Prospects of Fuel Cells and Hydrogen:

"Seeing Beyond the Press Releases"

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Sustainable Energy Systems:

Energy systems that can last for millennia

(adapted from John Turner, NREL 2006)

Questions for the Future of Energy:

- **Sustainability**
- **Resource availability**
- **Energy Payback**
- **Environmental impacts**
- **Geopolitical factors**
- **Security**
- **Supply for emerging markets**
- **Providing a sustainable energy carrier for transportation**

Answers:

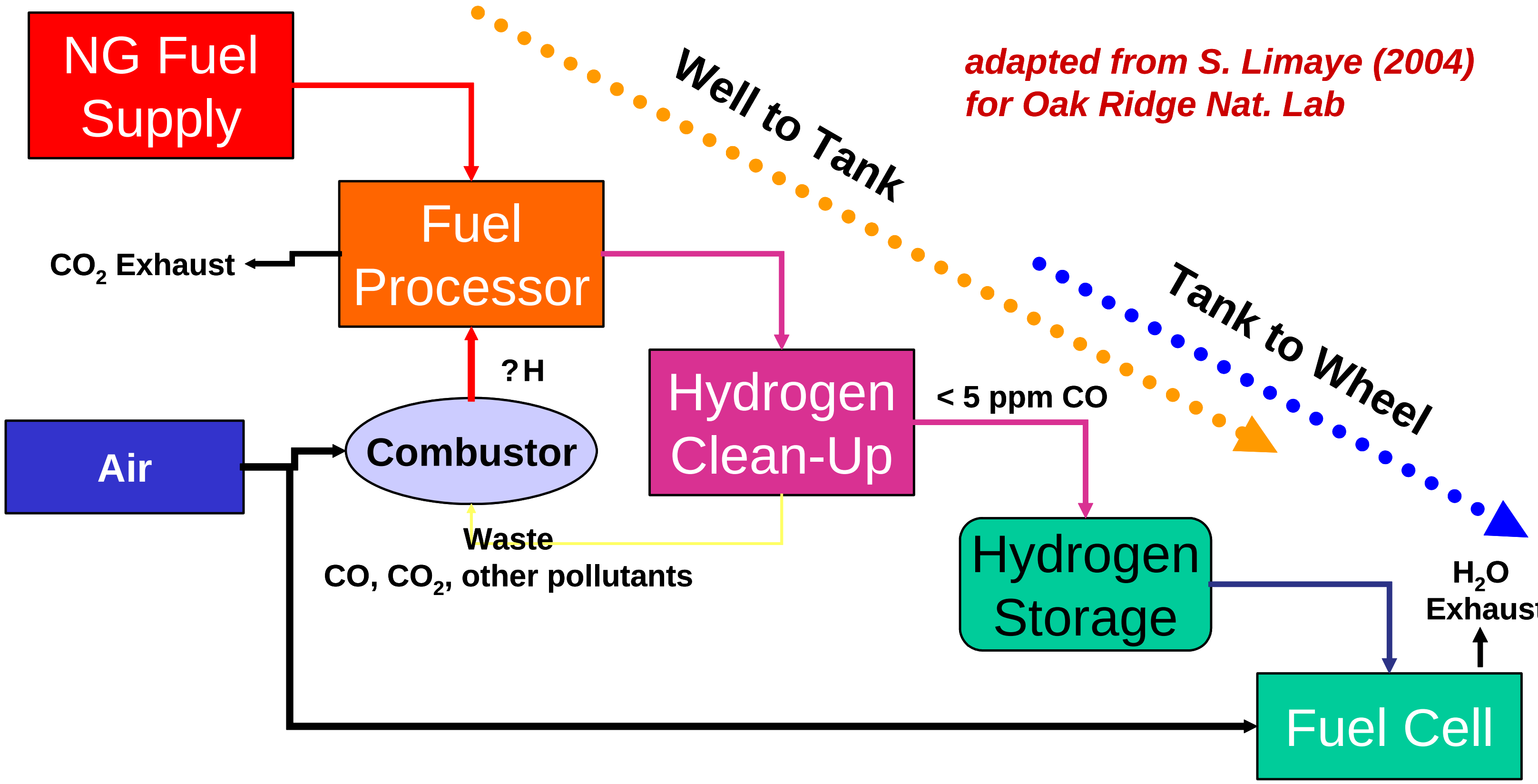
- **Biomass**
- **Solar**
- **Wind**
- **Geothermal**
- **Nuclear**
- **Hydrodynamic**
- **Wave**
- **Hydrogen**

Why Hydrogen?

- **Hydrogen like electricity is an energy carrier not an energy supply**
  - Unlike electricity, it can be stored relatively easily
  - Unlike hydrocarbons, it does not necessarily lead to local CO_2 and other emissions
- **Fuel cells for transportation will dictate the needs for H_2 infrastructure**
  - Leaders: Ballard, GM, Honda, UTC, other auto manufacturers
  - Low temperature fuel cells currently requiring high purity H_2 (<100 ppm CO) for necessary power density (approach 1 kW/liter of fuel cell, longer life (> 5000 hrs.)
  - Hydrogen IC engine as an alternative (BMW and Ford investing in this)
- **Hydrogen is clean and can be produced from several sources**
  - Fossil fuels with easier CO_2 sequestration
  - Low-temperature electrolysis
  - Nuclear power with high temperature electrolysis or thermochemical cycle
- **Current Use of Hydrogen: ~ 9 million tons/yr in U.S. and growing**
  - Equivalent in energy to about 0.3% of annual U.S. oil consumption
  - > 90% of H_2 production comes from steam reforming of natural gas ($CH_4 + H_2O$)
  - Primary uses today: are for refining petroleum and producing ammonia

Current Hydrogen Supply and Fuel Cell Utilization

- Approach for today involves reforming natural gas to H_2 and CO_2
- Overall well-to-wheel efficiencies are comparable to current-day hybrid vehicles but can be surpassed by proposed diesel hybrids (Wang 2003)
- Green-house gas emissions lower than proposed hybrids, but limited NG supply raises questions of sustainability (Wang 2003)



Economics of Hydrogen Fueling Scenarios

Gasoline Marketers Association:

$2 billion to convert 10% of current retail stations to hydrogen.

Shell Hydrogen: $19B for 25% conversion

Cost of initial nation-wide H_2 Infrastructure

ASSUMPTIONS
- 2% of cars run on H_2
- H_2 sold at 25% of retail sites

- ¼ Onsite electrolysis
- ¼ Onsite POx reformer
- ¼ Trucked in gas
- ¼ Trucked in liquid

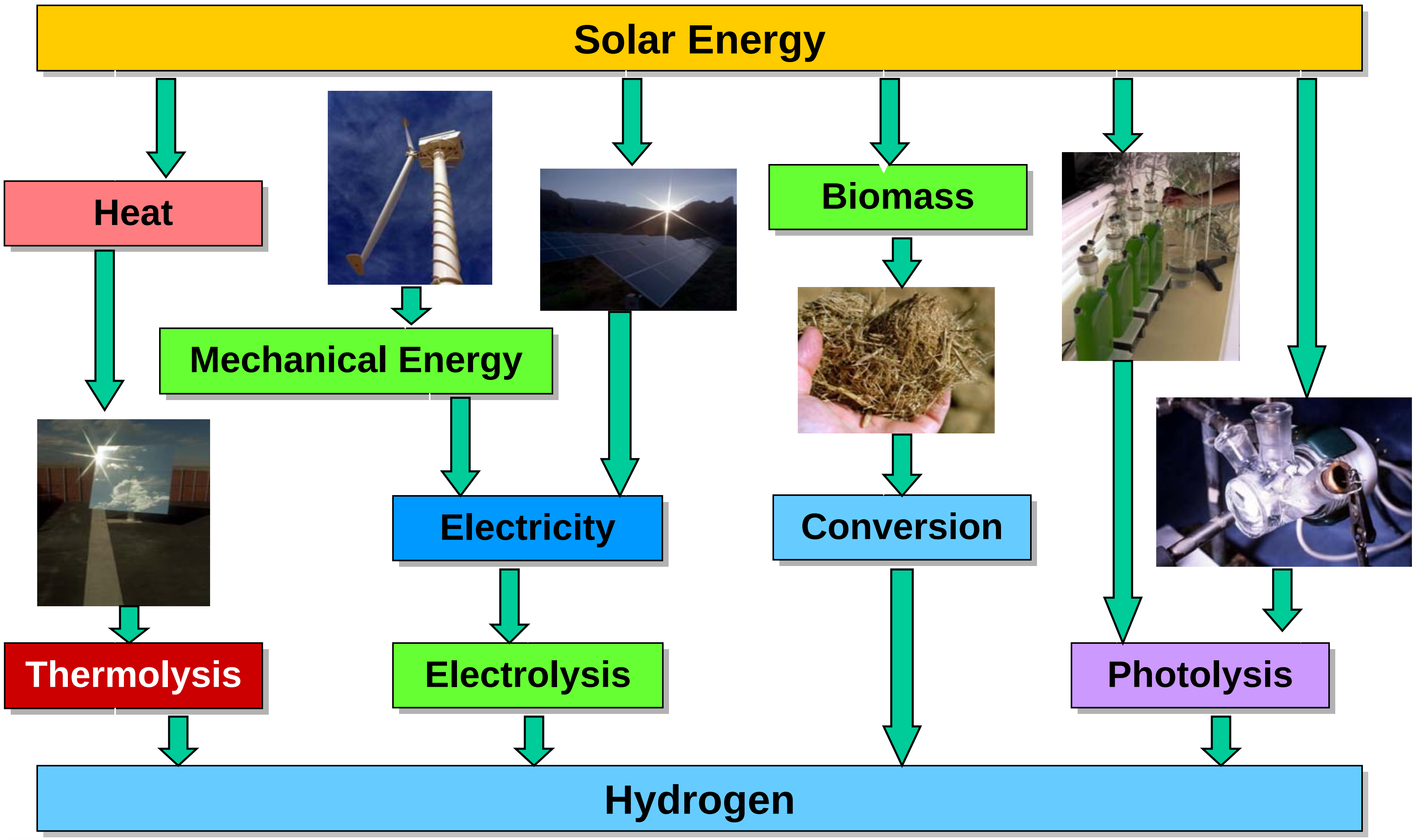
	Retail sites selling H_2	Cost of extra central production/ liquefaction	TOTAL COST
	43 980	$ 450m	$ 19bn
	3 425	$ 90m	$ 1.5bn
	13 831	$ 140m	$ 6bn

Shell Hydrogen

Alternative Local Production: Home Refueling

Sustainable Paths to Hydrogen

from John Turner, NREL 2006



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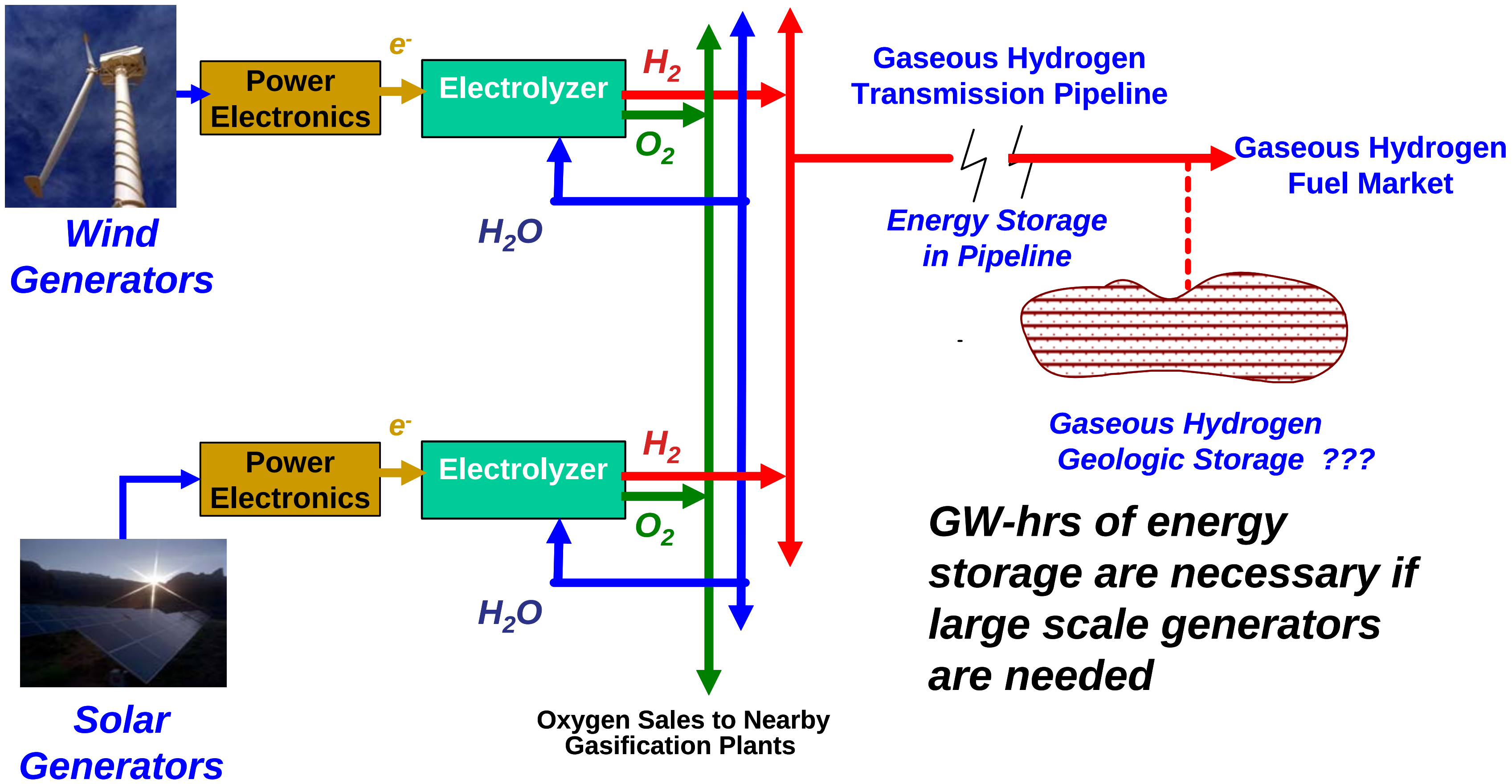
Renewable Hydrogen Supply

adapted from John Turner, NREL 2006

- **Renewable approaches to hydrogen supply still face challenges.**
  - Low efficiency of electrolyzer
  - Need for large-scale storage if non-local production



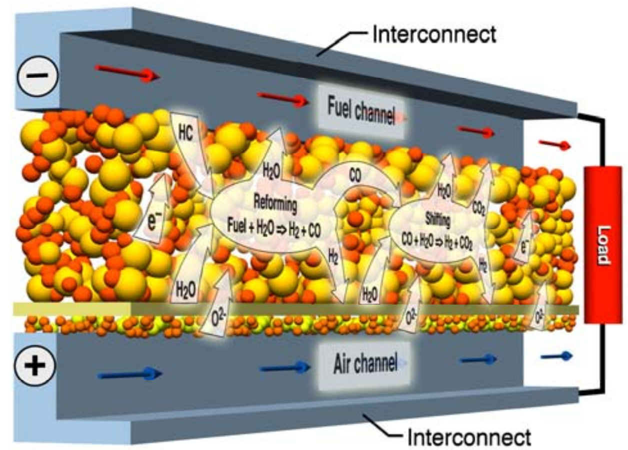
GW-hrs of energy storage are necessary if large scale generators are needed

Fuel Cell Technologies Going Forward

- ***Proton Exchange Membrane Fuel Cells***
  - Operation at low temperatures < 120ºC
  - Expensive precious metal catalysts
  - Fuel limited to relatively pure H_2 with inerts for high power applications
  - For portable power, dilute methanol or ethanol mixtures may become viable
  - H_2O management critical for most designs
- ***PEMFC primary applications – vehicles, small gensets, portable power***

85 kW H_2-fueled automobile PEM fuel cell stack provided by Ballard Power Systems

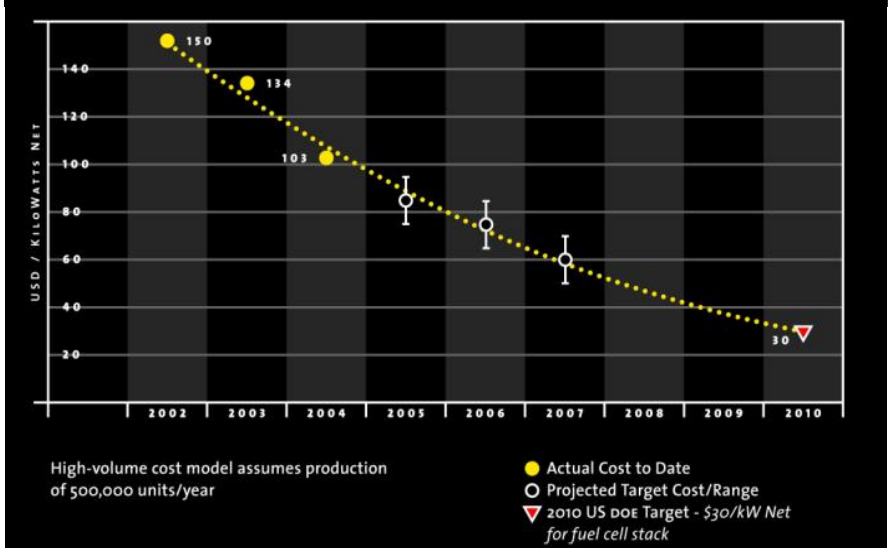
- ***Solid Oxide Fuel Cells***
  - Operation at high temperatures > 600ºC
  - Inexpensive catalysts
  - Potential for fuel flexibility – coal gas, NG, ethanol, biomass gases
  - Ideal for integration with C sequestration
  - Readily integrated with gas turbines for high efficiency hybrid plants
- ***SOFC primary applications – stationary / distributed power, APU's***



SOFC single cell schematic provided by R.J. Kee, Colorado School of Mines

PEM Fuel Cells –Challenges and Breakthroughs

- ***Vehicular fuel cell system development has brought this technology to some maturity but costs remain high even for mass production ($75 - $100/kW)***
  - Current DOE plan to make commercialization decisions regarding transportation fuel cells and large-scale H_2 production by 2015.
- ***Markets with high kW costs provide best opportunities for today***
  - *Electronic devices, portable generation, utility transport, public transport*
- ***What are the barriers***
  - Cost (precious metal catalyst and expensive polymer membrane)
  - Storing pure H_2 supply
  - Systems issues (H_2O management, storing pure H_2 or processing fuel)
- ***What are forward looking solutions***
  - Electrocatalyst with less precious metals
  - Higher temperature polymer membranes
  - More efficient H_2 purification processes
  - Light and safe materials for H_2 storage

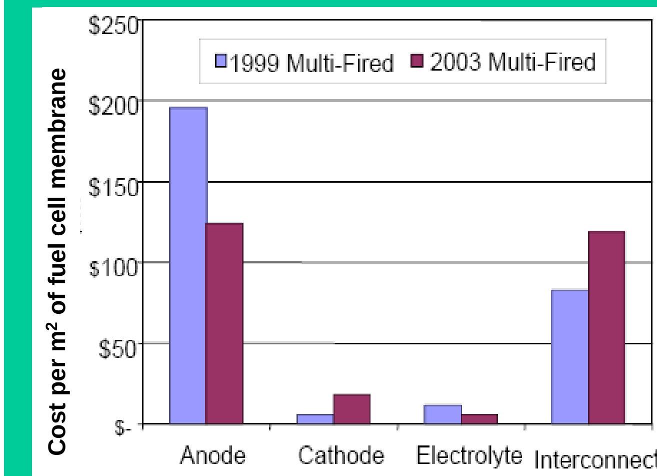


Fuel Cell System Cost (2000-2010)
From Ballard Power Systems

SOFC's – Identifying Technical Challenges and Breakthroughs

- ***Stationary power SOFC development funded by DOE has led to one realization, but further funding for small-scale power has led to new technology.***
  - Fabrication costs remain high for SOFC's (~$400/kW)
  - Operational cost benefits from very high efficiencies (>60% with hybrid gas turbine/SOFC's) and possible cogeneration.
- ***Markets with high fuel costs and steady operation –military portable generation and remote distributed power – provide best opportunities***
  - Materials issues still to be resolved for improved fuel flexibility and operability
- ***What are the barriers***
  - Low-temperature ceramic membranes
  - Low-cost catalyst with fuel flexibility and durability
- ***What are forward looking solutions***
  - New lower-temperature ceramic membranes
  - Electrocatalyst layers with fuel flexibility and durability
  - Improved integration with small gas turbines
  - Integration with sequestration technology

Cost breakout for NG-fired SOFC's TIAX Carlson et al. 2004



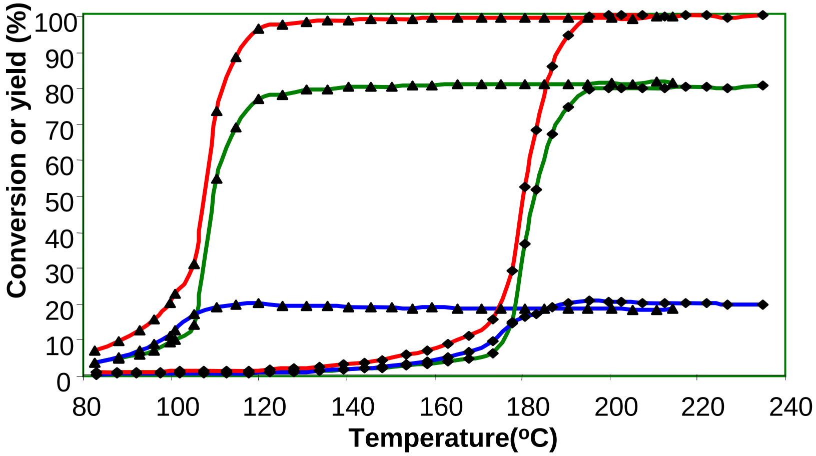
Nano-architectured Catalysts for PEM Fuel Cells

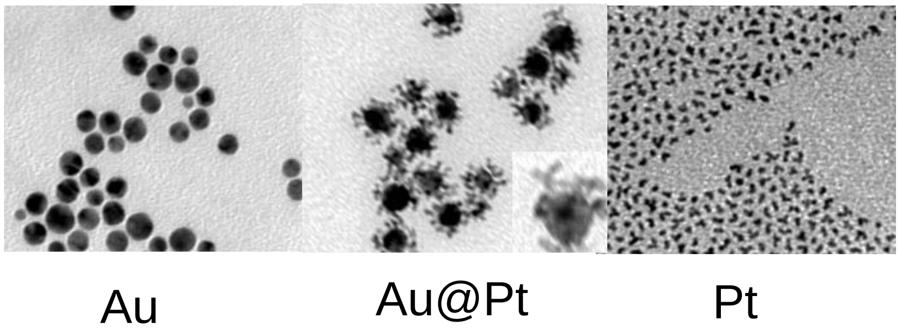
Profs. B. Eichhorn, G. Jackson, Ballard Power Systems

- ***Developing nanoparticle architecture through controlled liquid synthesis to design stable catalysts that have active precious metals only on outer shell***
  - *Reduced precious metal requirement*
  - *Nano-architectures provide superior tolerance for primary H_2 impurity, CO.*
- ***Successful development may improve PEM fuel cell system efficiency and operability with bio-derived fuels.***

Example Au@Pt heteroaggregate particles for H_2/CO oxidation

In 50%H_2, 0.2%CO, 0.5%O_2, Ar balance, Au@Pt nanoparticles light-off at lower *T* than pure Pt or Au + Pt nanoparticles for CO and H_2 oxidation.





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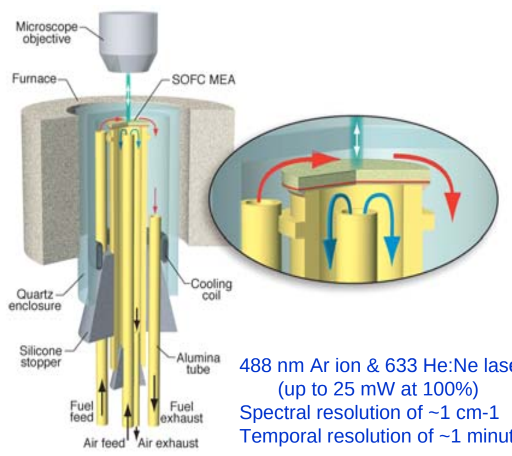
High-Temperature Fuel-Flexible Solid Oxide Fuel Cells

Profs. G. Jackson, B. Eichhorn, R. Walker

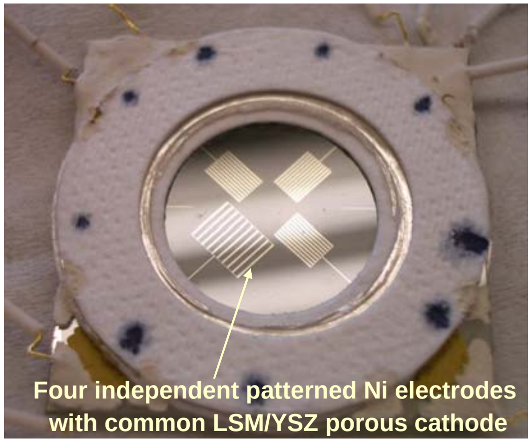
- **Exploring fundamental material issues to provide new understanding for optimizing design solid oxide fuel cell assemblies for operating on hydrogen, bio-derived fuels, and fossil fuels**
- **System design tools being developed to explore how solid oxide fuel cells can be used for making CO_2 capture more feasible.**

Optically accessible rigs for laser diagnostics to evaluate new materials

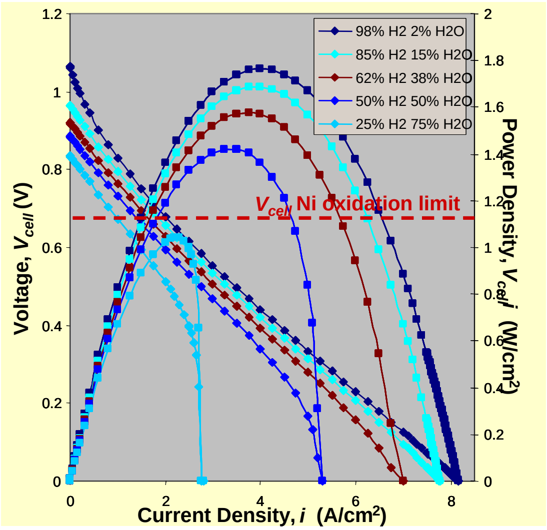


488 nm Ar ion & 633 He:Ne lasers (up to 25 mW at 100%)
Spectral resolution of ~1 cm-1
Temporal resolution of ~1 minute

Micro-fabricated fuel cell architectures to understand chemistry of H_2 and other fuels



Experimentally validated models for fuel cell design



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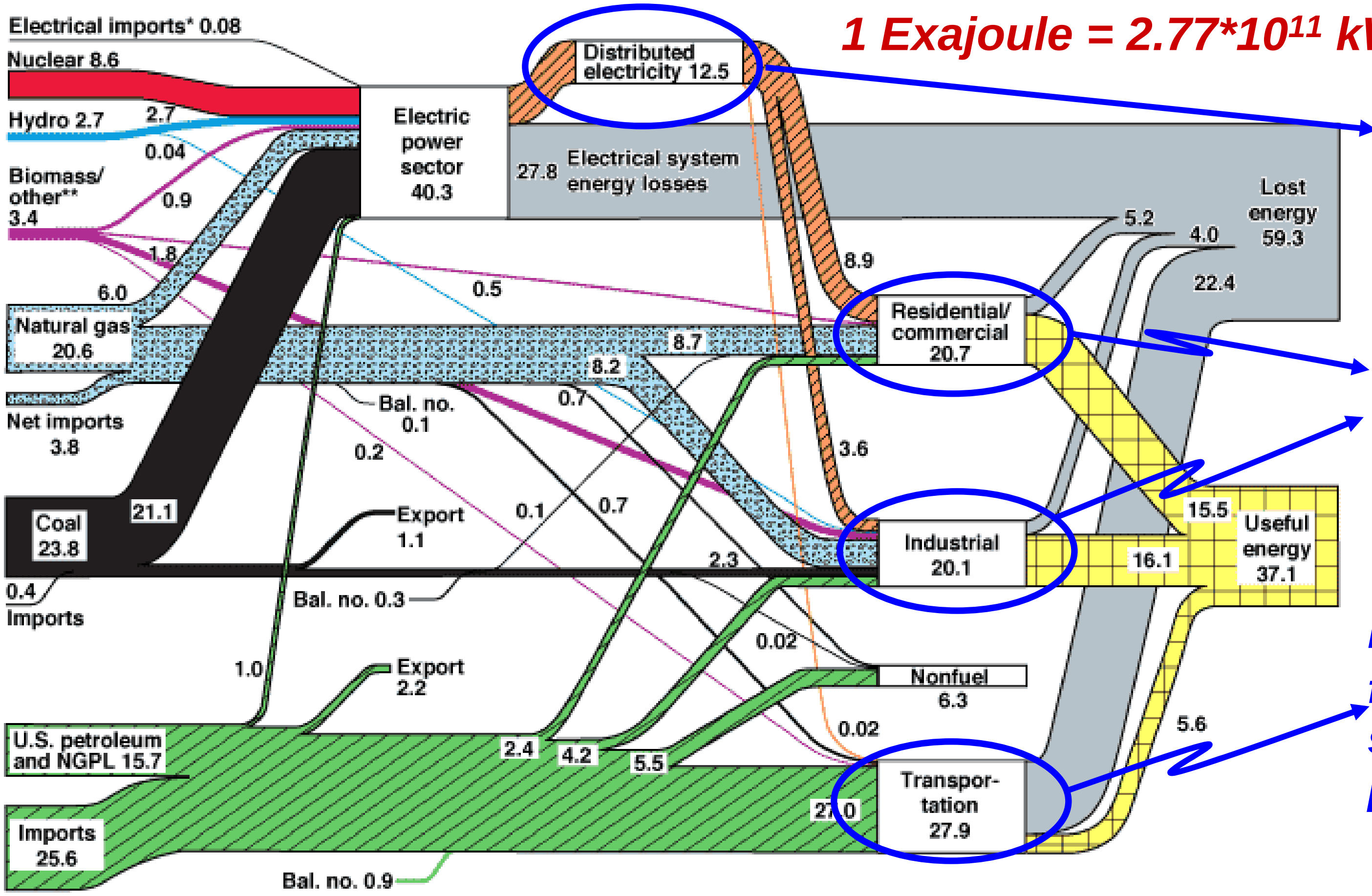
H_2 and Fuel Cells: Identifying the Opportunities

U.S. Energy Flow Trends – 2002
Net Primary Resource Consumption ~103 Exajoules

*1 Exajoule = 2.77*10[11] kWh*



Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2002.*
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

Potential for central power SOFC's with carbon capture

Potential for distributed power with combined cooling and heating with SOFC's and PEMFC's

Potential for H_2 derived from non-petroleum sources for PEMFC powered vehicles

from Lawrence Livermore Natl. Laboratory
http://eed.llnl.gov/flow (June 2004)