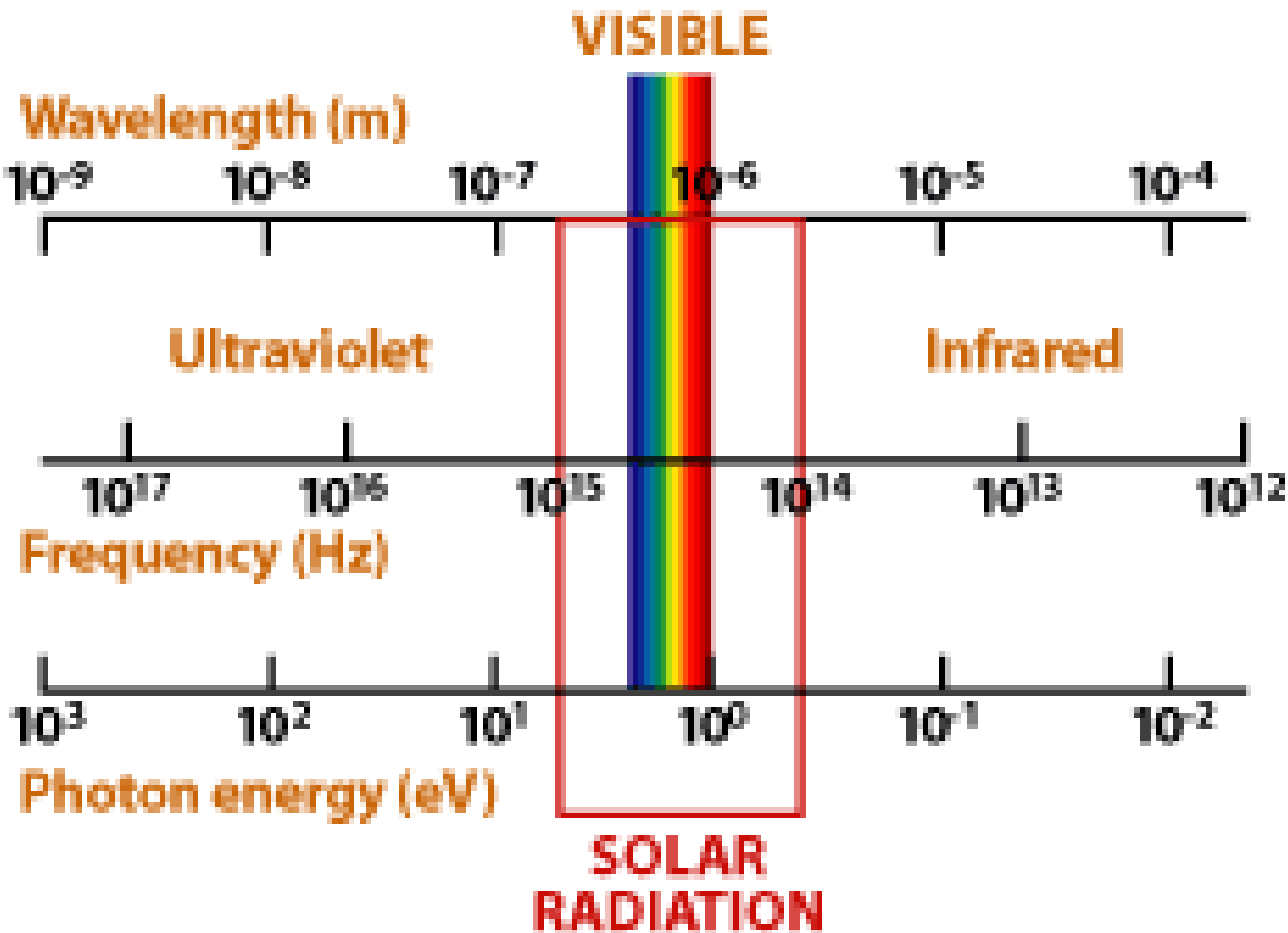
Wind Energy R&D Needs

- To develop wind mill designs with higher capacity factors
  - Pitch and yaw control, noise mitigation, performance enhancement (jet actuators)
- To improve the manufacturing methods and to reduce the cost of fabrication by an order of magnitude
- To fully characterize aerodynamic performance and power output forecasting of currently available and new wind turbine designs
- Integration of advanced power electronics and energy/power storage systems suitable to handle transients and outages



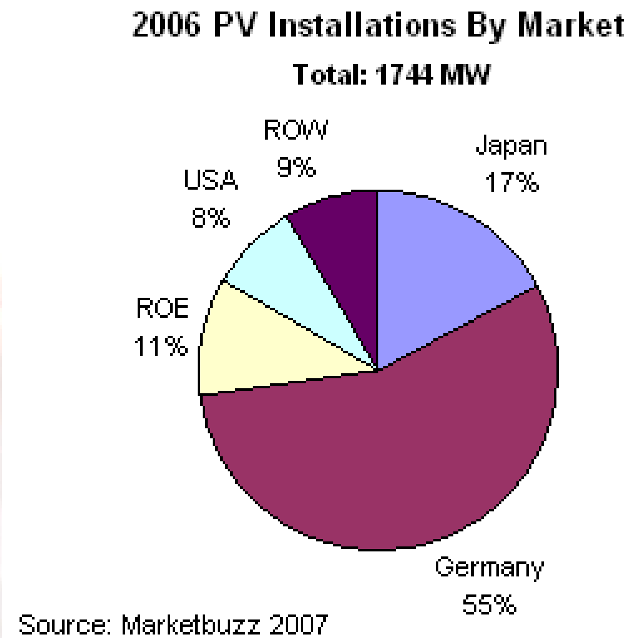


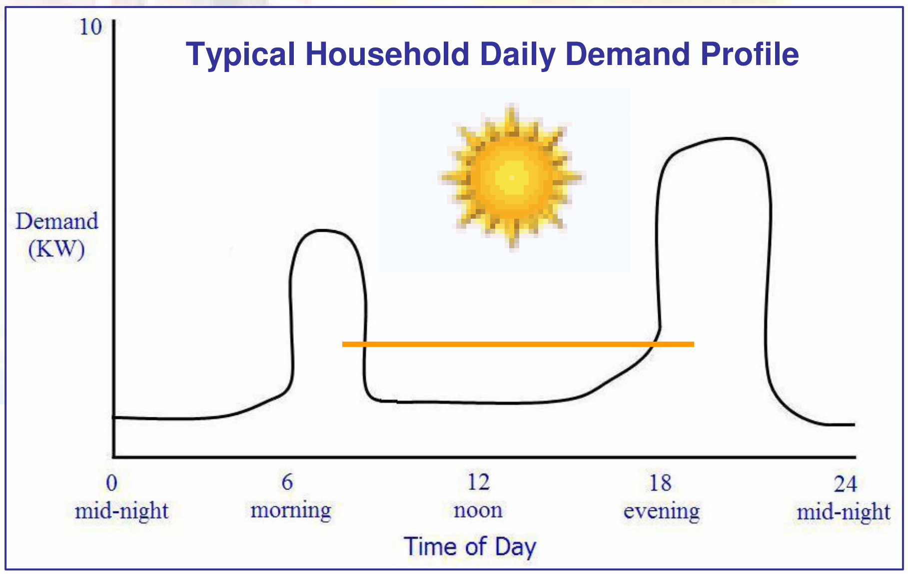
Solar Radiation



Photovoltaic (PV) Market Drivers

- World solar PV market installations reached a record high of 1,744 MW in 2006 - growth of 19% over the previous year.
- In 2006, 112 MW of PV was installed in the US (grid connected) - up from 80 MW in 2005.
- Demand was led by California, which accounted for 63% of the national market followed by New Jersey at 17%.
- Following the 2006 launch of the $3.3 billion California Solar Initiative (CSI) program, the growth prospects for the US grid connect market have increased dramatically.



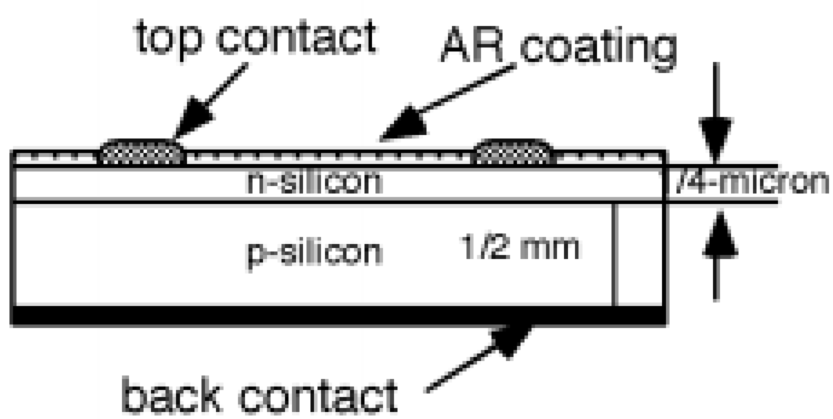


Photovoltaic Technologies - Silicon

A solar cell (or photovoltaic cell) is a semiconductor device that converts photons into electricity. Fundamentally, the device needs to fulfill only two functions: photogeneration of charge carriers (electrons and holes) in a light-absorbing material, and separation of the charge carriers to a conductive contact that will transmit the electricity. This conversion is called the photovoltaic effect.

Silicon cells all have the same general construction

- p-type silicon, typically boron (bottom)
- n-type silicon, typically phosphorus (top)
- Anti-reflective coating (TiO_2, Si_3N_4)
- Metal contacts

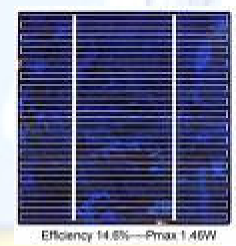


Side View

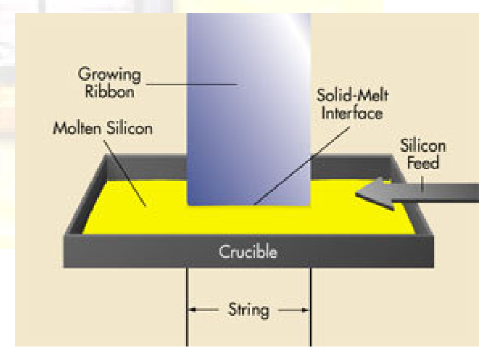
Photovoltaic Technologies - Silicon

- **Single Crystal**
  - Ingots drawn using Czochralski process
  - Ingots cut to produce wafers
  - Pros: Highest efficiency silicon cells
  - Cons: Ingots are cylindrical leading to round wafers and most expensive among all silicon technologies

- **Poly-Crystal**
  - Ingots cast in bricks
  - Ingots cut to produce wafers
  - Pros: Ingots can be cut into square wafers and Less costly to produce than single crystal
  - Cons: Lower efficiency than single crystal



- **Ribbon**
  - Films drawn from molten silicon
  - Pros: Lower silicon losses
  - Cons: Slow growth rates



Photovoltaic Technologies – Thin Film

Amorphous Silicon

- CVD using silane and hydrogen
  - ➢ Pros: Less material, flexible cells, and roll-to-roll processing
  - ➢ Cons: Lower efficiency

Copper Indium Gallium Selenide (CIGS)

- Flexible metal substrates offer an alternative to wafer-Si based cells
  - ➢ Pros: Less material, flexible cells, and roll-to-roll processing
  - ➢ Cons: High-manufacturing costs, Indium (over a quarter of world's In)

Cadmium Telluride (CdTe)

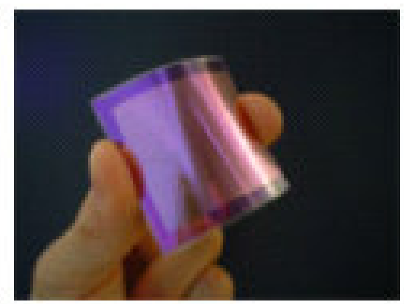
- CdTe p-type layer w. CdS n-type layer and ITO conducting layer
  - ➢ Pros: Less material, flexible cells, and roll-to-roll processing
  - ➢ Cons: Cadmium

III-V Triple Junction Concentrator Cells

- Metalorganic vapor phase epitaxial growth on Germanium substrate
  - ➢ Pros: High efficiency (39%)
  - ➢ Cons: High-manufacturing costs, smaller cells

Polymer/Organic

- Thin-films of organic semiconductors
  - ➢ Pros: Low materials costs and roll-to-roll manufacturing
  - ➢ Cons: Low efficiency and degradation



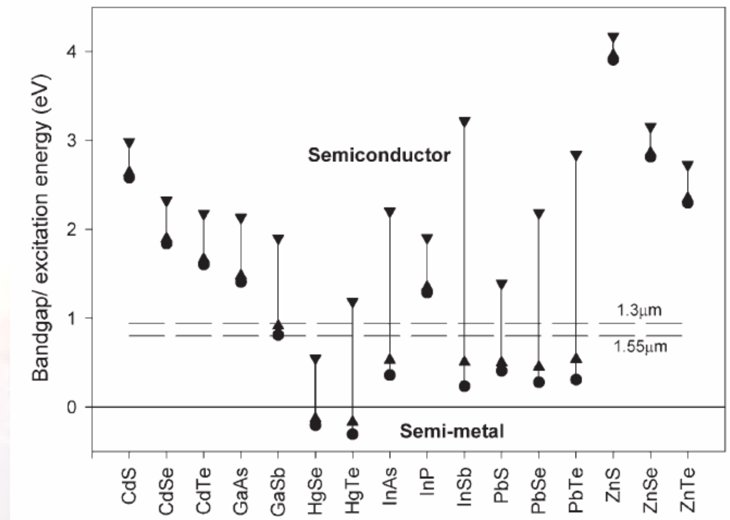
Conformal Solar Cells

Current PV Technologies - Issues

- High cost of Photovoltaics is driven by (a) low photoconversion efficiency, (b) expensive processing, and (c) extensive use of materials
- Only photons that match the bandgap of the semiconductor can be harvested for electrical energy generation
- The excess energy in higher frequency photons (that in blue and violet end of the spectrum) is wasted as heat
- In Gratzel cells, exciton generation in organic dye is very efficient for visible wavelengths (>1.5 eV) but its poor for long and short wavelengths
- The stability of organics, photo-bleaching, thermal degradation, etc. are major concerns with DSSCs

Photovoltaics Development

- Developing photovoltaic devices that are nano-architectured to achieve high efficiency by
  - increasing the interface area to generate high charge carrier populations with minimal recombination, and
  - harvesting a wider range of photon energies to exploit multi-level exciton generation processes



Nano-Architectured Inorganic PV Cells

- Inorganic, low-cost, high-efficiency solar cell architectures that utilize nanomaterials that are capable of multi-exciton generation
- These nano-architectured p-n junction cells offer
  - increased efficiency by the use of wider range of photons
  - Increased in-plane interface area for facilitating charge carrier generation, separation and transport
  - Low out-of-plane interface area to inhibit recombination

Organic PV Cells

- Developing efficient organic and hybrid organic/inorganic photovoltaic cells (OPVs and HPVs)
  - increase OPV efficiency by developing films with optimal nano-scale morphologies for optimal exciton separation and charge transport.
  - develop robust dye-sensitized solar cells (DSSCs, or Gratzel-cells) by using solid and gel electrolytes as well as all inorganic nano-architectured Gratzel-cells.
  - incorporate multi-exciton generating nanoparticles in conjugated polymers, and functionalized titania templates and particles for processing large-area, low-cost, and efficient hybrid photovoltaics.

Improving the Available PV Technologies

Dramatically lowering the manufacturing costs by the use of traditional, vacuum-free, large-area, low-temperature processing technique to deposit thin film photovoltaic materials by

- developing novel processing methodologies based on recent advances in the synthesis of nano-particles and nano-structures aimed at bridging the gap between the presently used processes that are optimized for microelectronics (ex: chemical vapor deposition, plasma deposition) and those applicable for large area fabrication (ex: sol-gel, dip coating, spin coating, screen printing);
- developing innovative technologies to further improve silicon based PV technologies with novel thermal emitters, broad-band anti-reflective coatings, etc
- enhance solar light absorption by integrating photonic bandgap structures in the active layer of photovoltaic cells.

Industrial Collaborative Projects

Starfire

- Develop a parametric understanding of the CVD process to deposit silicon carbide (SiC) and silicon nitride (Si3N4) from a proprietary polymeric precursor
  - The SiC and Si3N4 coatings will be targeted for applications such as thermal emitter and anti-reflective applications on silicon photovoltaic systems.

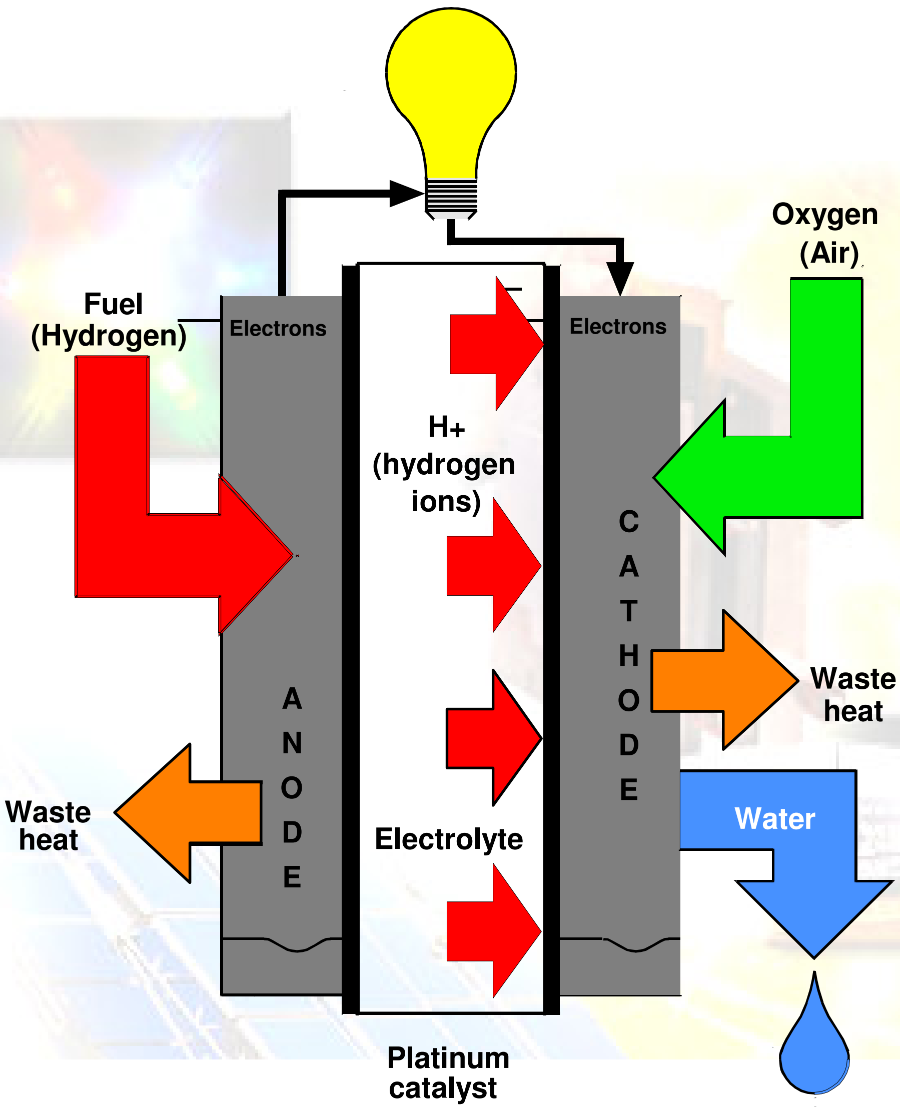
Durable Systems

- Develop a natural gas fueled TPV system for integration into a residential forced air furnace
  - Design a TPV system with power output sufficient to operate a residential furnace in the event of a power outage.

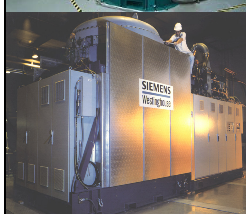
Applied Materials

- Substantially improve energy efficiency of a thermophotovoltaic (*TPV*) generator
  - Develop an efficient photonic-crystal radiator (>50%) using advanced silicon processing; improve radiator's high temperature stability and optical performance; explore a novel design to fully capture (>90%) and concentrate solar radiation using Fresnel lenses.

How Does A Fuel Cell Work



Types of Fuel Cells

Type	Applications	Comments
 Alkaline	80 – 100 C Space	Used by NASA on space missions. Efficiencies can reach 70%. Reliable but expensive.
 PEM	80 – 100 C Premium power and Transportation	Field units in demonstration. Limited Commercialization. Efficiencies reach 40%. Limited heat recovery. Potential for low cost.
 Phosphoric Acid	200 – 220 C Stationary power and large vehicular (buses)	Most mature and commercially available. In use at hospital, hotel, school, airport terminal, and small utility plants. El efficiencies reach 40% and 70% with cogeneration.
 Molten Carbonate	600 – 650 C Distributed Power and small utility	Commercially available. In use at WWTPs and some commercial buildings. El efficiencies approach 50% and 80% with cogeneration.
 Solid Oxide	900 – 1000 C Stationary and utility power & Transportation	Currently in demonstration (100 kW). El Efficiencies approach 60% and 85% with cogeneration. Various designs and Applications.

Fuel Cells & Applications

Cell / Fuel Type	PEM	PBI	PAFC	MOFC	SOFC	DMFC
Natural Gas	S & T	S & T	S	S	S & T	
Methane (LFG/ADG)	S		S	S	S	
Propane	S					
Methanol	P	P				P
Ethanol			S	S	T & P	
LPG/Diesel			T	T	T & P	
Hydrogen	S & T	S & T				P
JP – 8					P	

S: Stationary, T: Transportation, P: Portable
Green: Commercial, Orange: Demonstration, Red: Development

Fuel Cell R&D Needs

- Better coordinated and focused effort to develop one or two fuel cell options
  - High-temp chemistries for stationary applications
  - PEM for transportation
- R&D focus on component performance enhancement through improvements in membranes, electrodes, alternative catalysts, system engineering, etc.
- Integration of advanced power electronics and energy/power storage systems suitable to handle transients and outages.
- To improve the manufacturing methods and to reduce the system integration cost by an order of magnitude.

The Future Electricity Distribution Grid of New York State – A Test Bed Validation ($1.5 Million)

Establish a DG-Test Bed to understand the operational characteristics of the distribution grid under a high degree of DG penetration

- Electrical implications from the high penetration and diversity of distributed resources on the utility distribution grid will be examined.
- Stability and dynamic behavior of utility distribution grids with small system inertia - the feasibility of installing DE storage devices to counter balance natural intermittency, system stability and power quality will be studied.
- Power quality interactions among inverter-based DG, particularly relating to harmonics and voltage sags and surges, will be examined.
- New DG control features that meet IEEE 1741 will be developed and tested.

Superconductivity

- **Nearly zero electrical resistance at low temperatures**
  - Low Temperature Superconducting (LTS)
    - Metallic – Niobium based
    - Require cryogenic cooling/liquid Helium
  - High Temperature Superconducting (HTS)
    - Ceramic – BSCO, YBCO, etc.
    - Superconducting at 77 K (Liquid Nitrogen Temp.)
    - Difficult to process into defect-free wires
- **High Temperature Superconducting (HTS) Products**
  - power generators - increase efficiency by 0.45% (nearly one-half of the remaining generator losses)
  - large motors – motors consume half of country's electric energy
  - transformers – eliminate nearly 80% (all I2R) of transformer losses (saving $250 M+ for NYS)
  - power lines (underground) - increase power delivery by a factor of 3 to 5 in the same diameter duct and enable two-way power transmission in the future

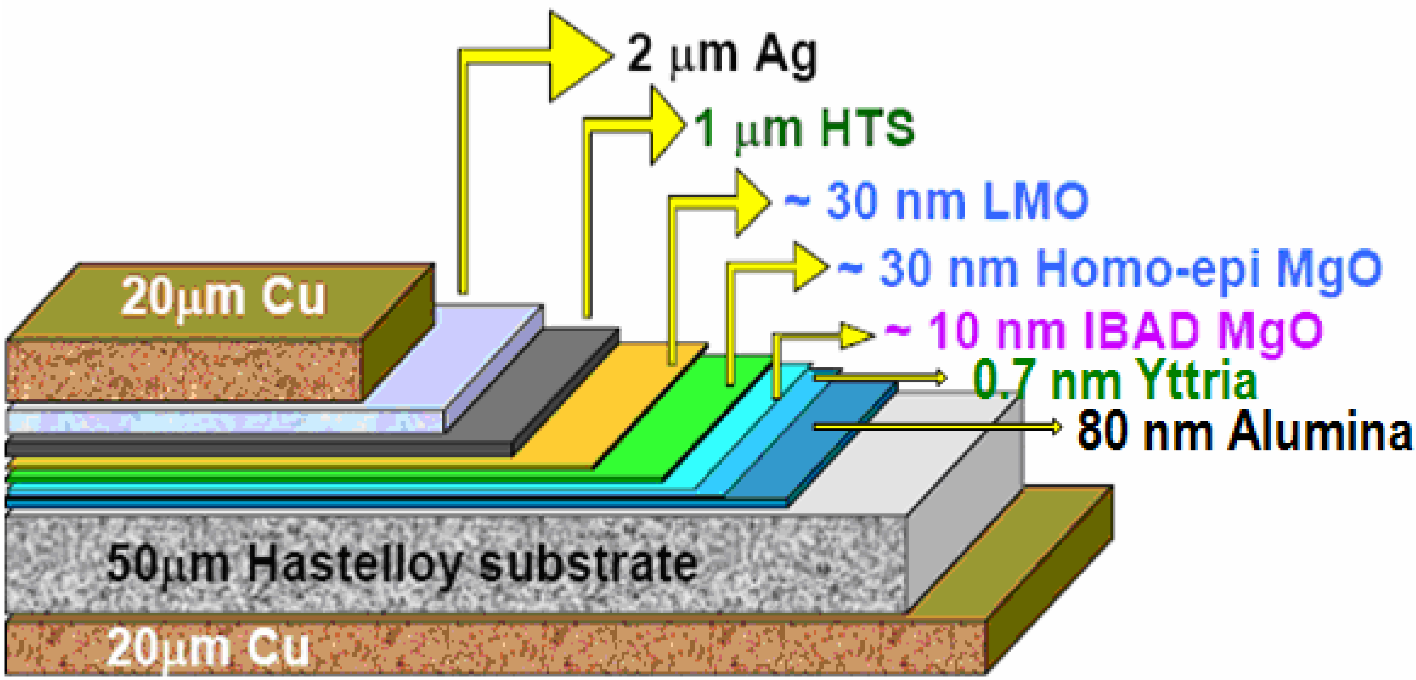
High Temperature Superconductivity (HTS)

Develop new photolithographic etching techniques to produce striated 2G (YBCO) HTS tape

- ➢ Reduces ac losses in 2G HTS materials

• Identify and demonstrate use of process alternatives to copper electroplating and enable direct application of copper over HTS (eliminating silver layer)

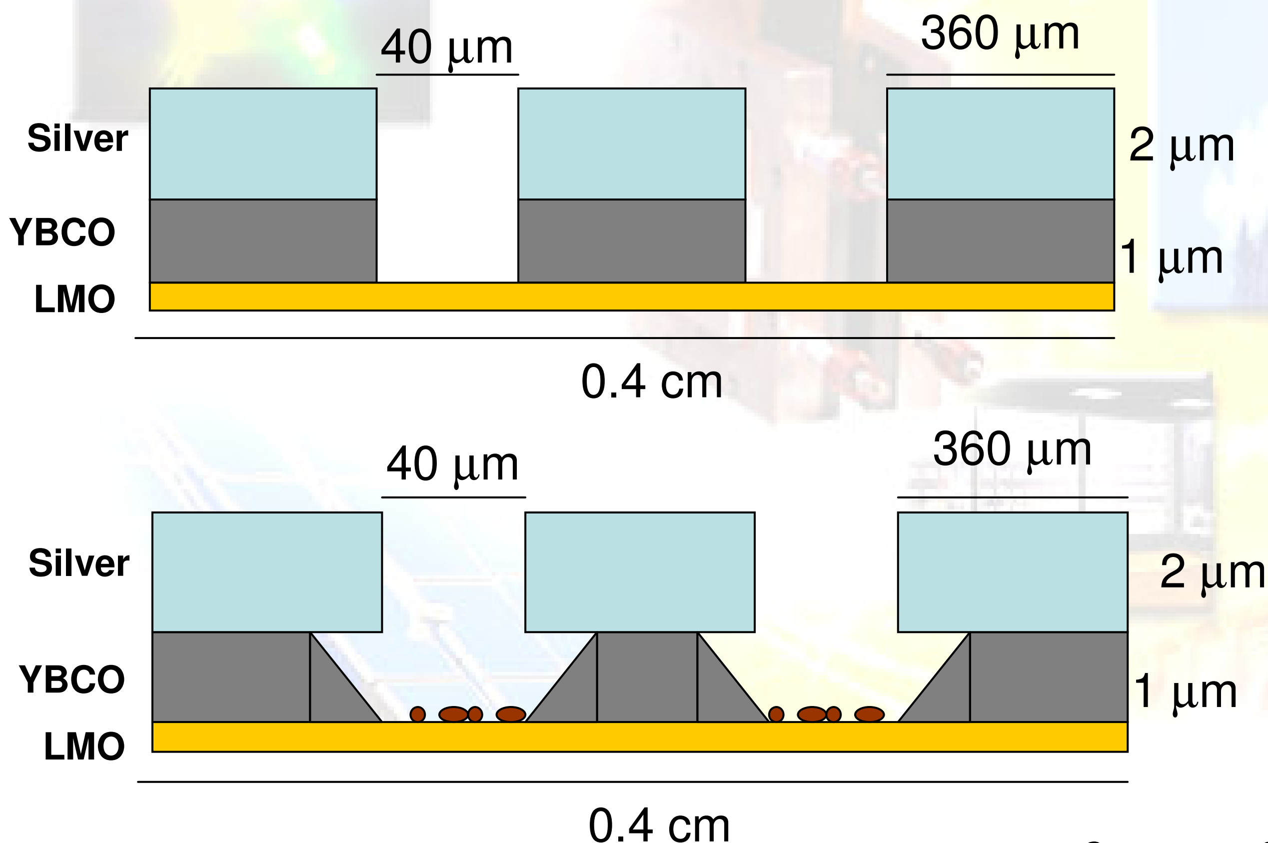
- ➢ The project supports processes that are suitable for the roll-to-roll manufacturing of 2G HTS tape.



Picture: Courtesy of SuperPower

HTS - AC loss

- Current in a superconductor generates a magnetic field around the conductor, which is called the self-field. With the alternating current, the alternating self-field penetrates the superconductor during each current cycle. Even if there is no external magnetic field, the variation of the self-field inside the material causes a hysteresis loss, which is called self-field loss
- One promising approach to reduce the hysteresis loss is to divide a wide tape into several narrow superconducting stripes separated by non-superconducting barriers.



Courtesy of G. Pethuraja

Summary & Conclusions

Critical energy issues facing us today need a viable and sustainable long-term strategy with contributions from

- Fundamental Technology Development
- Energy Efficiency
- Clean and/or Renewable Generation
- Public Policy and Financial Incentives
- Education & Outreach

ACKNOWLEDGEMENTS

Collaborators

Prof. G. Ramanath

Prof. Partha Dutta

Dr. G. Pethuraja

Rick Robertson

Adam Gennett

Doug Notaro

CENTER FOR FUTURE ENERGY SYSTEMS

FUEL CELLS AND HYDROGEN • ENERGY EFFICIENCY • RENEWABLE ENERGY

Rensselaer

FUTURE ENERGY SYSTEMS