GLOBAL CLIMATE AND ENERGY PROJECT | STANFORD UNIVERSITY

GCEP

Advanced Energy Technologies

International Energy Workshop| STANFORD, CA

Sally Benson

Director, Global Climate and Energy Project
Stanford University

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GLOBAL CHALLENGES – GLOBAL SOLUTIONS – GLOBAL OPPORTUNITIES

Technology Requirements for our Global Energy System

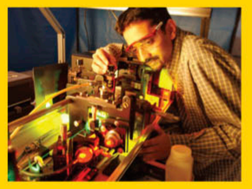
Accessible
- Reliable
- Useful
- Equitable

Affordable
- Predictable
- Competitive
- Resilient
- Profitable

Protective
- Air Quality
- Climate
- Water Resources
- Ecosystems

Secure
- Compatible with National Interests
- Immune from Political Manipulation
- Abundant in Times of Turmoil

Global Climate and Energy Project Goals



Excellent science

Breakthrough energy technologies

Future energy thought leaders and research workforce

Clean sustainable planet

- Discovering new scientific concepts for energy supply and conversions
- Developing breakthrough energy technologies
- Educating future energy thought leaders and research workforce

….to enable affordable, safe, secure and clean energy for everyone

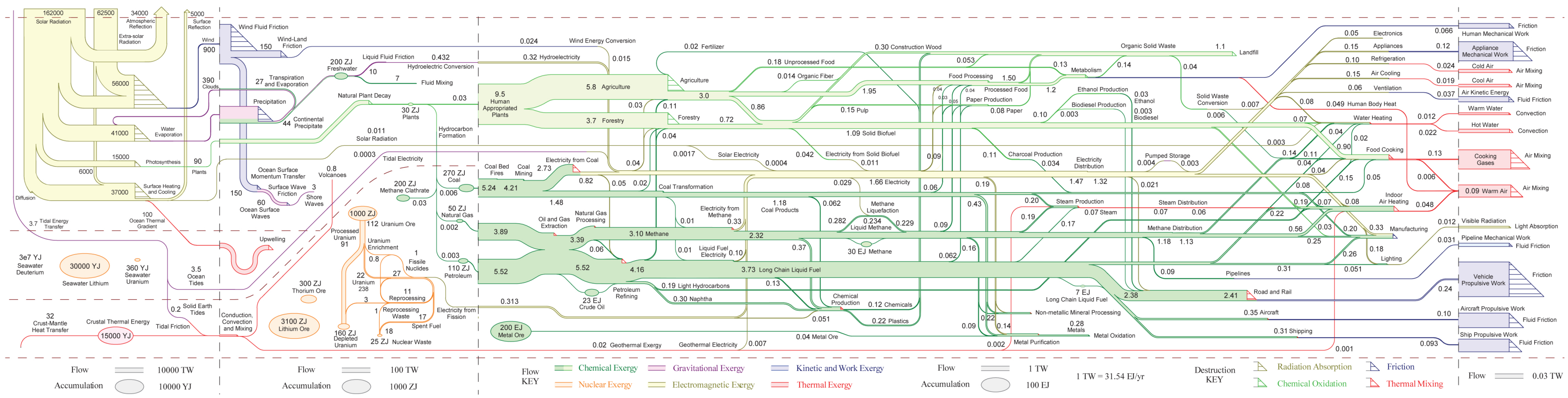
9 billion people = 2 times current global energy supply

Strategy

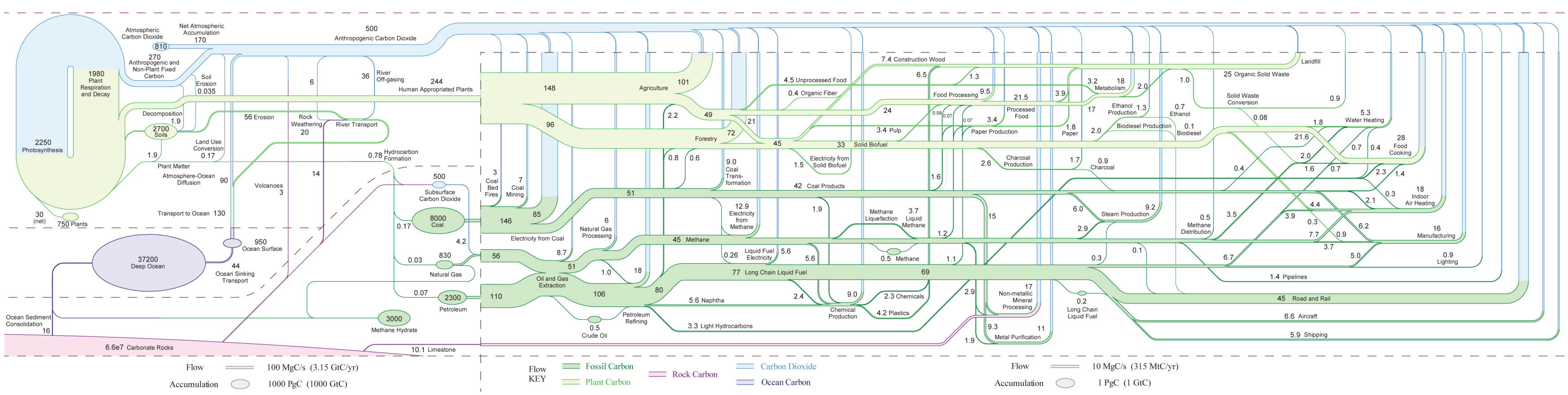
- Develop a deep understanding of our energy system
  … energy resources
  … energy use
  … energy system tradeoffs and co-benefits
- Identify areas of research with the greatest potential for providing affordable, safe, secure, and clean energy
- Support use-directed fundamental scientific and engineering research
- Share ideas and results with the global energy community
- Foster follow-on and scale-up research to commercialize successful inventions

Exegetic Analysis of the Global Energy System

a. Global Exergy Accumulation, Flow, and Destruction



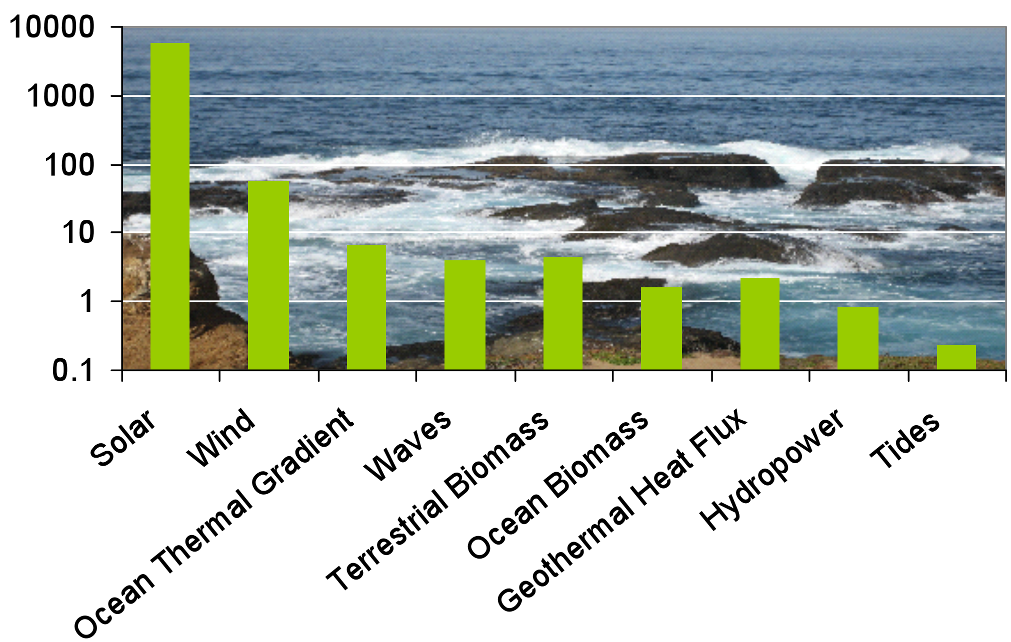
b. The Natural and Anthropogenic Carbon Cycle



Energy System Insights

Energy Resources

- Renewable energy resources from the sun and wind are large compared to human energy use… biomass is a very distant 3rd
- Fossil fuels won't run out any time soon…but have large CO_2 emissions …and energy security concerns …will be more expensive
- Nuclear energy resources are large… but challenges are significant



Energy Systems Insights

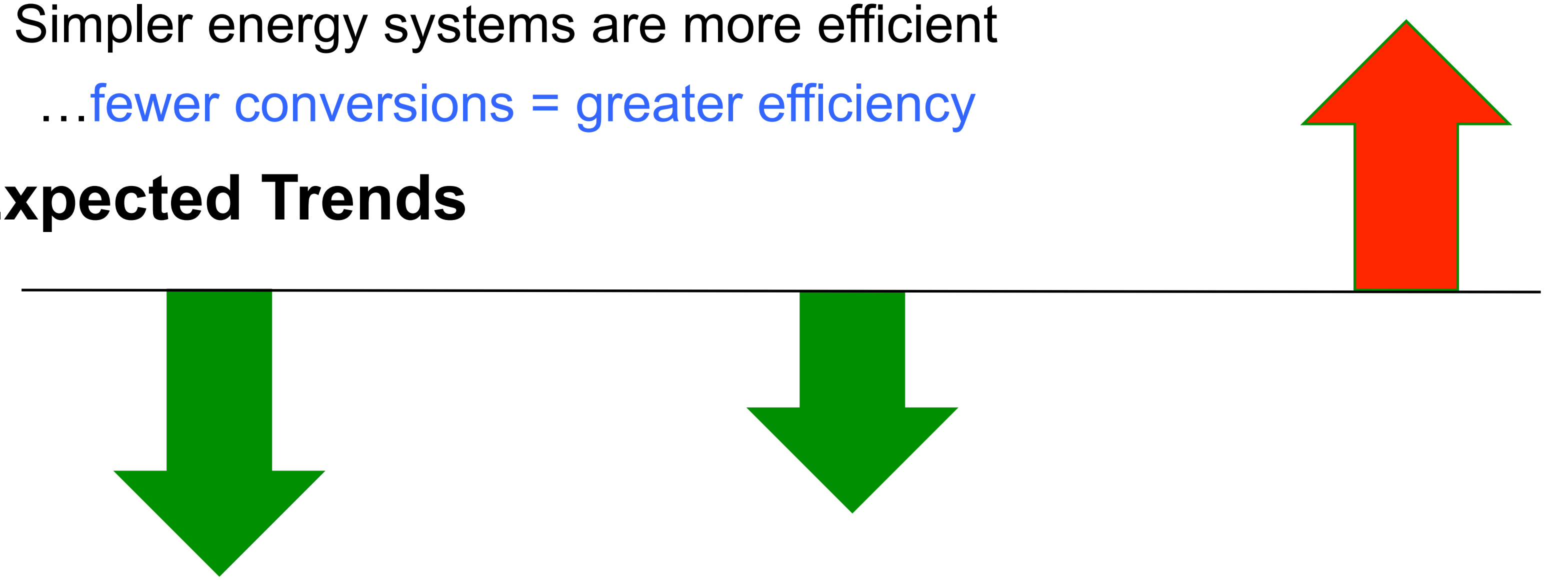
Energy Conversions

- Human energy use requires transformations from one form to another
- All energy conversions are inefficient but can be improved

  … electricity, transportation, buildings
- Simpler energy systems are more efficient

  …fewer conversions = greater efficiency

Expected Trends



End Use Energy Efficiency

Energy Conversion Technology Efficiency (e.g. improved engines)

Lower resource extraction efficiency (e.g. oil sands)

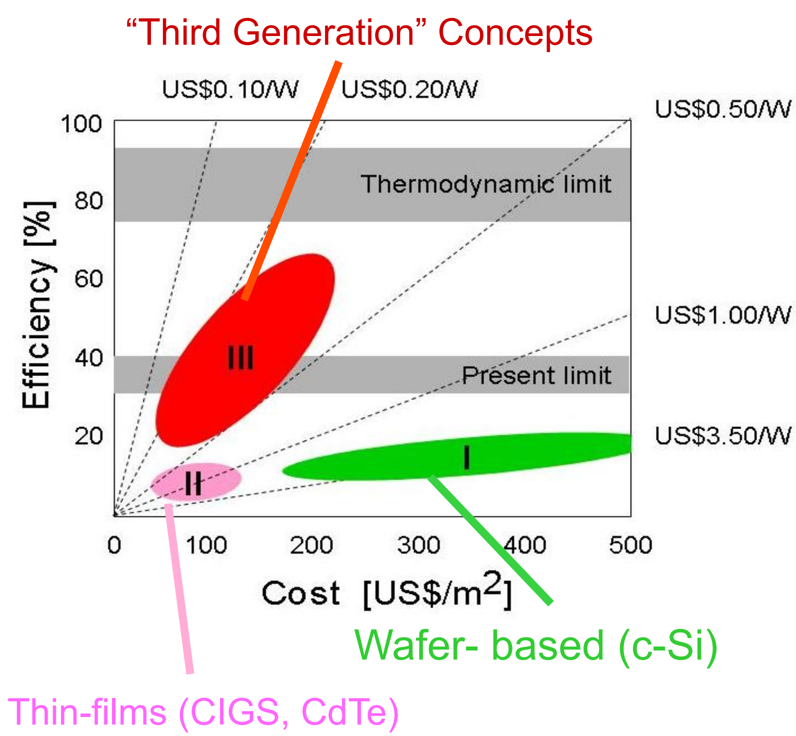
It Costs Energy to Generate Energy

$$Energy\ Payback\ Time = \frac{Embodied\ Energy}{Annual\ Energy\ Generation}$$

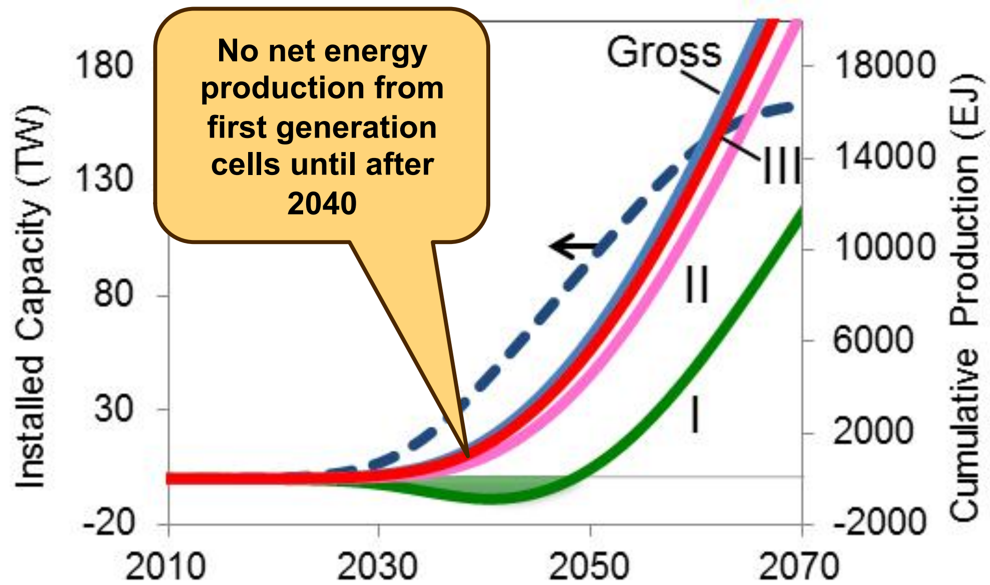
$$Energy\ Return\ on\ Investment = \frac{Lifetime\ Energy\ Generation}{Embodied\ Energy}$$

Lakeview Gusher:	Geothermal:	Biofuels:	Wind Farm:	Hydro:	Coal:	PV Panels:	Nuclear:
EROI ~ 40,000	EROI ~ 5-20	EROI ~ 1-5	EROI ~ 20-30	EROI ~ 20-200	EROI ~ 20-300	EROI ~ 5-15	EROI ~ 10-20
PB ~ 3 mins	PB ~ 2-5 y		PB ~ 0.6-1.5y	PB ~ 1-3 y	PB ~ 0.5-5 y	PB ~ 3-8 y	PB ~ 2-4 y

It costs energy to generate energy



Net Energy Yields for PV



Embodied Energy

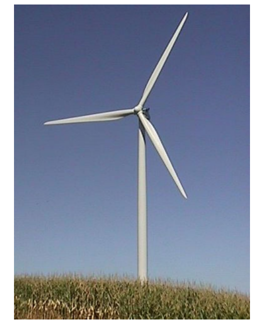
Gen 1: 60 MJ/MW
Gen 2: 17 MJ/MW
Gen 3: 6 MJ/MW

PV capacity growth rate of 30% per year from Year 2000 stabilizing at 1000 EJ/yr by 2100

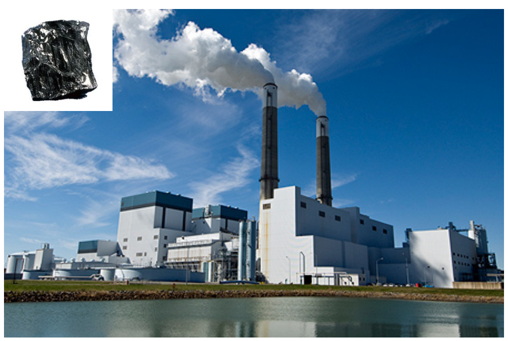
Capacity Factors and Conversion Efficiency For New Energy Technologies Tends to be Low

Nuclear
- Capacity Factor = 80 %
- Avg. Conv. Efficiency = 30 %

Natural Gas
- Capacity Factor = 11 %
- Avg. Conv. Efficiency = 40 %



Wind
- Capacity Factor = 35 %
- Avg. Conv. Efficiency = 50%



Coal
- Capacity Factor = 70 %
- Avg. Conv. Efficiency = 30 %

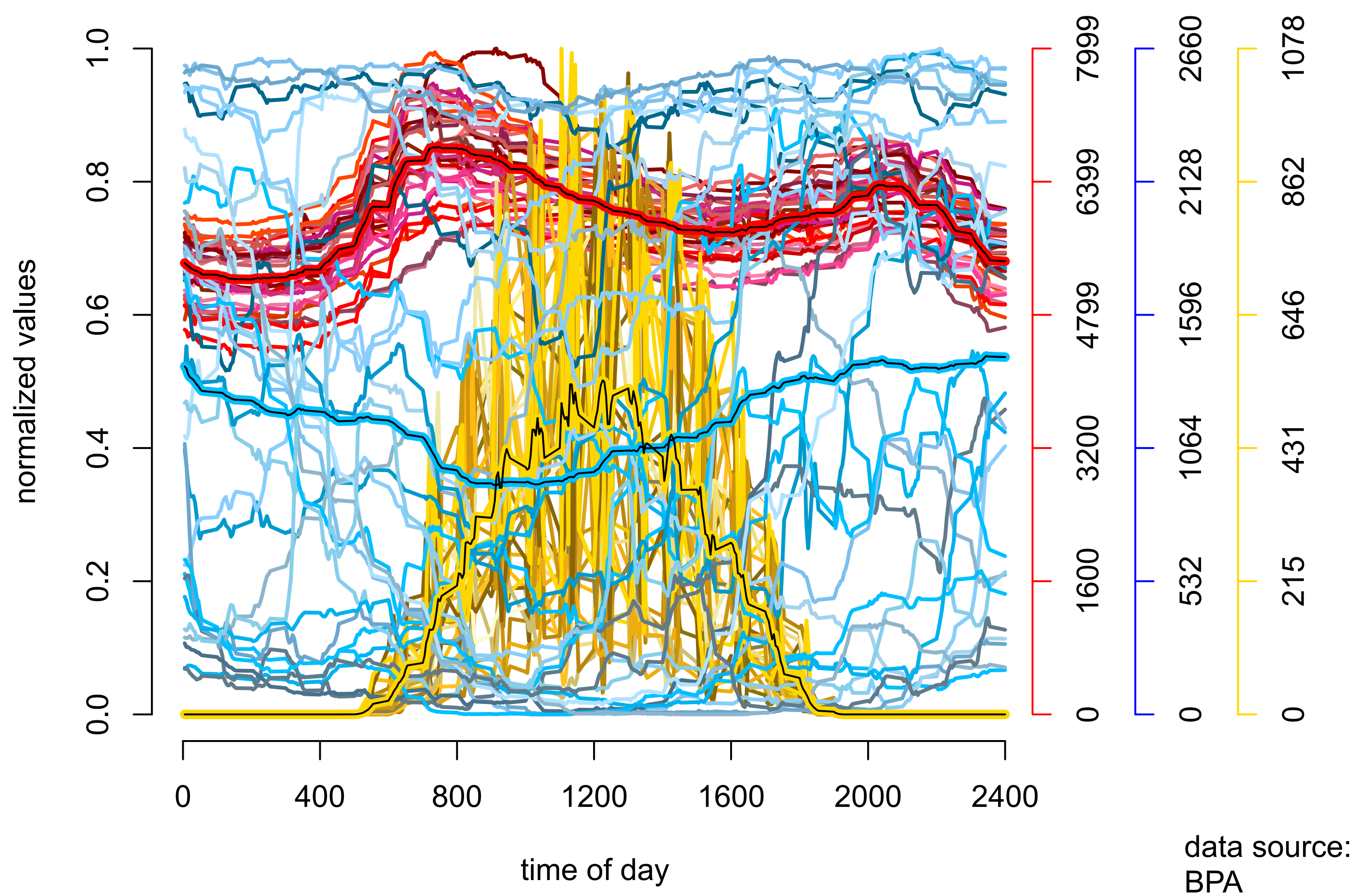
Solar
- Capacity Factor = 20 %
- Avg. Conv. Efficiency = 15 %

Hydro
- Capacity Factor = 40 %
- Avg. Conv. Efficiency = 90%

Source: US EIA, http://www.eia.doe.gov/cneaf/electricity/epa/epata6.html

Intermittent resources require storage

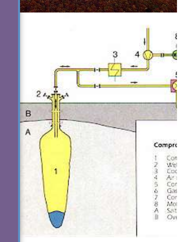
April 2010, 30 days of demand (MW), wind (MW), and solar (W/m2)



data source: BPA

Power Stability

Electric Grid-Scale Storage



Challenges: Cost, Energy Losses, Implementation at scale

Energy Systems Insights

Energy Technology Requirements

- Scale is enormous, therefore

  …portfolio of energy supply and conversions

  …rely on earth abundant and non-toxic materials

  …maximize conversion efficiencies

  …minimize water use

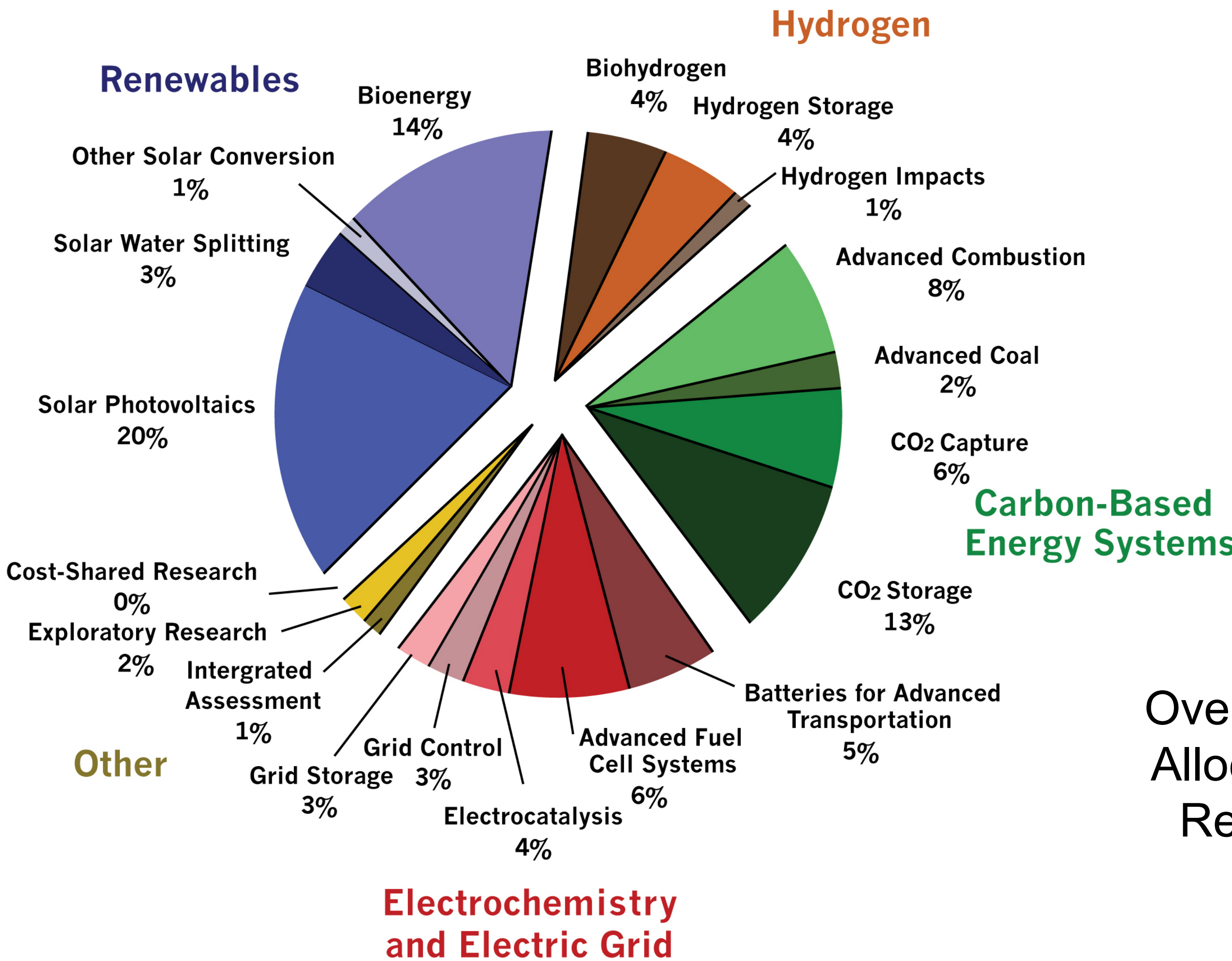
  …short energy payback times

  ... large energy return on investment, durable energy technologies

  ... maximize capacity factor

  … large scale storage will be needed for a renewable-dominated energy system

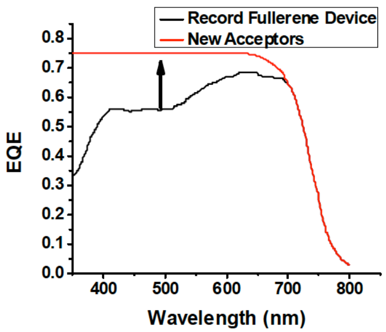
GCEP Research Portfolio, April, 2011
- Cumulative since Beginning of Project

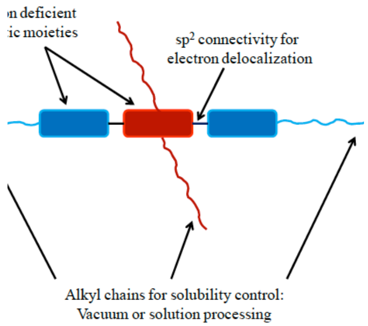


Over $106M Allocated to Research

GCEP Research Projects in Solar Energy

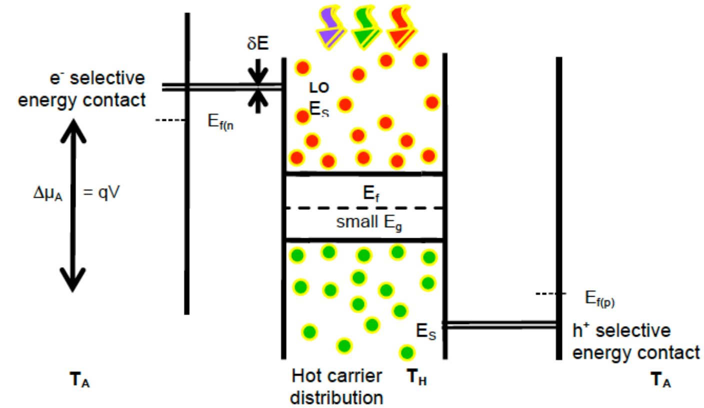
Advanced Electron Transport Materials – McGehee and Sellinger





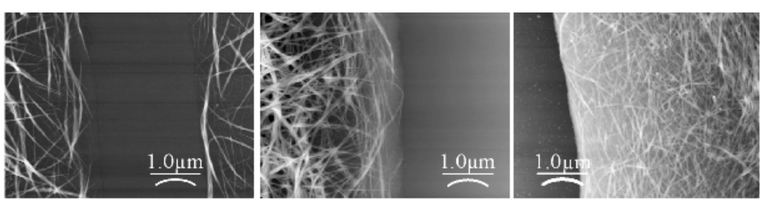
Tailor-made molecules for enhanced light-capture in organic photovoltaics

Hot Carriers - Conibeer



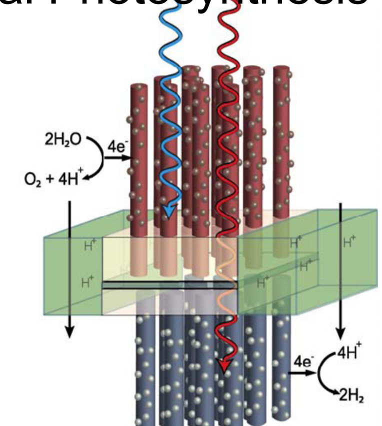
Capturing electrons before they “hit ground” for increased solar cell efficiency

Carbon Nanotube Electrodes - Bao



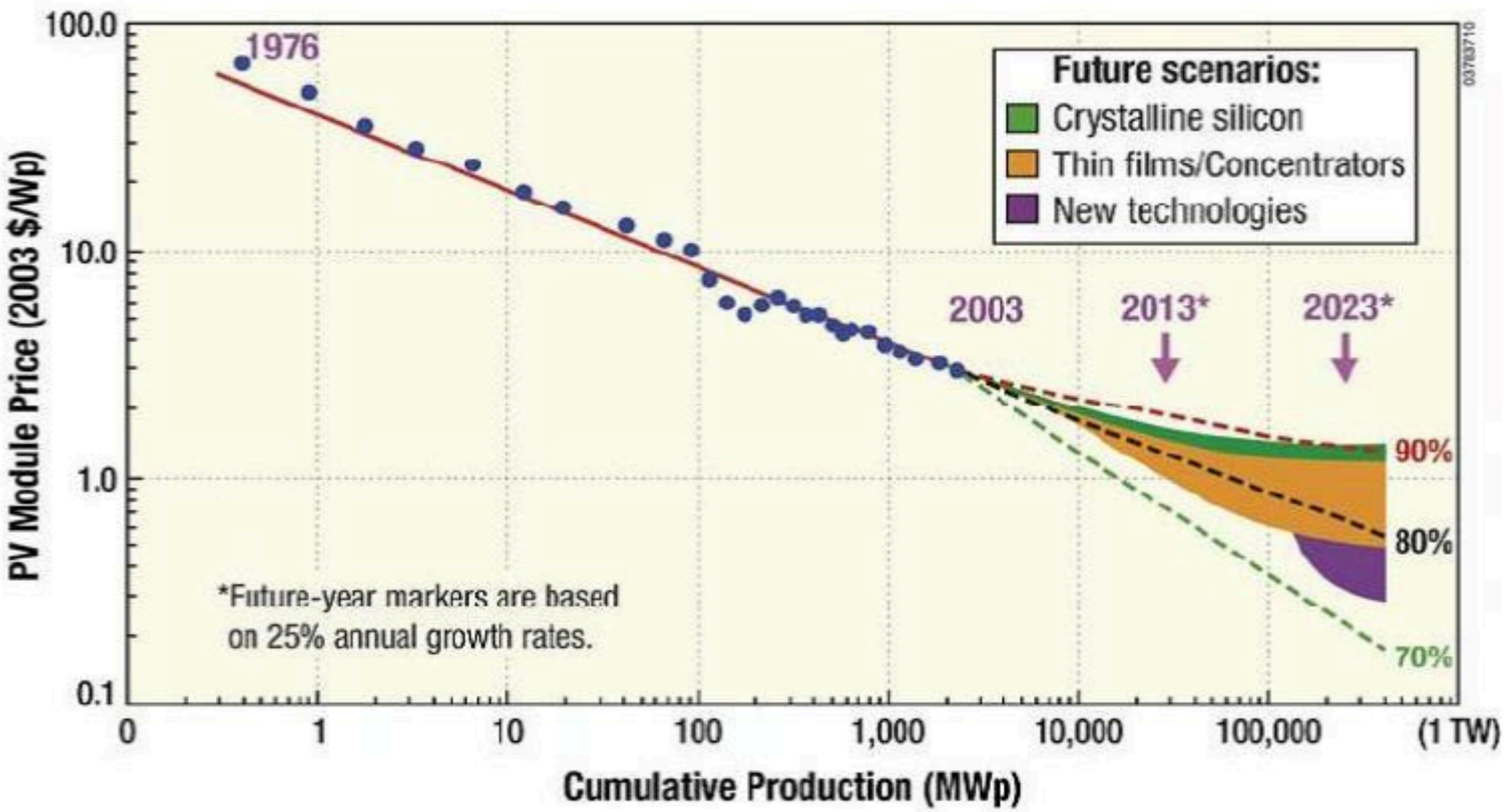
Self-sorting networks for high performance solar cells

Artificial Photosynthesis - Lewis



Direct Hydrogen Production from Solar Energy

Costs of Solar PV Are Decreasing Quickly: Prospects Are Excellent



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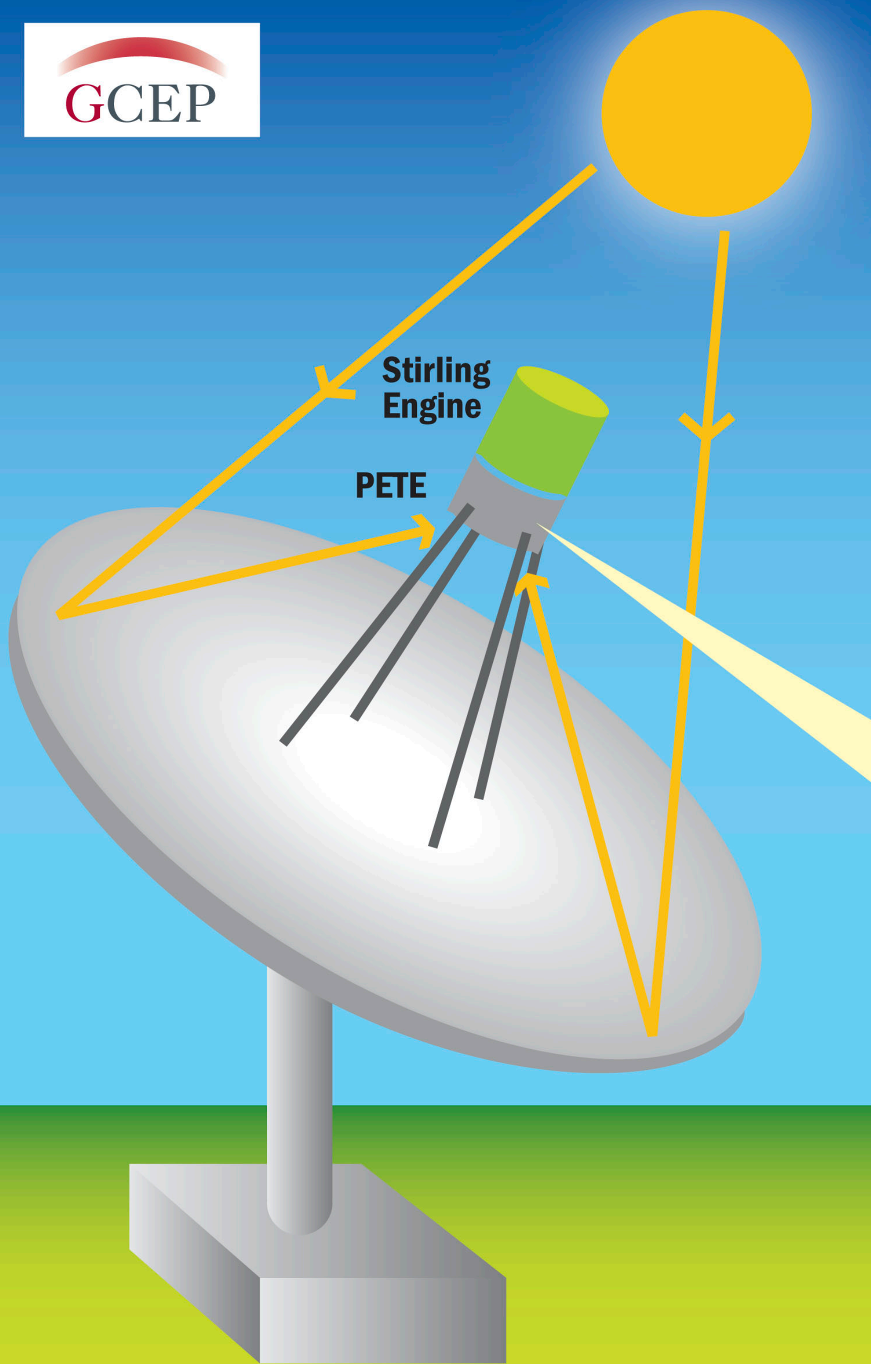
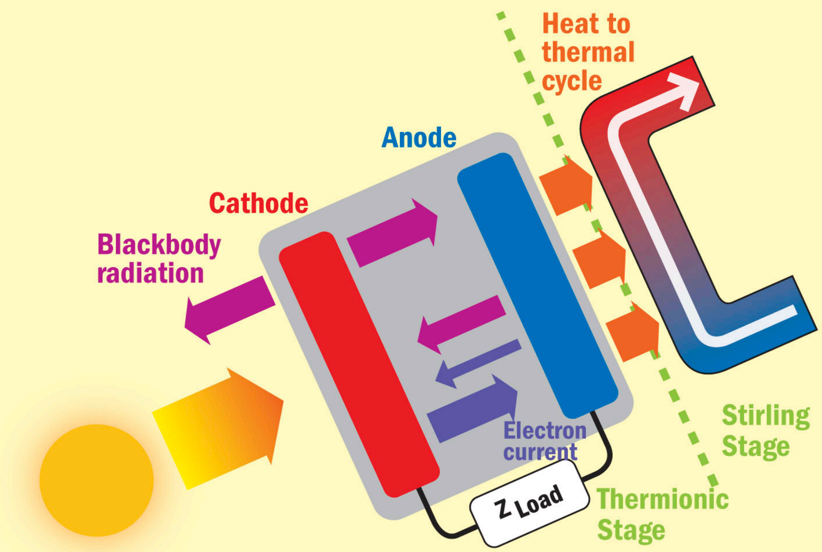
GCEP RESEARCH FOR ADVANCED SOLAR ENERGY CONVERSION

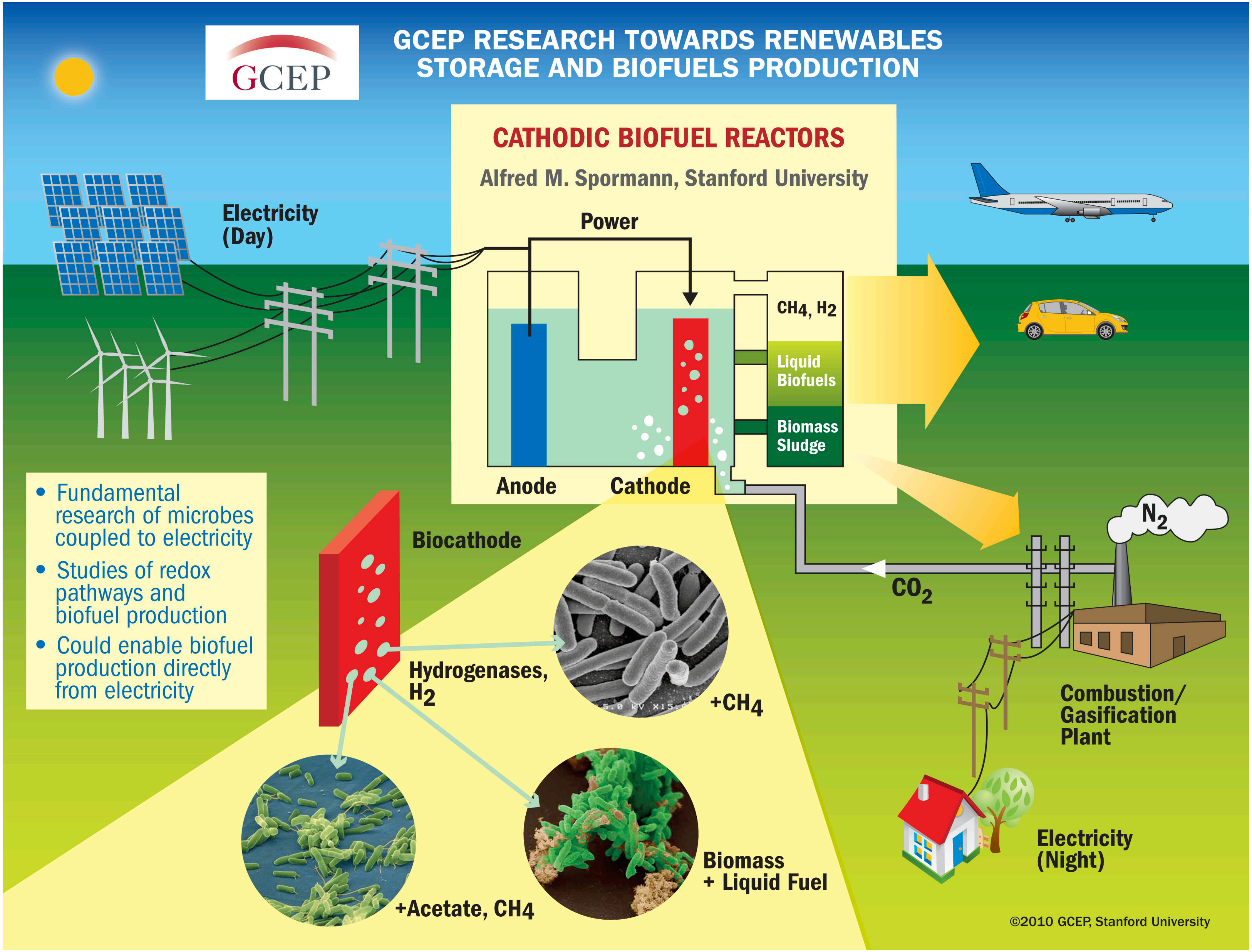


PHOTON ENHANCED THERMIONIC EMISSION (PETE) FOR SOLAR CONCENTRATOR SYSTEMS

Nick Melosh and ZX Shen, Stanford University



- Approach combines quantum and thermal mechanisms into a single physical process.
- Waste heat from PETE device is used to power a secondary thermal engine.
- Theoretical combined conversion efficiencies for solar electricity generation are above 50%.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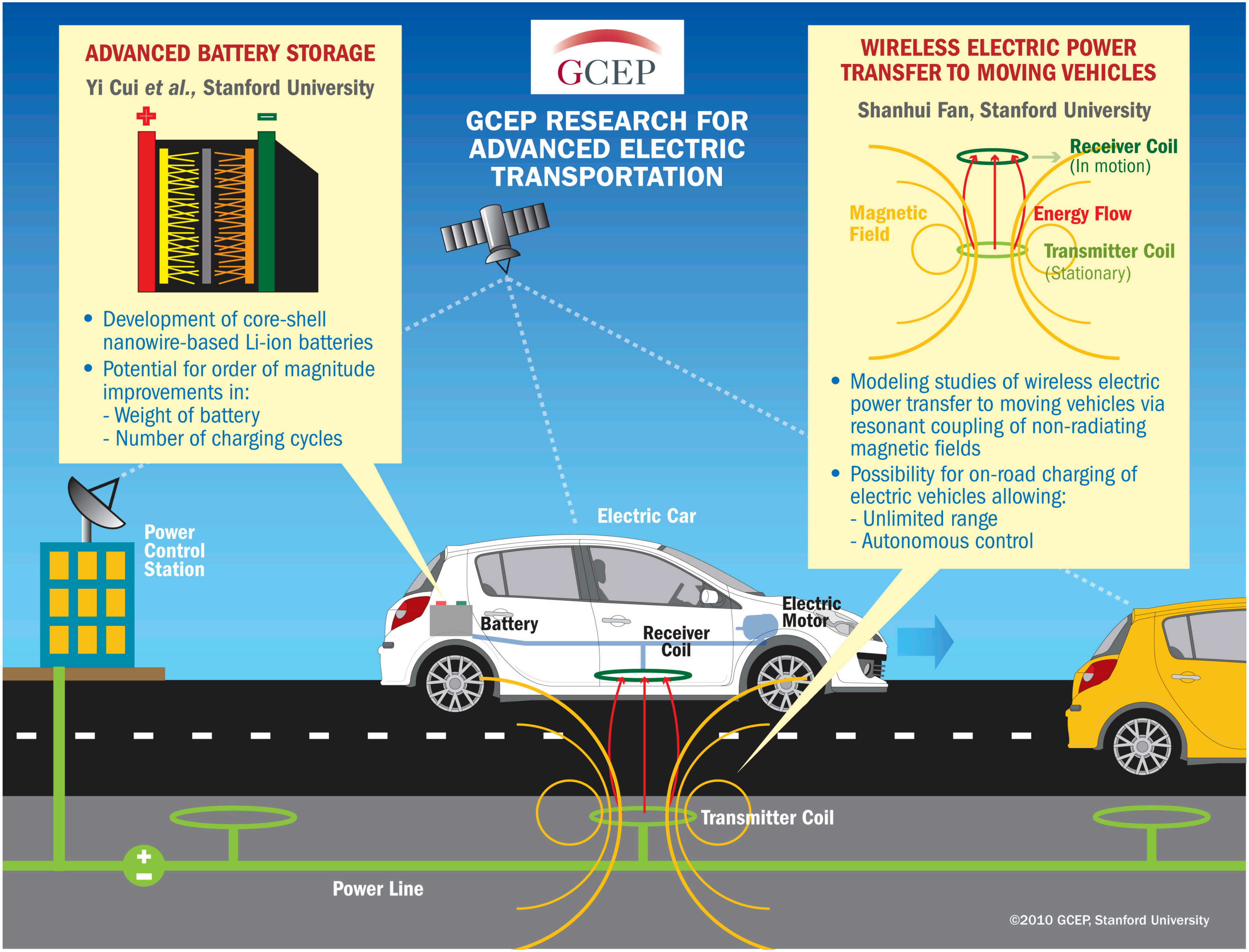
GCEP RESEARCH TOWARDS RENEWABLES
STORAGE AND BIOFUELS PRODUCTION
CATHODIC BIOFUEL REACTORS
Alfred M. Spormann, Stanford University
Electricity (Day)
Power
CH_4, H_2
Liquid Biofuels
Biomass Sludge
Anode
Cathode
Biocathode
Hydrogenases, H_2
+CH_4
+Acetate, CH_4
Biomass + Liquid Fuel
CO_2
N_2
Combustion/ Gasification Plant
Electricity (Night)
• Fundamental research of microbes coupled to electricity
• Studies of redox pathways and biofuel production
• Could enable biofuel production directly from electricity
©2010 GCEP, Stanford University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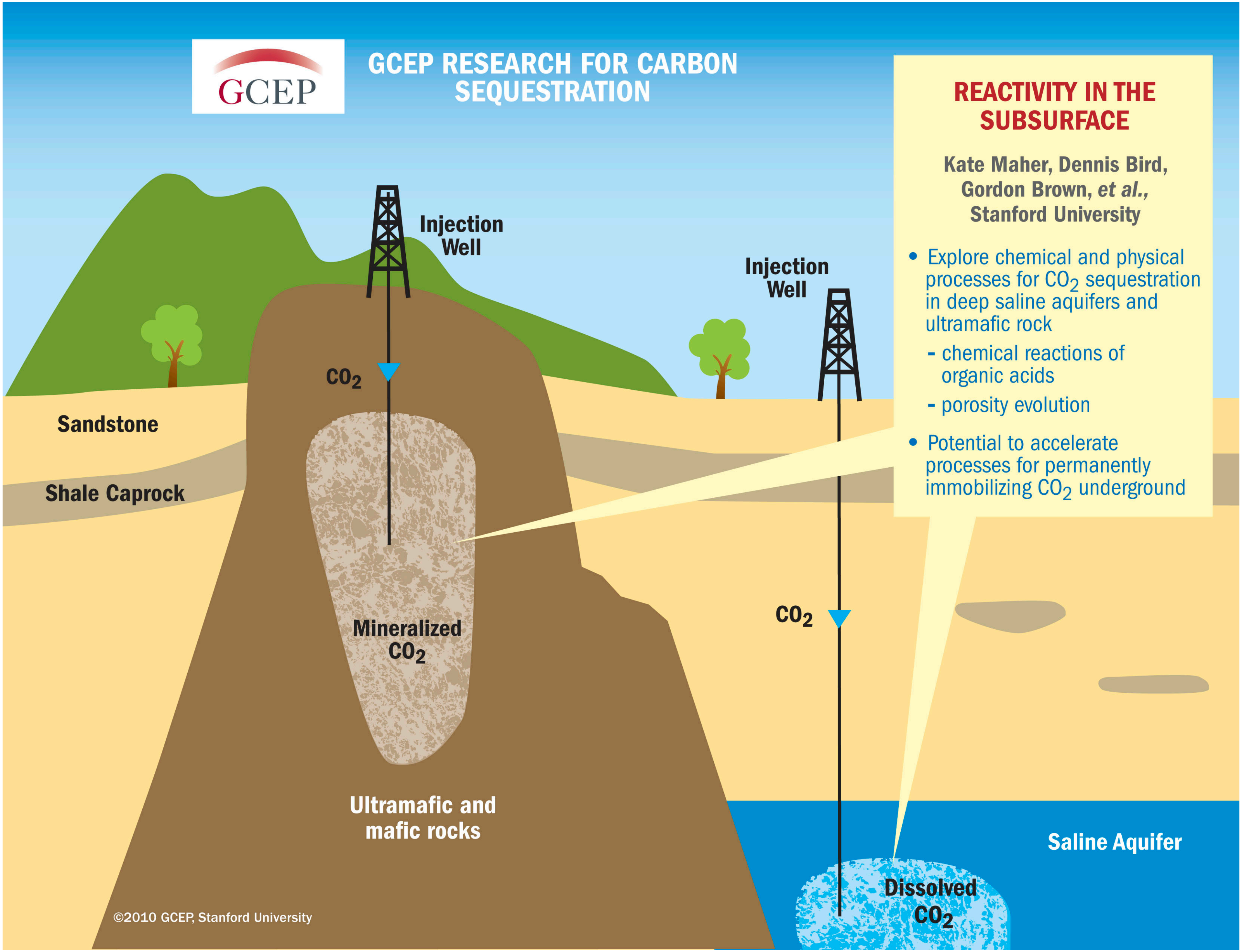
GCEP RESEARCH FOR ADVANCED ELECTRIC TRANSPORTATION
ADVANCED BATTERY STORAGE
Yi Cui et al., Stanford University
• Development of core-shell nanowire-based Li-ion batteries
• Potential for order of magnitude improvements in:
- Weight of battery
- Number of charging cycles
WIRELESS ELECTRIC POWER TRANSFER TO MOVING VEHICLES
Shanhui Fan, Stanford University
Receiver Coil
(In motion)
Magnetic Field
Energy Flow
Transmitter Coil
(Stationary)
• Modeling studies of wireless electric power transfer to moving vehicles via resonant coupling of non-radiating magnetic fields
• Possibility for on-road charging of electric vehicles allowing:
- Unlimited range
- Autonomous control
Power Control Station
Electric Car
Battery
Receiver Coil
Electric Motor
Transmitter Coil
Power Line
©2010 GCEP, Stanford University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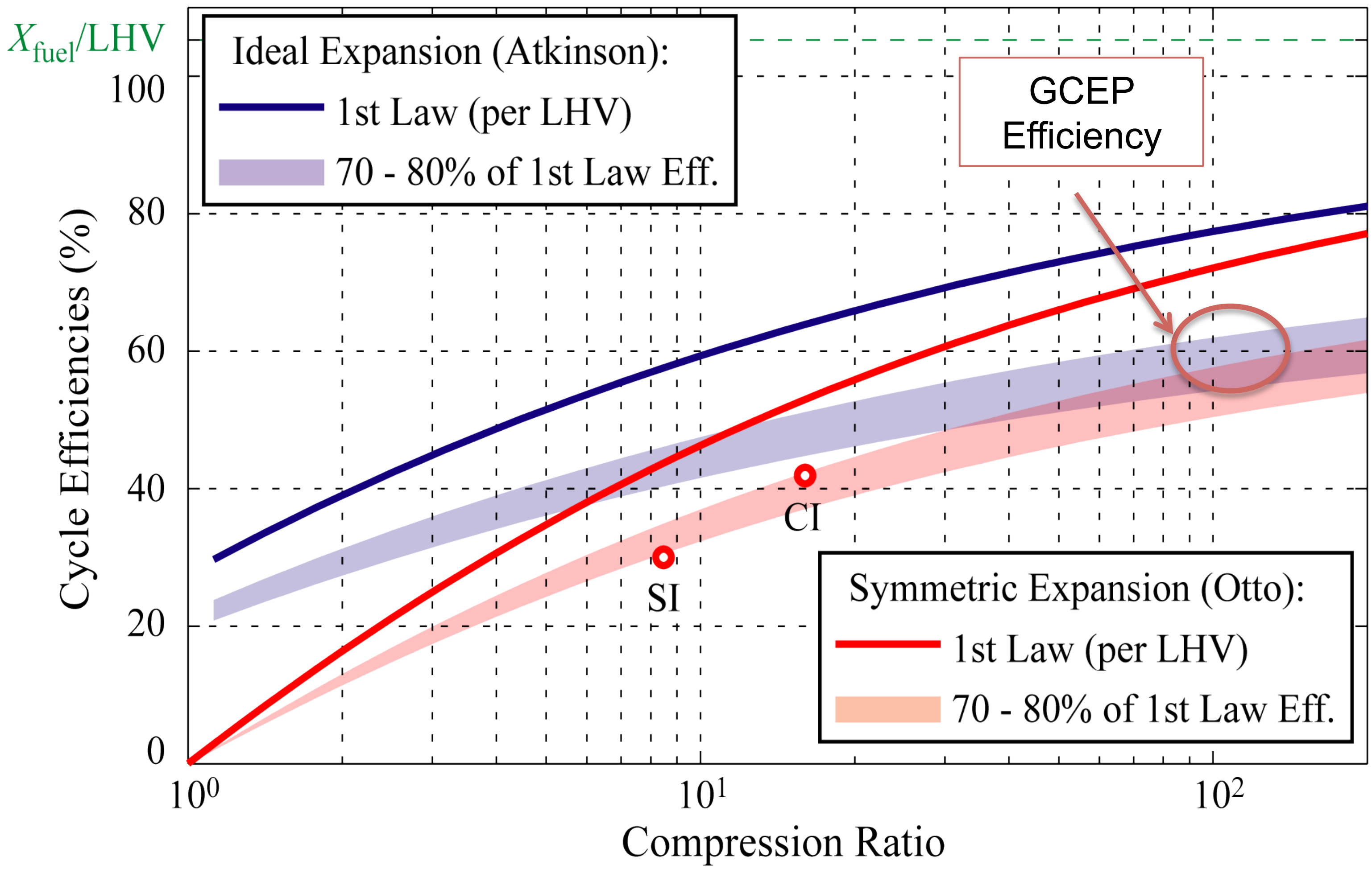
GCEP RESEARCH FOR CARBON SEQUESTRATION
REACTIVITY IN THE SUBSURFACE
Kate Maher, Dennis Bird, Gordon Brown, *et al.*, Stanford University
• Explore chemical and physical processes for CO_2 sequestration in deep saline aquifers and ultramafic rock
- chemical reactions of organic acids
- porosity evolution
• Potential to accelerate processes for permanently immobilizing CO_2 underground
Injection Well
Injection Well
CO_2
CO_2
Sandstone
Shale Caprock
Mineralized CO_2
Ultramafic and mafic rocks
Saline Aquifer
Dissolved CO_2
©2010 GCEP, Stanford University

GCEP Research in Carbon-Based Energy Systems

Advanced Combustion through Exergy Management - *Edwards*



Enable single-cycle efficiency > 60%

Commercialization of New Energy Technologies

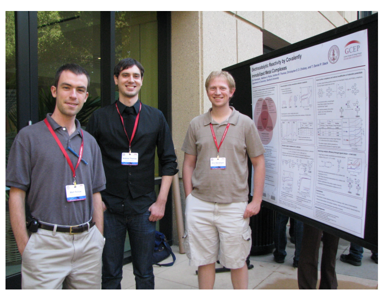
Transition to Commercial Sector, e.g.:

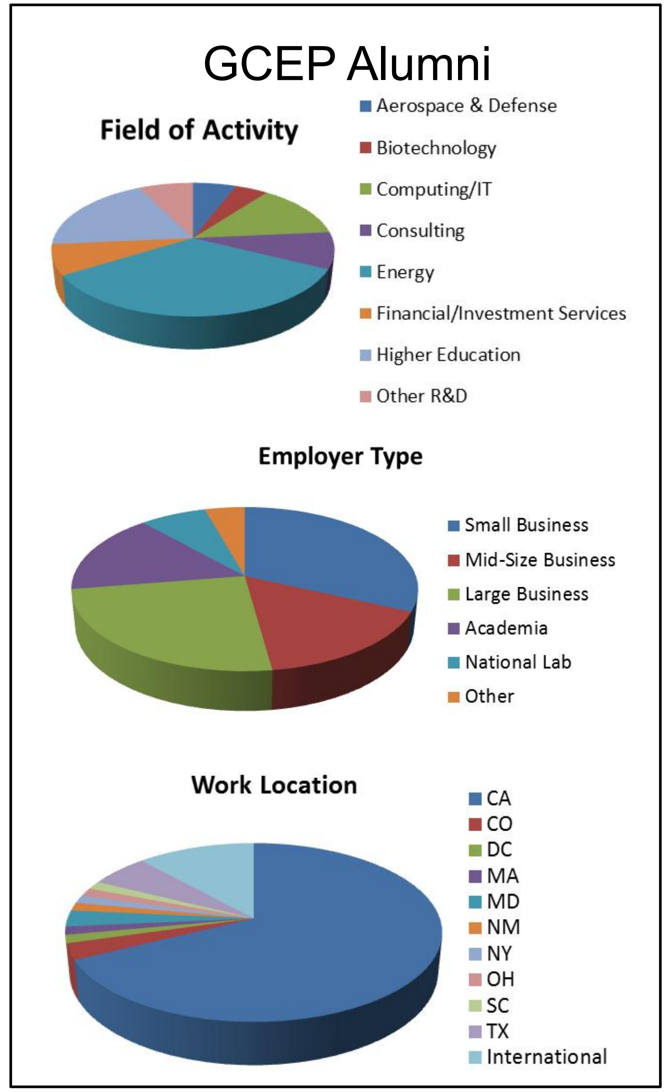
- C3 Nano
  - Revolutionary new transparent electrode material for applications including flexible displays, touch screens, solar cells and smart windows.
  - $3M in funding
- Amprius
  - Lithium batteries and materials that enable dramatic improvements in energy density.
  - $25M in funding
- EtaGen
  - High-efficiency engines for distributed generation applications
  - Funded by Khosla Ventures

Future Energy Thought Leaders and Research Workforce

Graduate and Post-Doc Students

- Close to 500 graduate and post-doctoral students have been funded by GCEP
- Many alumni now work throughout the field





Concluding Remarks

- Energy transition is rife with challenges and opportunities
- Energy resources are abundant
- Cascade of emerging and innovative technologies are needed to meet growing energy needs while protecting human health and the environment
- Critical R&D needs
  - ➢ Improve efficiency of everything
  - ➢ Sustained improvements in solar and wind power
  - ➢ Decarbonization of fossil fuels
  - ➢ Safe nuclear power
  - ➢ Large scale energy storage, including synthetic fuels
- Coming soon: Efficient energy systems integration
  - ➢ Full systems EROI, energy payback times

Acknowledgements

- The Global Climate and Energy project is supported by
  - ExxonMobil
  - GE
  - Schlumberger
  - Toyota