Fuel cells: A Technology Status Update

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"Science & Technology – Survival of a Nation"
First Science Congress of EAS
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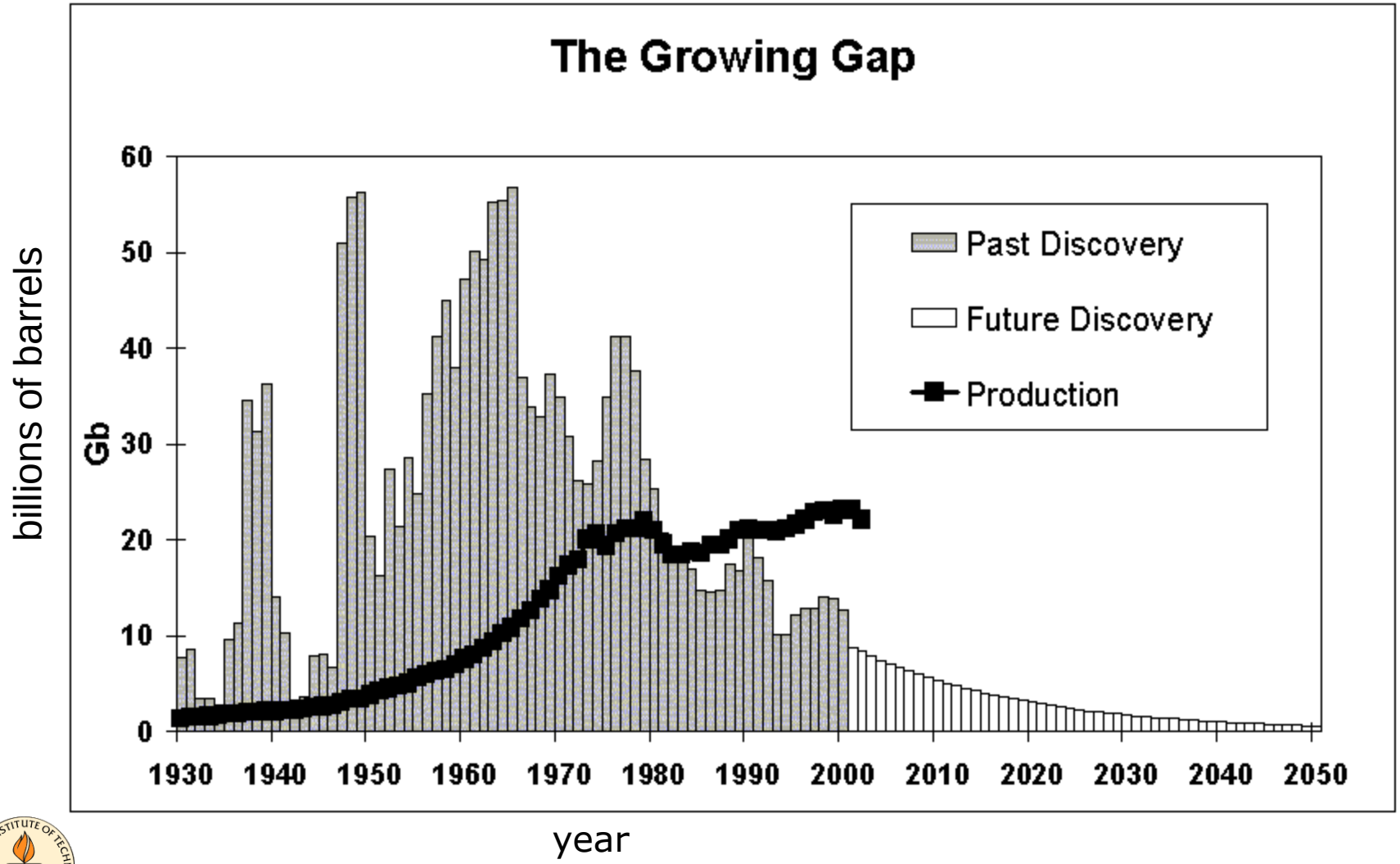
The Problem of Energy

- Diminishing supply?
- Resource distribution?
- Environmental damage?

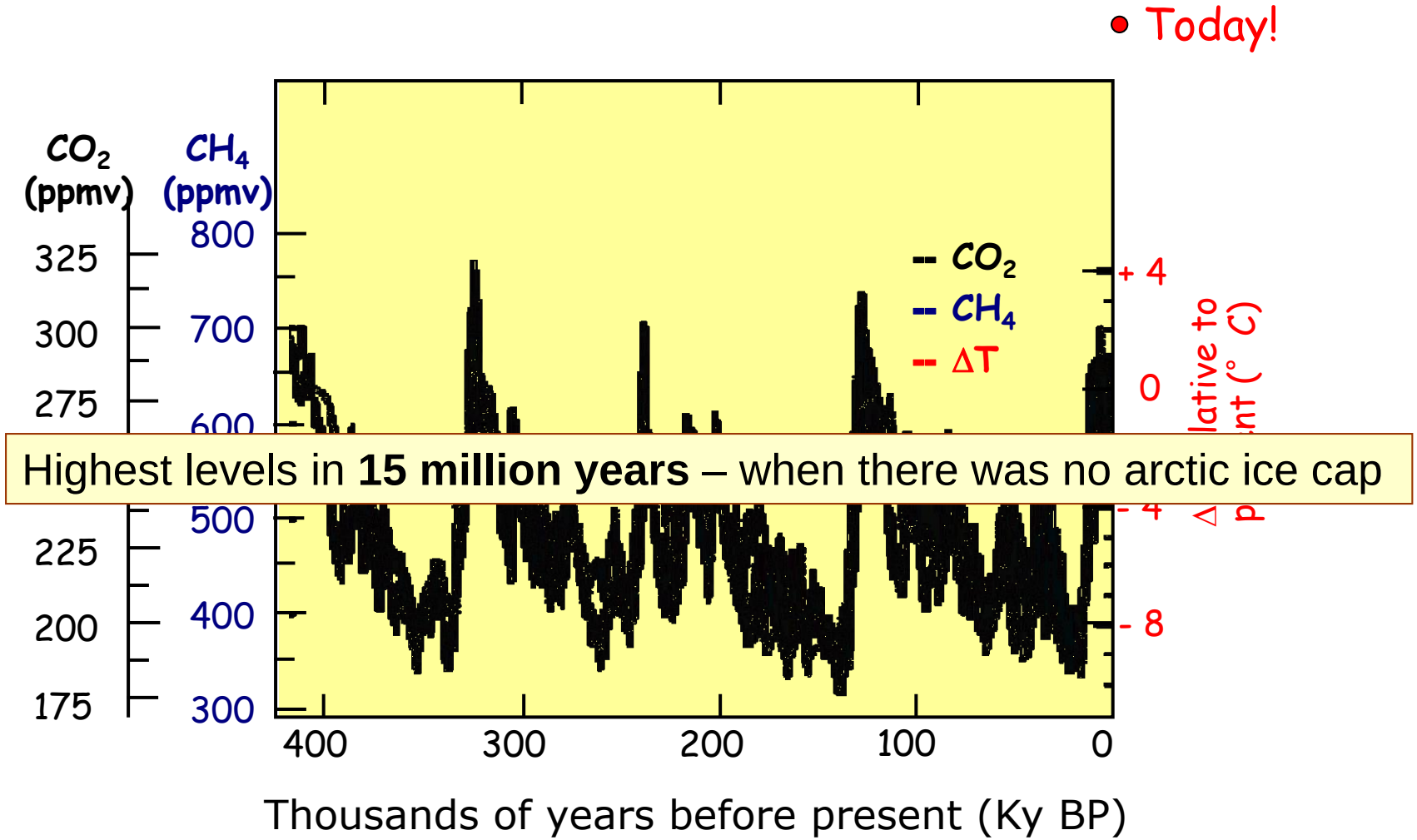
- Yes, eventually
- 65% of petroleum reserves in the Mid-east
  - Fossil fuels account for > 70% of use
- Yes, despite US disbelief / denial
  - CO_2 levels highest in **15 million years**

Oil Discovery and Production

Source: Collin J. Campbell, Oil Depletion Analysis Centre



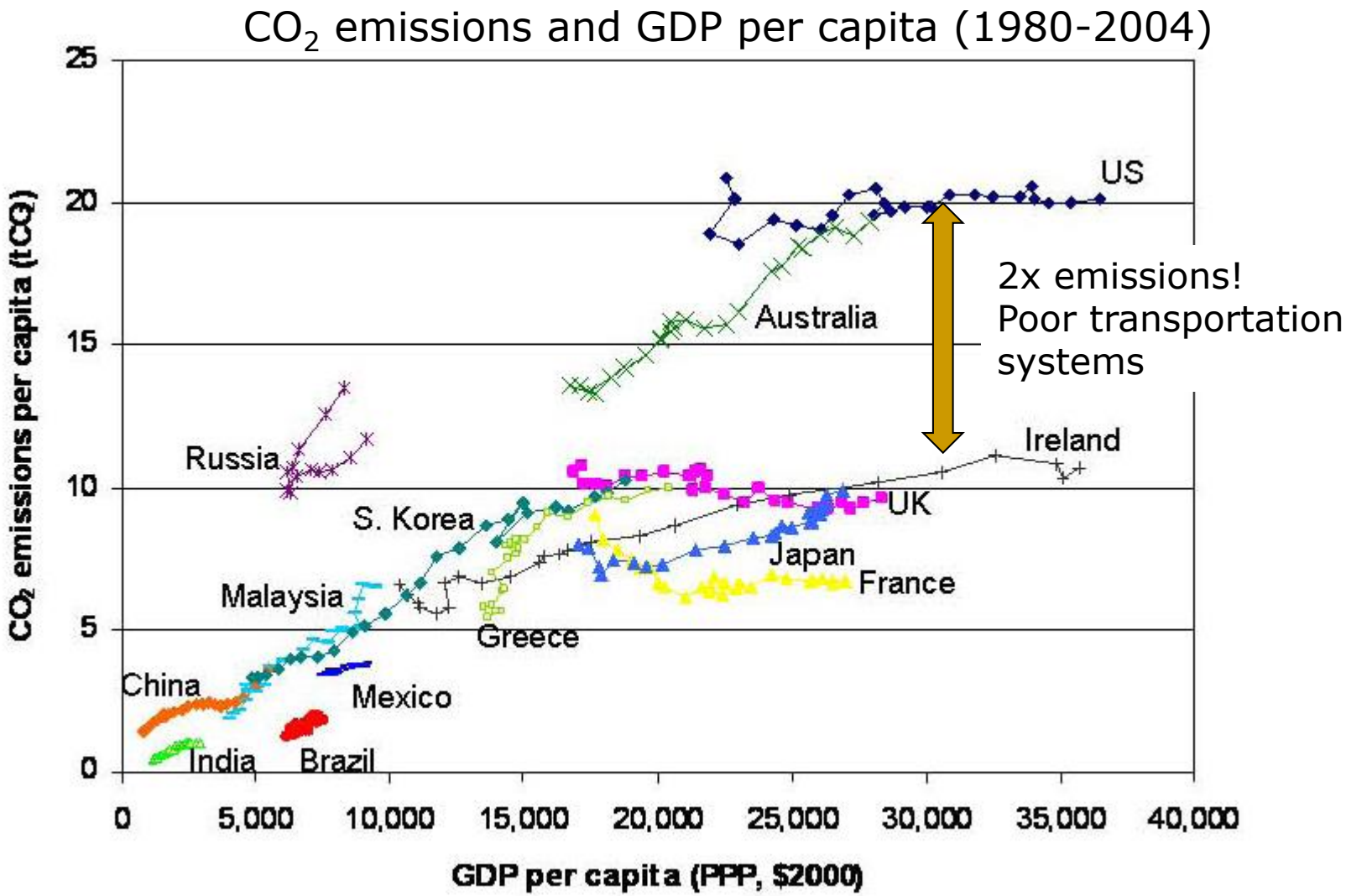
The Environmental Outlook



Highest levels in **15 million years** – when there was no arctic ice cap

Intergovernmental Panel on Climate Change, 2001; http://www.ipcc.ch
*N. Oreskes, Science **306**, 1686, 2004; D. A. Stainforth et al, Nature **433**, 403, 2005*

Can U.S. Mistakes be Avoided?

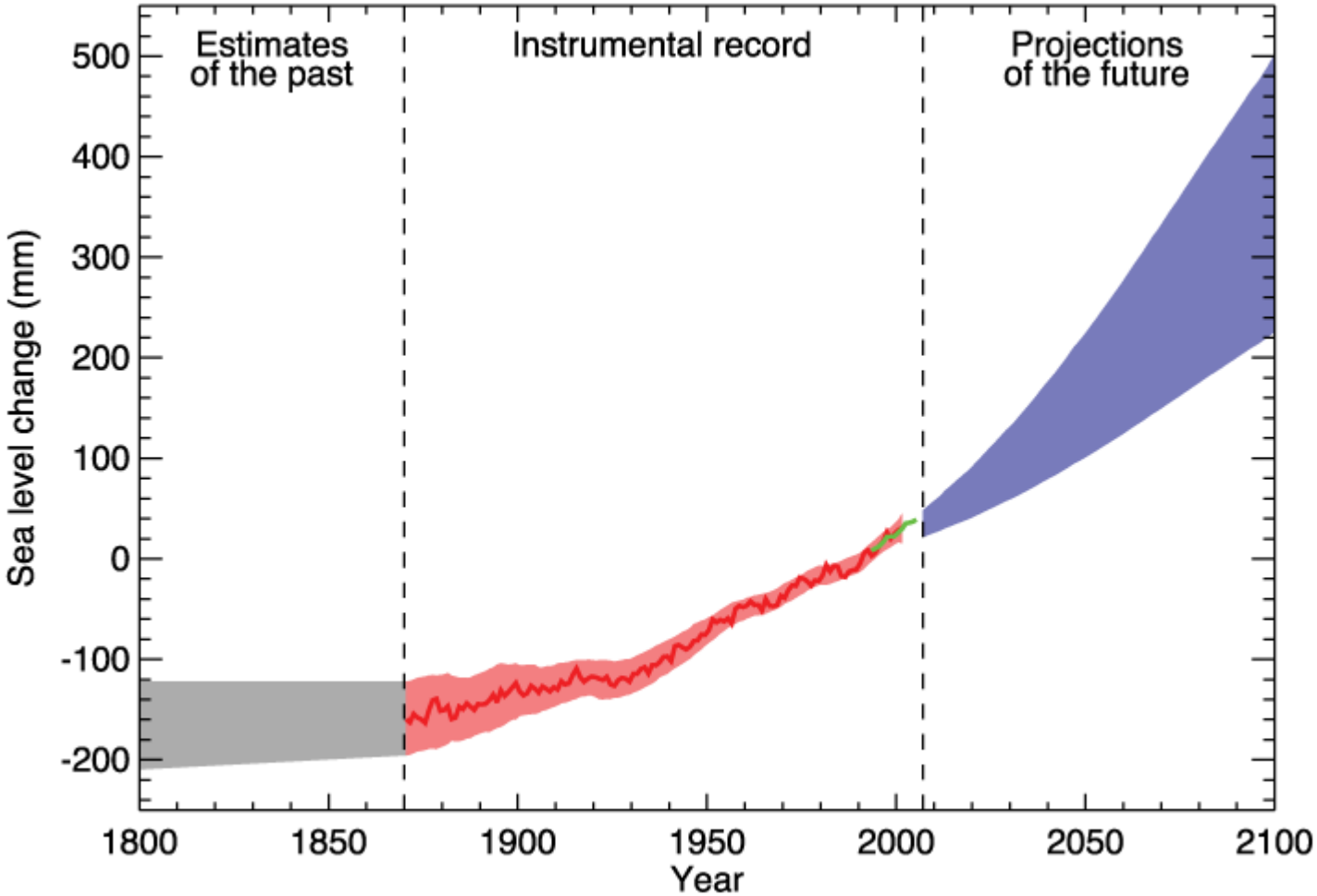


Energy Utilization (2003)

Country	Energy usage (per capita, GJ)	Energy intensity (tons oil/$ GDP)
Hong Kong	101	91
Germany	177	164
Eritrea	8.4	215
United States	327	222
South Africa	109	265
Ethiopia	*12*	*390*
Tanzania	20	784
World Average	--	213

Example of Impact: Sea Level

Source: USEPA



Features of 'the' Energy Solution

- Environmentally benign
- Adequate domestic supply
- Conveniently transported
- Conveniently used
- Conveniently stored for on-demand use

The Energy Resources

Courtesy: Nate Lewis

To stabilize CO_2:
~ 20 TW by 2050

Solar
1.2×10^5 TW at Earth surface

Wind
2-4 TW extractable

Biomass
5-7 TW gross
all cultivatable
land not used
for food

Tide/Ocean Currents
2 TW gross

Geothermal
12 TW gross over land
small fraction recoverable

Hydroelectric
4.6 TW gross
1.6 TW technically feasible
0.9 TW economically feasible
0.6 TW installed capacity

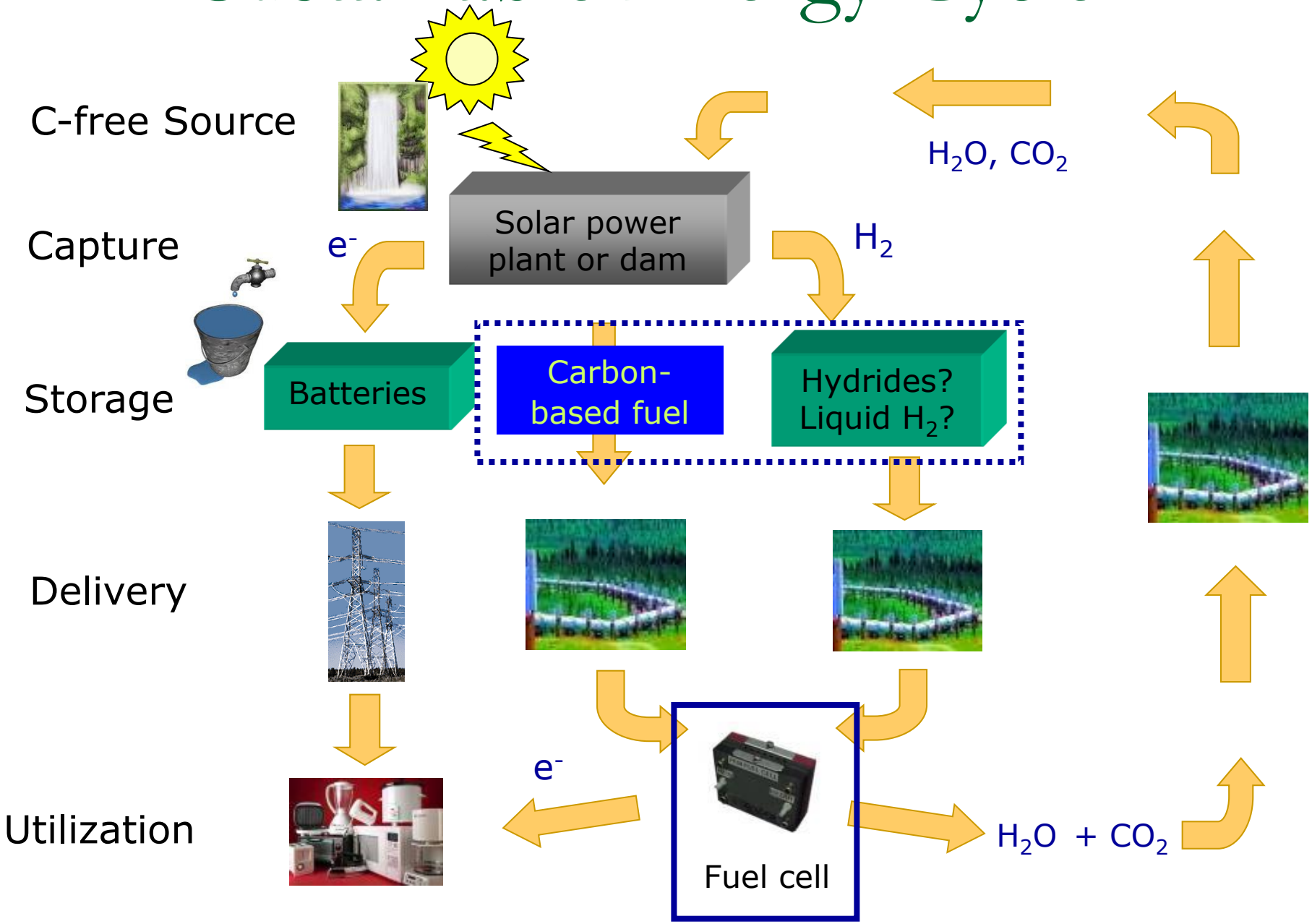
Nuclear
Waste disposal
60 yr uranium supply

Fossil with sequestration
1% / yr leakage -> lost in 100 yrs

Features of 'the' Energy Solution

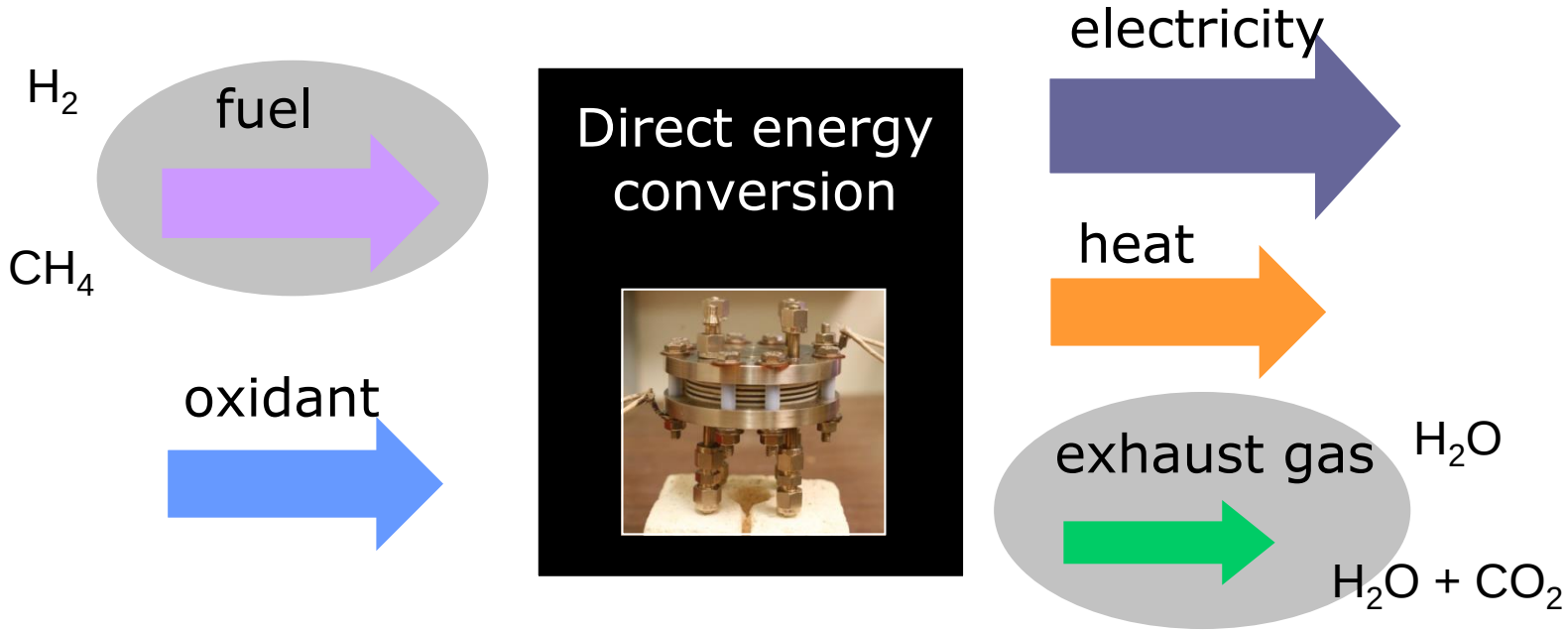
	Solar	Hydro/Geo
Environmentally benign	✓	
Adequate domestic supply	✓	?✓
Conveniently transported		
As electricity, after conversion	grid	
As fuel, after conversion	✓	
Conveniently used		
As electricity, after conversion	✓	
As fuel, after conversion	✓	
Conveniently stored	X	✓

A Sustainable Energy Cycle

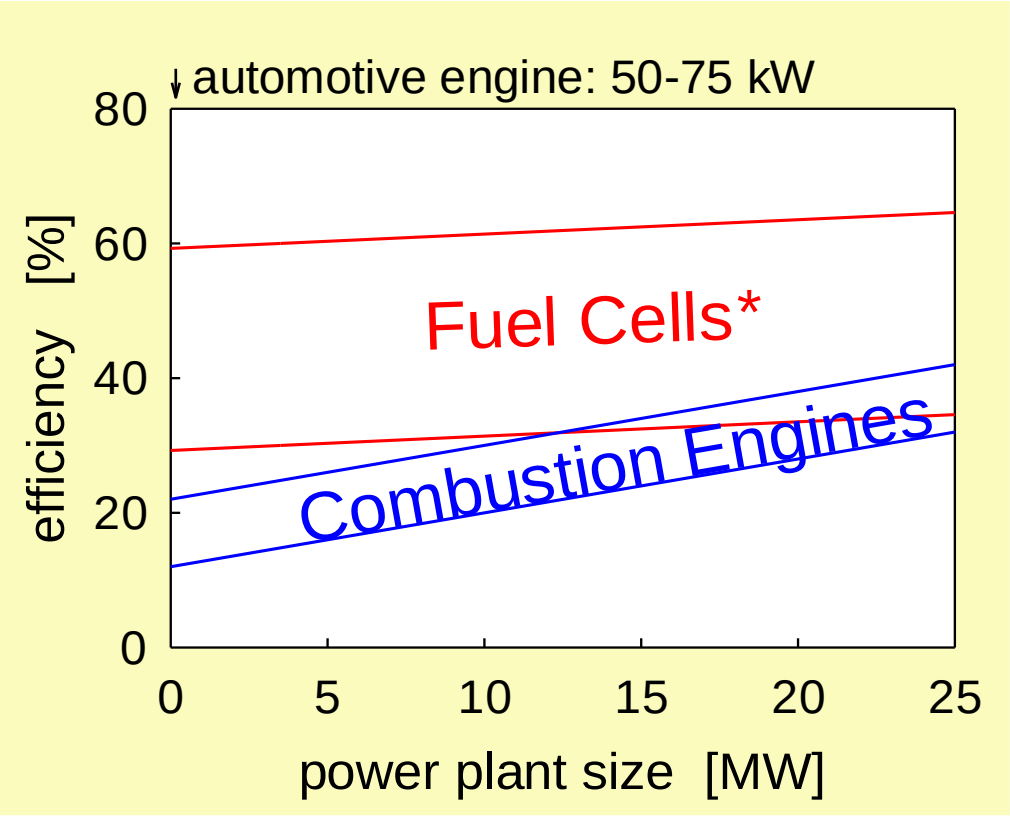


What is a Fuel Cell?

- What does it do?
- How does it work?
- How do measure performance?
- How can be make it better?



Fuel Cells: Part of the Solution?



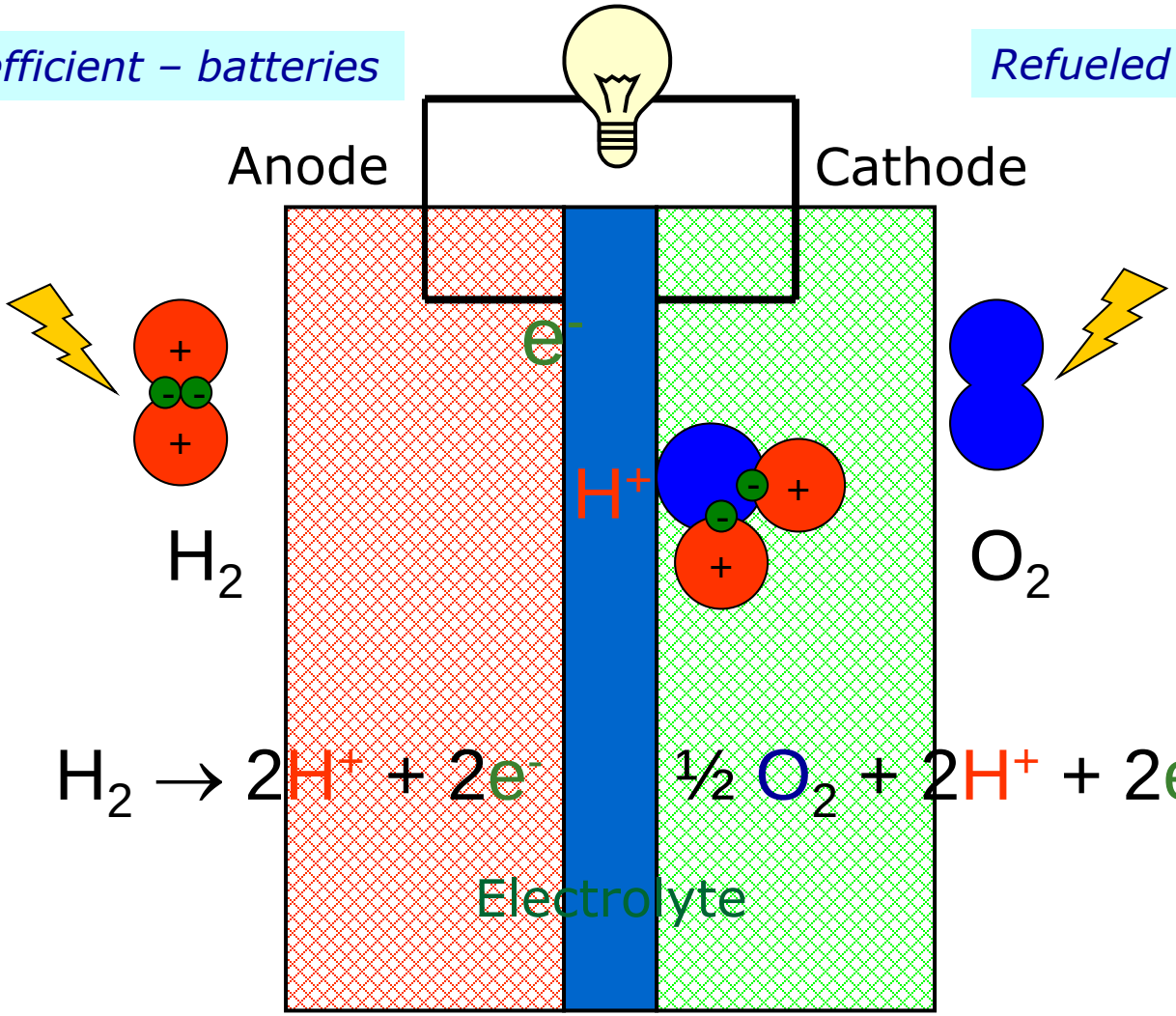
- High efficiency
  - low CO_2 emissions
- Size independent
- Various applications
  - stationary
  - automotive
  - portable electronics
- Controlled reactions
  - "Zero Emissions"
- Operable on hydrogen
  - (if suitably produced)

*Can be as high as 80-90% with co-generation

Fuel Cell: Principle of Operation

Clean, efficient – batteries

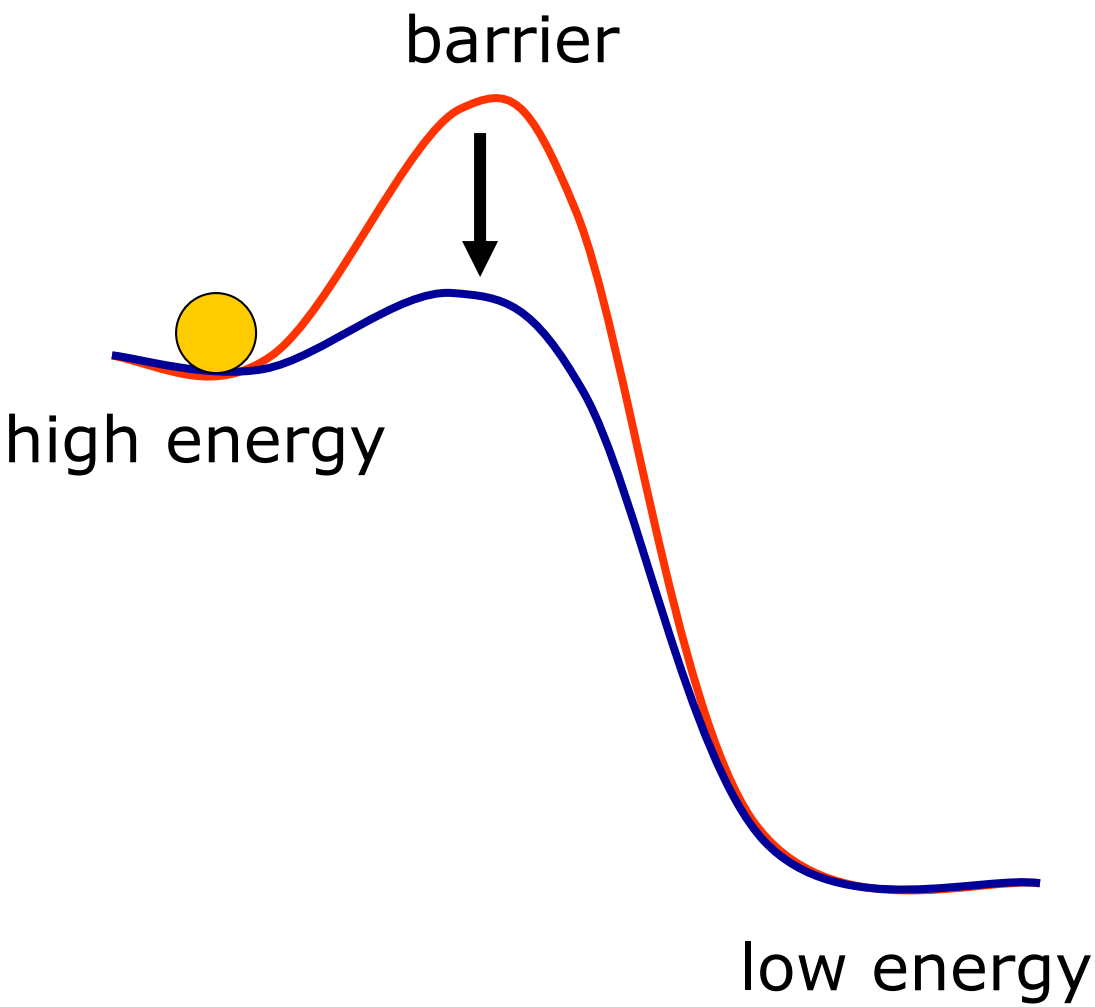
Refueled – engines



$H_2 \rightarrow 2H^+ + 2e^-$ $\quad$ $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Overall: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$

Catalysis

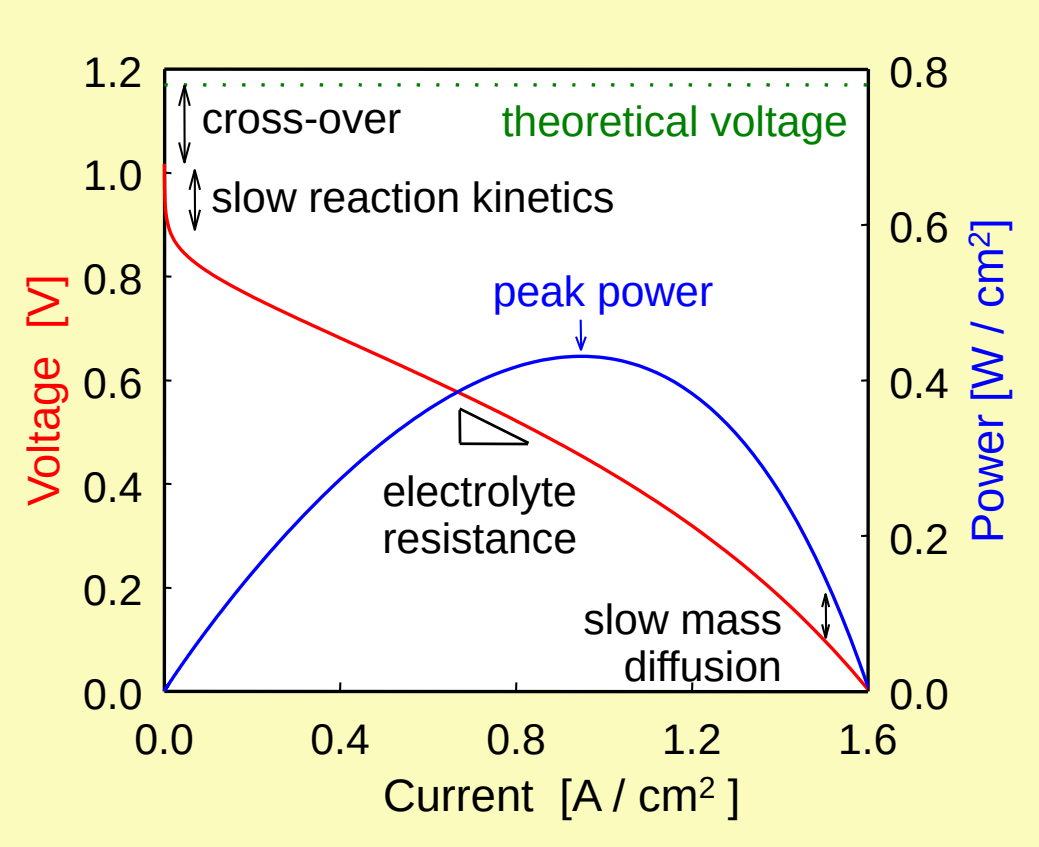


Fuel Cell Performance

$H_2 + ½ O_2 \rightarrow H_2O$

1.17 Volts (@ no current)

- Voltage losses
  - Fuel cross-over
  - Reaction kinetics
  - Electrolyte resistance
  - Slow mass diffusion
- Power = I*V
- Objectives
  - Minimize losses
  - Maximize voltage, power



Fuel Cell Types

Types differentiated by **electrolyte**, temperature of operation

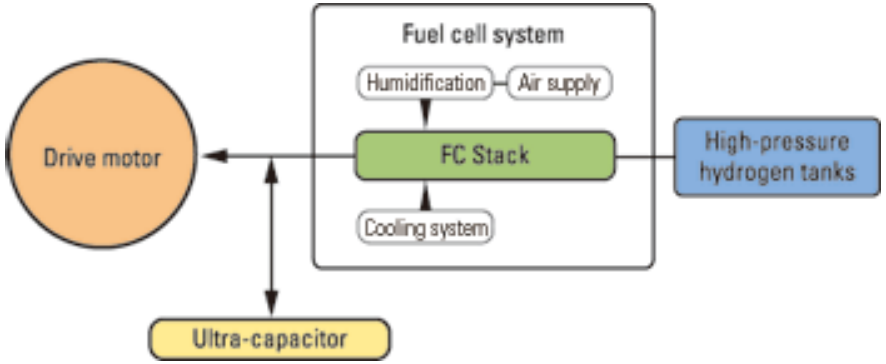
Portable — Stationary

Type °C	**PEM** 90-110	**AFC** 100-250	**PAFC** 150-220	**MCFC** 500-700	**SOFC** 700-1000
Fuel	H_2 + H_2O	H_2	H_2	HC + CO	HC + CO
Electrolyte *Ion*	Nafion $H_3O^+ \downarrow$	KOH $OH^- \uparrow$	H_3PO_4 $H^+ \downarrow$	Na_2CO_3 $CO_3^{2-} \uparrow$	Y-ZrO_2 $O^{2-} \uparrow$
Oxidant	O_2	O_2 + H_2O	O_2	O_2 + CO_2	O_2

← Easy thermal cycling — Fuel flexibility, efficiency →

Most substantial recent investments and development activity

Development Activities (PEM)

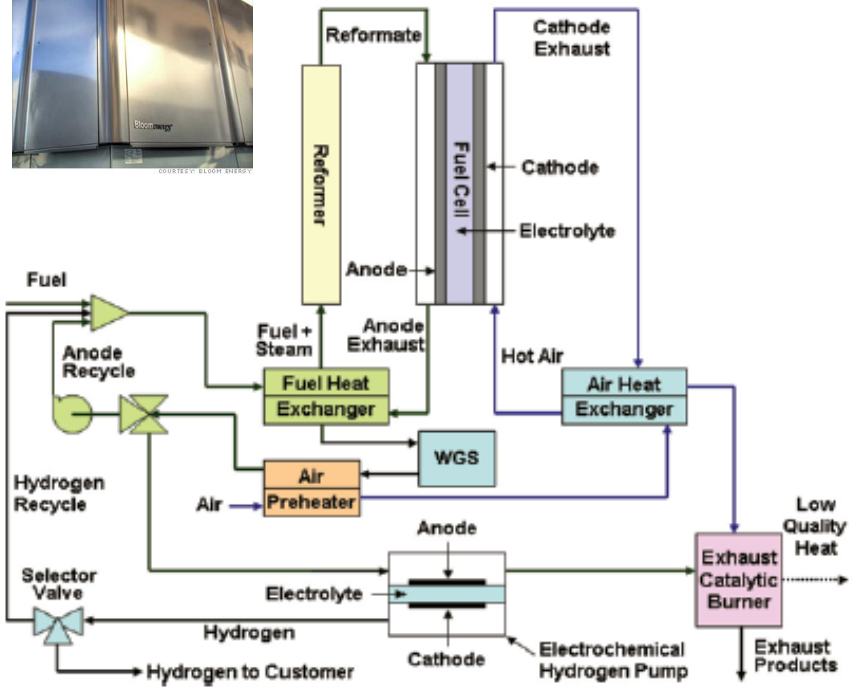


- Honda FCX Clarity
  - Released summer 2008
  - H_2 available markets (LA)
- 86 kW PEM fuel cell
- 68 mpg equivalent
  - 1.5 x gas-electric hybrid
- 270 mile range
- 5,000 psi H_2 tank
  - approx 4 kg H_2
- Lithium-ion battery pack
  - Replaces ultra-caps

- Challenges: Cost, durability, availability of H_2

Development Activities (SOFC)

Bloom Energy Systems

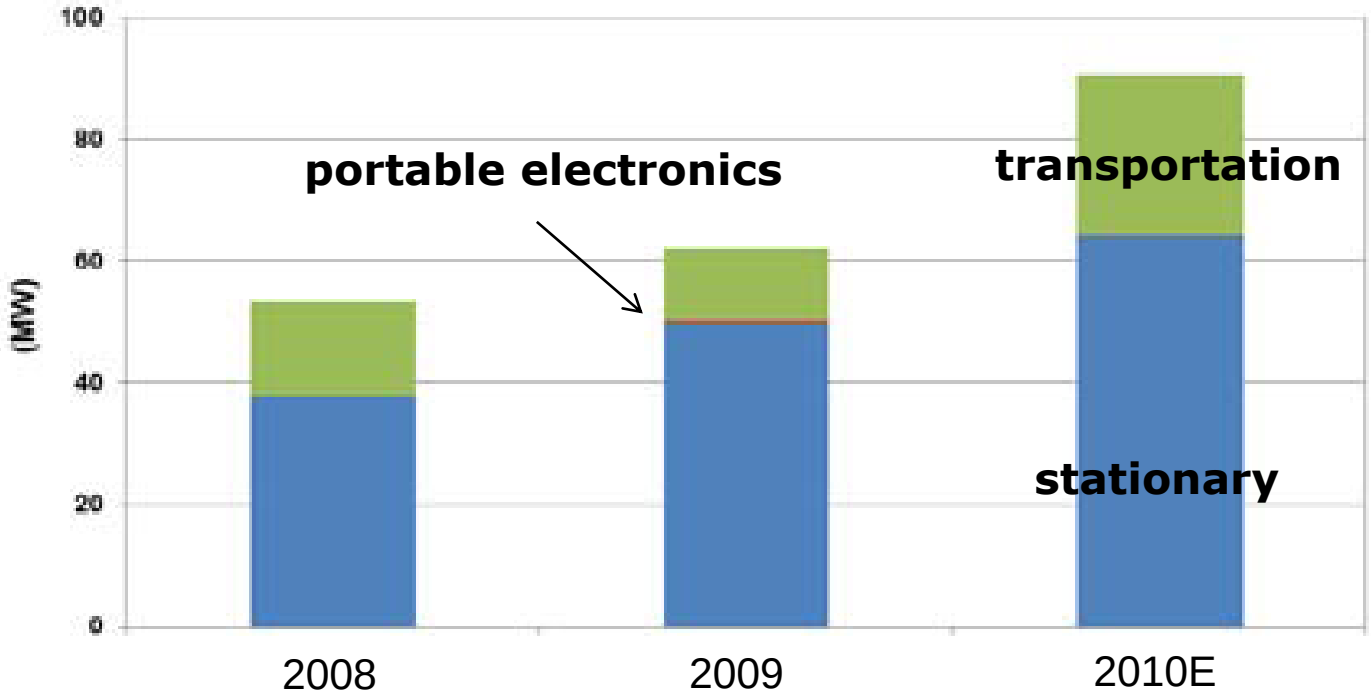


- 100 kW SOFC
- Natural gas
- Fuel-to-electricity %??
- Electricity to date
  - 11m kWh
- Hydrogen by-product
- 2008 price: $750,000
- VC funding: ~$600m
- Conventional technology
- Future: electrolysis

- Challenges: Cost, cost, cost ($7,500/kW)

Commercialization Sectors

Total MW's Shipped per Annum in US by Application



Source: DOE 2010 Fuel Cell Technology Market Report

In Africa??? "Fuel Cells Africa: The Paradigm Shift" has a web presence

Fuel Cell Types

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Oxidant	O_2	O_2 + H_2O	O_2	O_2 + CO_2	O_2

← Easy thermal cycling — Fuel flexibility, efficiency →

Fuel Cell Types

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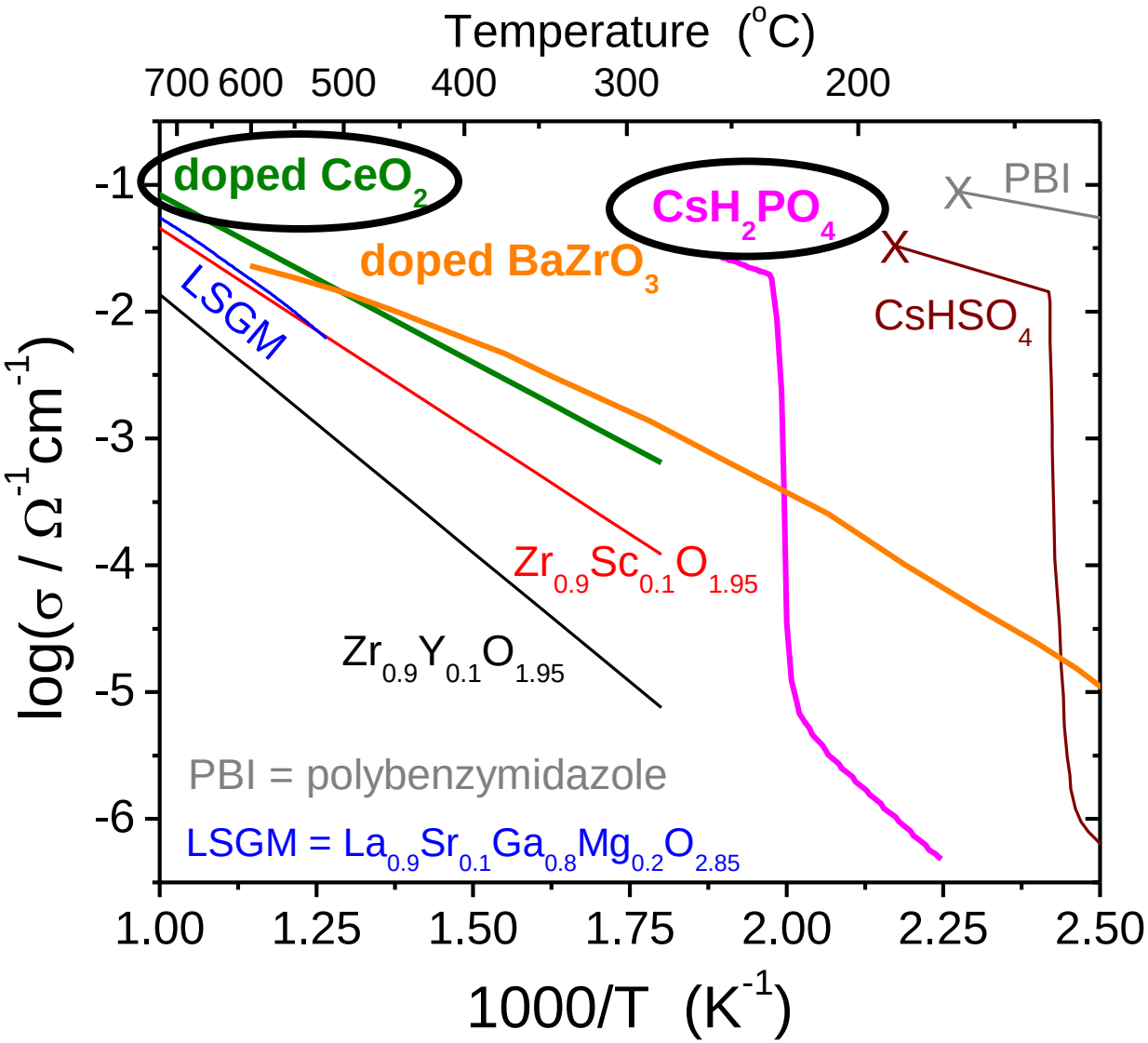
Fuel	H_2 + H_2O	H		+ CO	HC + CO
Electrolyte *Ion*	Nafion $H_3O^+ \downarrow$	KC OH		$_2CO_3$ $O_3^{2-} \uparrow$	Y-ZrO_2 $O^{2-} \uparrow$
Oxidant	O_2	O_2 + H_2O	O_2	O_2 + CO_2	O_2

Corrosive liquids

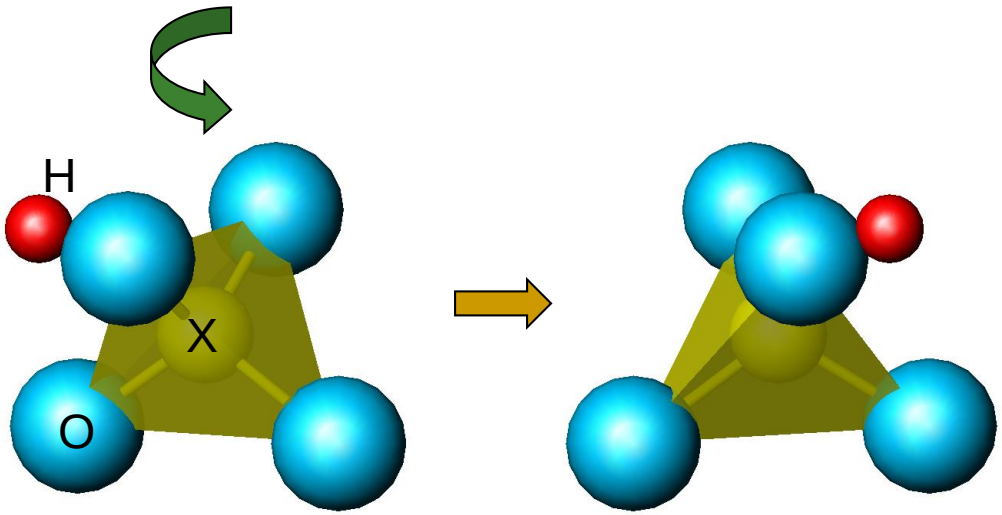
Fuel flexibility, efficiency → ← Easy thermal cycling

Target regime

Candidate Solid Electrolytes

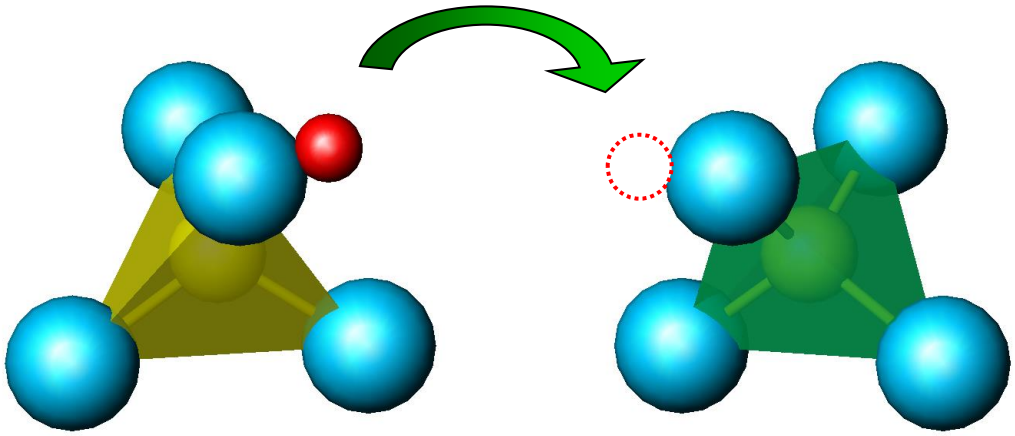


Proton Transport in CsH_2PO_4



Polyanion group reorientation

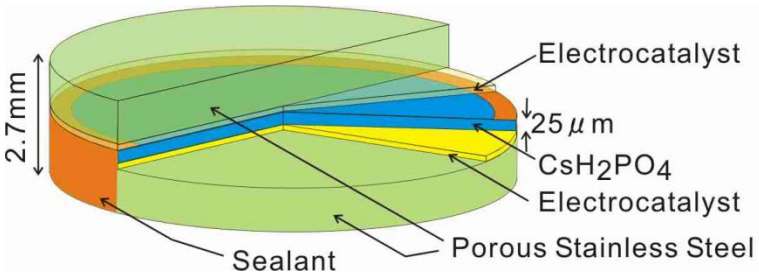
10^{-11} seconds

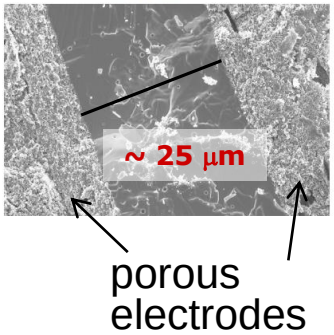


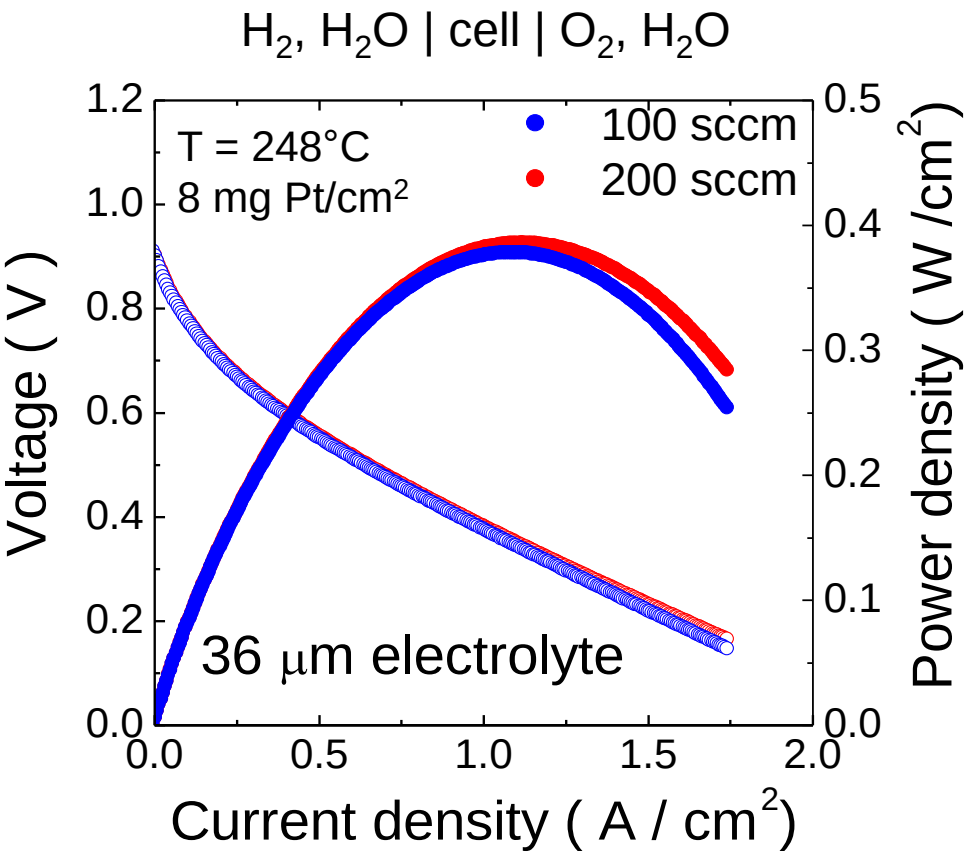
Proton transfer

10^{-9} seconds

Fuel Cell Operation







S.M. Haile, D.A. Boysen, C.R.I. Chisholm & R.B. Merle, *Nature* **410**, 910-913 (2001).

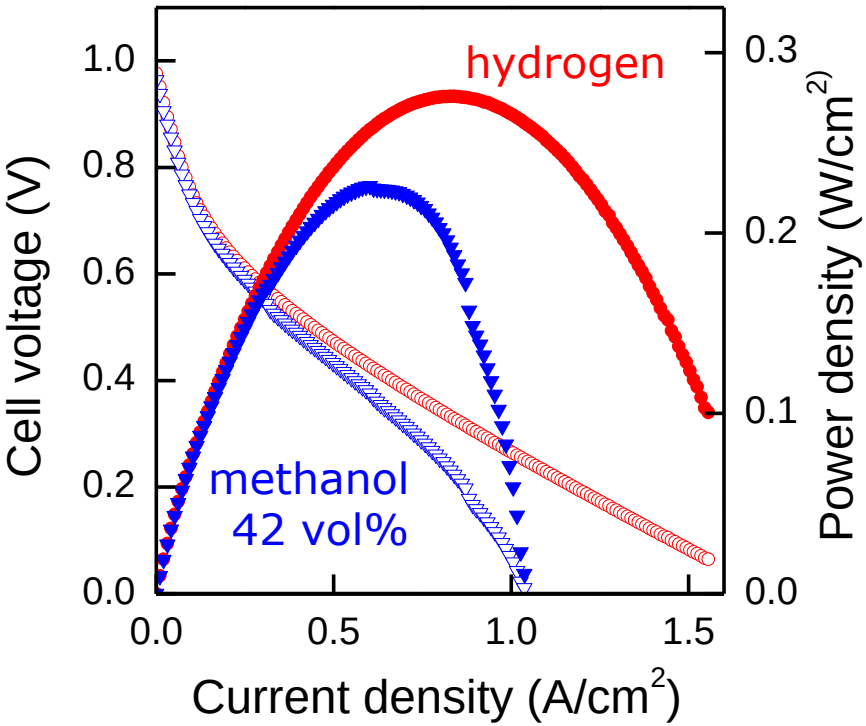
T. Uda & S.M. Haile, *Electrochemical and Solid State Lett*. **8,** A245-A246 (2005).

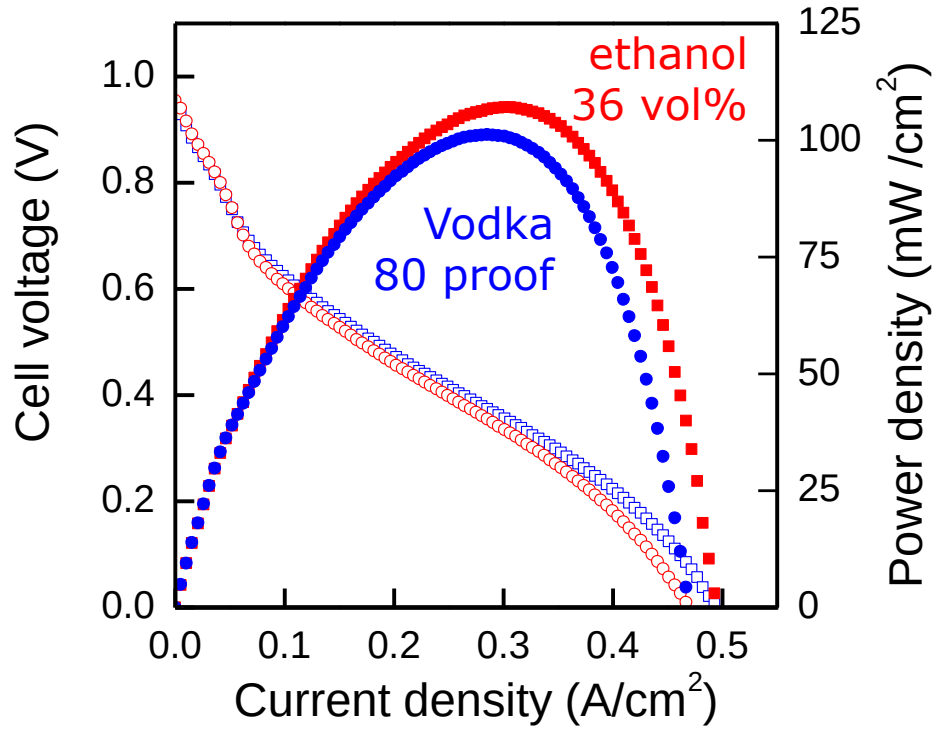
Open circuit voltage: 0.9-1.0 V Peak power density: 285-415 mW/cm²

Fuel Flexibility: Alcohol Fuels

Incorporate additional catalyst at anode: "reformer"

Aids conversion of alcohol + water to hydrogen (then H^+)





T = 260 °C; 47 μm membrane

From Breakthrough to Product

2001

1 cm^2 of fuel cell area

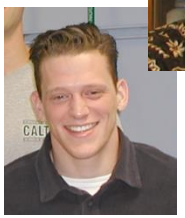
36 mg Pt for 10 mW

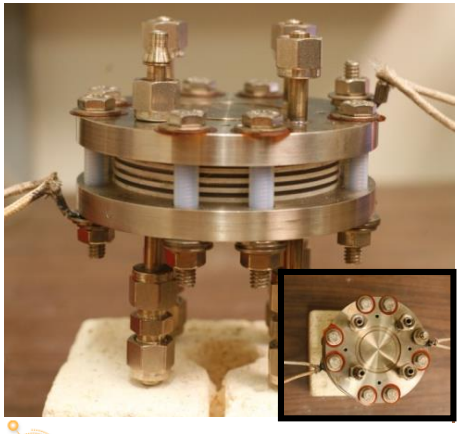
43 g Pt for 60 W bulb

~ $2,163 in Pt

Calum

Dane





SUPERPROTONIC

2007

1 mg Pt for 200 mW

2.5 g Pt for 60 W bulb

~ $126 in Pt

2010

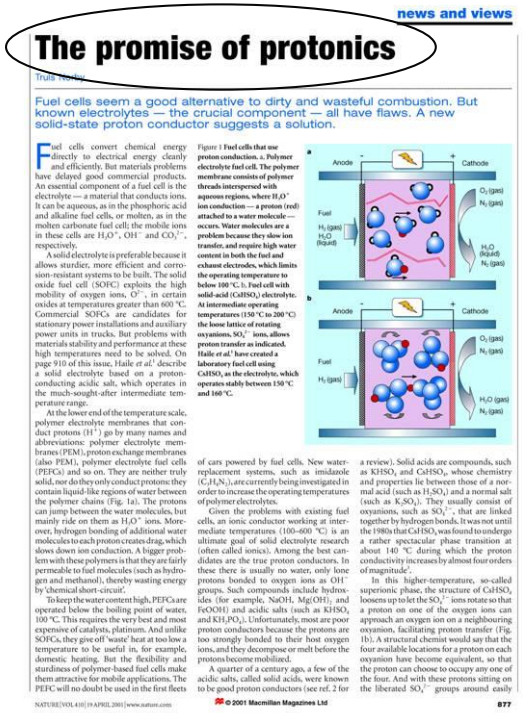
SAFCell

2008

Tom Friedman talking to his wife on an SAFC powered cell phone, 2007

Impact

The promise of protonics



news and views

The promise of protonics

Truls Norby

Fuel cells seem a good alternative to dirty and wasteful combustion. But known electrolytes — the crucial component — all have flaws. A new solid-state proton conductor suggests a solution.

Fuel cells convert chemical energy directly to electrical energy cleanly and efficiently. But materials problems have delayed good commercial products. An essential component of a fuel cell is the electrolyte — a material that conducts ions. It can be aqueous, as in the phosphoric acid and alkaline fuel cells, or molten, as in the molten carbonate fuel cell; the mobile ions in these cells are H_3O^+, OH^- and CO_3^{2-}, respectively.

A solid electrolyte is preferable because it allows sturdier, more efficient and corrosion-resistant systems to be built. The solid oxide fuel cell (SOFC) exploits the high mobility of oxygen ions, O^{2-}, in certain oxides at temperatures greater than 600 °C. Commercial SOFCs are candidates for stationary power installations and auxiliary power units in trucks. But problems with materials stability and performance at these high temperatures need to be solved. On page 910 of this issue, Haile *et al.*[1] describe a solid electrolyte based on a proton-conducting acidic salt, which operates in the much-sought-after intermediate temperature range.

At the lower end of the temperature scale, polymer electrolyte membranes that conduct protons (H^+) go by many names and abbreviations: polymer electrolyte membranes (PEM), proton exchange membranes (also PEM), polymer electrolyte fuel cells (PEFCs) and so on. They are neither truly solid, nor do they only conduct protons: they contain liquid-like regions of water between the polymer chains (Fig. 1a). The protons can jump between the water molecules, but mainly ride on them as H_3O^+ ions. Moreover, hydrogen bonding of additional water molecules to each proton creates drag, which slows down ion conduction. A bigger problem with these polymers is that they are fairly permeable to fuel molecules (such as hydrogen and methanol), thereby wasting energy by 'chemical short-circuit'.

To keep the water content high, PEFCs are operated below the boiling point of water, 100 °C. This requires the very best and most expensive of catalysts, platinum. And unlike SOFCs, they give off 'waste' heat at too low a temperature to be useful in, for example, domestic heating. But the flexibility and sturdiness of polymer-based fuel cells make them attractive for mobile applications. The PEFC will no doubt be used in the first fleets of cars powered by fuel cells. New water-replacement systems, such as imidazole ($C_3H_4N_2$), are currently being investigated in order to increase the operating temperatures of polymer electrolytes.

Given the problems with existing fuel cells, an ionic conductor working at intermediate temperatures (100–600 °C) is an ultimate goal of solid electrolyte research (often called ionics). Among the best candidates are the true proton conductors. In these there is usually no water, only lone protons bonded to oxygen ions as OH^- groups. Such compounds include hydroxides (for example, NaOH, $Mg(OH)_2$ and FeOOH) and acidic salts (such as $KHSO_4$ and KH_2PO_4). Unfortunately, most are poor proton conductors because the protons are too strongly bonded to their host oxygen ions, and they decompose or melt before the protons become mobilized.

A quarter of a century ago, a few of the acidic salts, called solid acids, were known to be good proton conductors (see ref. 2 for a review). Solid acids are compounds, such as $KHSO_4$ and $CsHSO_4$, whose chemistry and properties lie between those of a normal acid (such as H_2SO_4) and a normal salt (such as K_2SO_4). They usually consist of oxyanions, such as SO_4^{2-}, that are linked together by hydrogen bonds. It was not until the 1980s that $CsHSO_4$ was found to undergo a rather spectacular phase transition at about 140 °C during which the proton conductivity increases by almost four orders of magnitude[3].

In this higher-temperature, so-called superionic phase, the structure of $CsHSO_4$ loosens up to let the SO_4^{2-} ions rotate so that a proton on one of the oxygen ions can approach an oxygen ion on a neighbouring oxyanion, facilitating proton transfer (Fig. 1b). A structural chemist would say that the four available locations for a proton on each oxyanion have become equivalent, so that the proton can choose to occupy any one of the four. And with these protons sitting on the liberated SO_4^{2-} groups around easily

Figure 1 **Fuel cells that use proton conduction. a, Polymer electrolyte fuel cell. The polymer membrane consists of polymer threads interspersed with aqueous regions, where H_3O^+ ion conduction — a proton (red) attached to a water molecule — occurs. Water molecules are a problem because they slow ion transfer, and require high water content in both the fuel and exhaust electrodes, which limits the operating temperature to below 100 °C. b, Fuel cell with solid-acid ($CsHSO_4$) electrolyte. At intermediate operating temperatures (150 °C to 200 °C) the loose lattice of rotating oxyanions, SO_4^{2-} ions, allows proton transfer as indicated. Haile *et al.*[1] have created a laboratory fuel cell using $CsHSO_4$, as the electrolyte, which operates stably between 150 °C and 160 °C.**

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Nature: News & Views

Some Like It Medium Hot

ScienceNOW -- 2001 (418): 1

Science now

18 April 2001 7:00 PM

Some Like It Medium Hot

Fuel cells have the potential to generate energy without pollution. But some run too cold to be efficient, while the others are too hot to be practical. But a newly tested type of fuel cell might be just right, though it's still a long way from appearing in automobile showrooms.

Just right. Fuel cells might someday power automobiles cleanly and efficiently, but only if they can run within a reasonable temperature range.
CREDIT: PHOTODISC

The beauty of fuel cells is that they directly generate electricity from the chemical energy stored in pure hydrogen or other fuels, bypassing the mess and waste of combustion (Science, 16 June 2000, p. 1955). One very efficient design operates at temperatures above 600°C, so it must be constructed of expensive, heat-resistant materials. A low-temperature variety of fuel cell works best at a mere 80°C, but it is less efficient, relies on expensive catalysts, and feeds on a smaller repertoire of fuels than its high-temperature cousin. Researchers have been on the quest for a fuel cell that works between these two temperatures, in a range that would be suitable for vehicles.

The key fuel cell component that determines its operating temperature is the electrolyte, a layer of material that conducts charged atoms from one side of the cell to the other. Chemists have known for decades that a class of compounds called solid acids conduct hydrogen ions efficiently at moderate temperatures, but these materials had never been put to work in a fuel cell.

Now materials scientist Sossina Haile and colleagues at the California Institute of Technology in Pasadena have constructed the first fuel cell based on a solid acid. They sandwiched a thin layer of a solid acid called cesium hydrogen sulfate between electrodes and pressed it tight for good contact. The fuel cell ran on hydrogen for several days at a favorable 160°C, although it produced just 1% as much energy as existing fuel cells. Haile says that tinkering with the electrolyte composition and thinning the solid acid layer will improve the efficiency.

The result is "one of the more important discoveries lately" in the study of fuel cell electrolytes, says Jack Brouwer, associate director of the National Fuel Cell Research Center at the University of California, Irvine. But many caution that it's a long way from the laboratory to a working product. Says Subhash Singhal, director of fuel cell research at the Pacific Northwest National Laboratory in Richland, Washington, "no one is going to start using them on a large scale immediately."

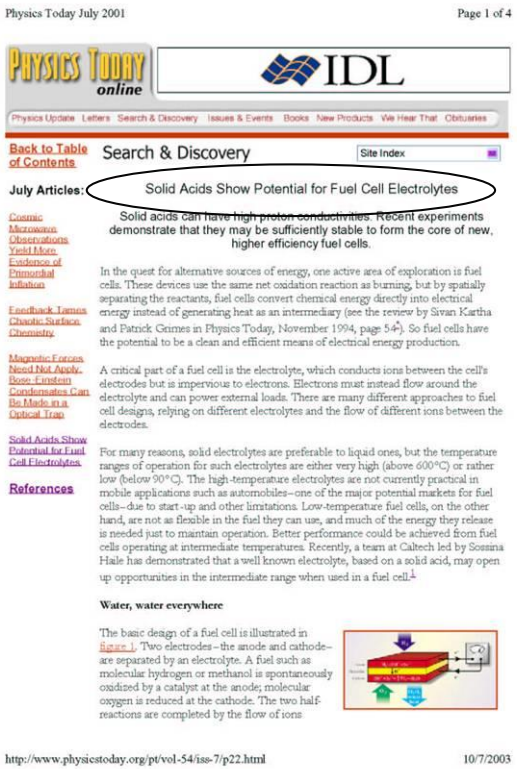
—R. JOHN DAVENPORT

Related sites

Sossina Haile's faculty page
A diagram of how fuel cells work
National Center for Fuel Cell Research
Fuel Cells 2000

Science Now Magazine

Solid Acids Show Promise...



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Solid Acids Show Potential for Fuel Cell Electrolytes

References

Solid Acids Show Potential for Fuel Cell Electrolytes

Solid acids can have high proton conductivities. Recent experiments demonstrate that they may be sufficiently stable to form the core of new, higher efficiency fuel cells.

In the quest for alternative sources of energy, one active area of exploration is fuel cells. These devices use the same net oxidation reaction as burning, but by spatially separating the reactants, fuel cells convert chemical energy directly into electrical energy instead of generating heat as an intermediary (see the review by Sivan Kartha and Patrick Grimes in Physics Today, November 1994, page 54). So fuel cells have the potential to be a clean and efficient means of electrical energy production.

A critical part of a fuel cell is the electrolyte, which conducts ions between the cell's electrodes but is impervious to electrons. Electrons must instead flow around the electrolyte and can power external loads. There are many different approaches to fuel cell designs, relying on different electrolytes and the flow of different ions between the electrodes.

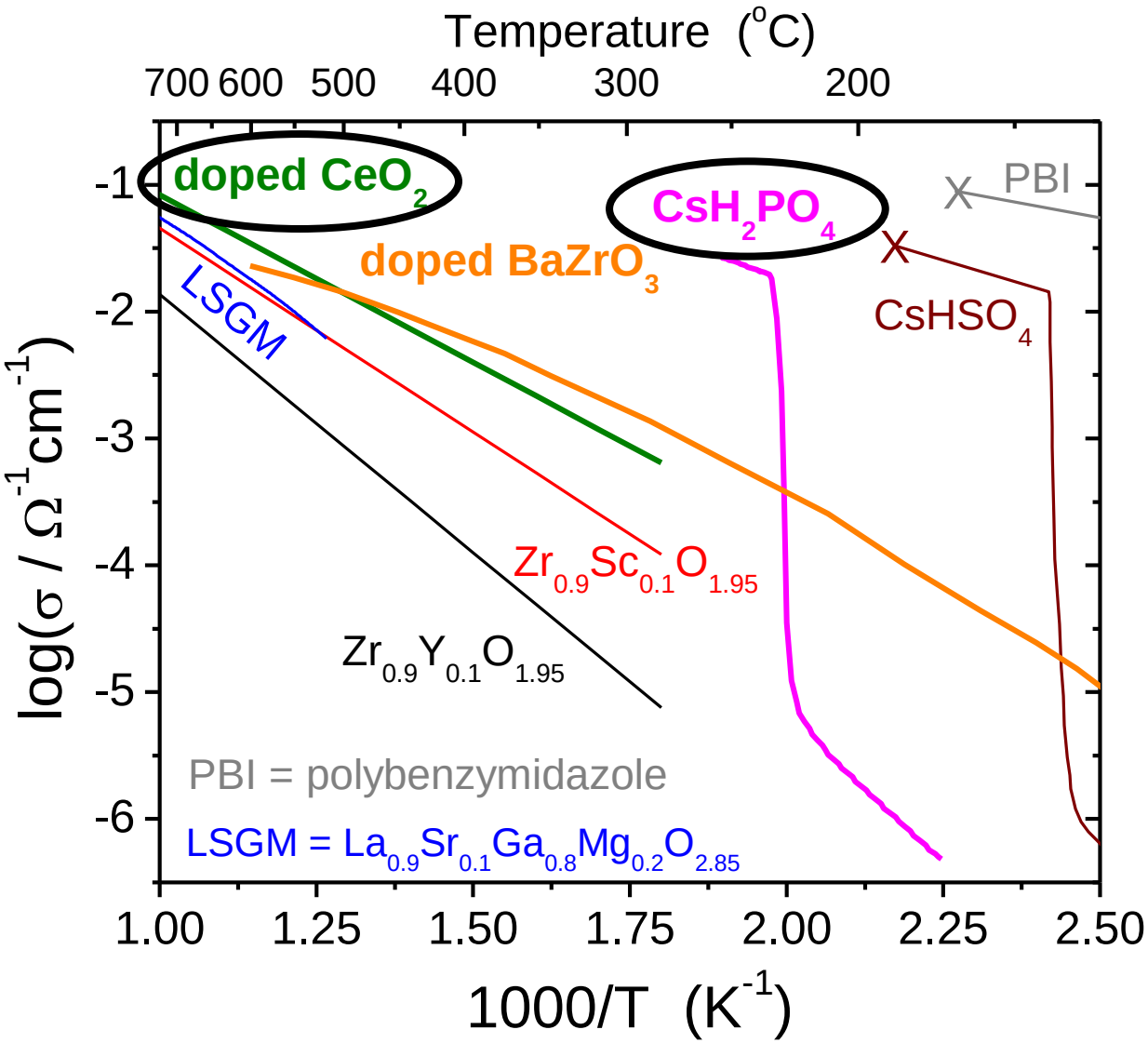
For many reasons, solid electrolytes are preferable to liquid ones, but the temperature ranges of operation for such electrolytes are either very high (above 600°C) or rather low (below 90°C). The high-temperature electrolytes are not currently practical in mobile applications such as automobiles—one of the major potential markets for fuel cells—due to start-up and other limitations. Low-temperature fuel cells, on the other hand, are not as flexible in the fuel they can use, and much of the energy they release is needed just to maintain operation. Better performance could be achieved from fuel cells operating at intermediate temperatures. Recently, a team at Caltech led by Sossina Haile has demonstrated that a well known electrolyte, based on a solid acid, may open up opportunities in the intermediate range when used in a fuel cell.[1]

Water, water everywhere

The basic design of a fuel cell is illustrated in Figure 1. Two electrodes—the anode and cathode—are separated by an electrolyte. A fuel such as molecular hydrogen or methanol is spontaneously oxidized by a catalyst at the anode; molecular oxygen is reduced at the cathode. The two half-reactions are completed by the flow of ions

Physics Today Online

Candidate Solid Electrolytes

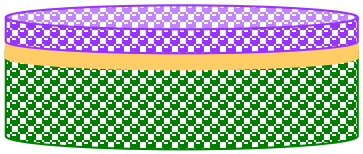


State-of-the-Art SOFCs

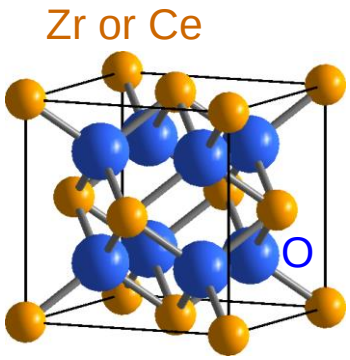
Component Materials

cathode (air electrode) — $(La,Sr)MnO_3$

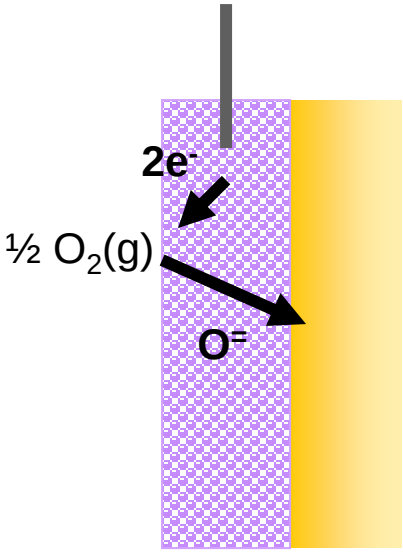
electrolyte — $Zr_{0.92}Y_{0.08}O_{2.96}$ = yttria stabilized zirconia (YSZ)



anode (fuel electrode) — Ni + YSZ composite



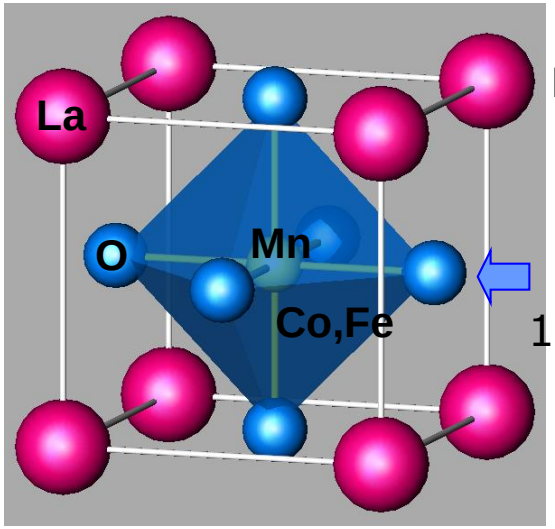
- Cathode typically has highest losses
  - Prepared as thinnest component
  - Murky literature
  - Limited understanding
- Cathode function
  - $\frac{1}{2} O_2 + 2e^- \rightarrow O^=$
    gas — current collector — electrolyte



New Cathodes for Solid Oxide Fuel Cells

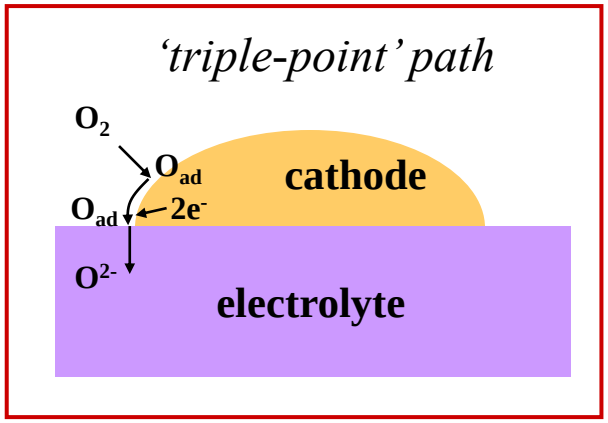
- Traditional cathodes
  - $A^{3+}B^{3+}O_3$ perovskites
  - Poor O^{2-} transport
  - Limited reaction sites
- Our approach
  - High O^{2-} flux materials
  - Extended reaction sites
  - $A^{2+}B^{4+}O_3$ perovskites

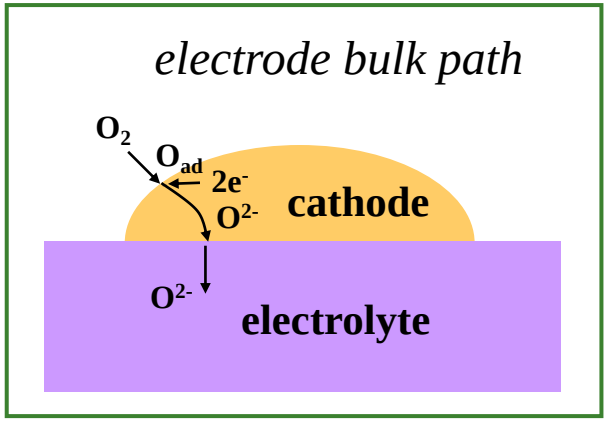
$(Ba_{0.5}Sr_{0.5})(Co_{0.8}Fe_{0.2})O_{2.4}$



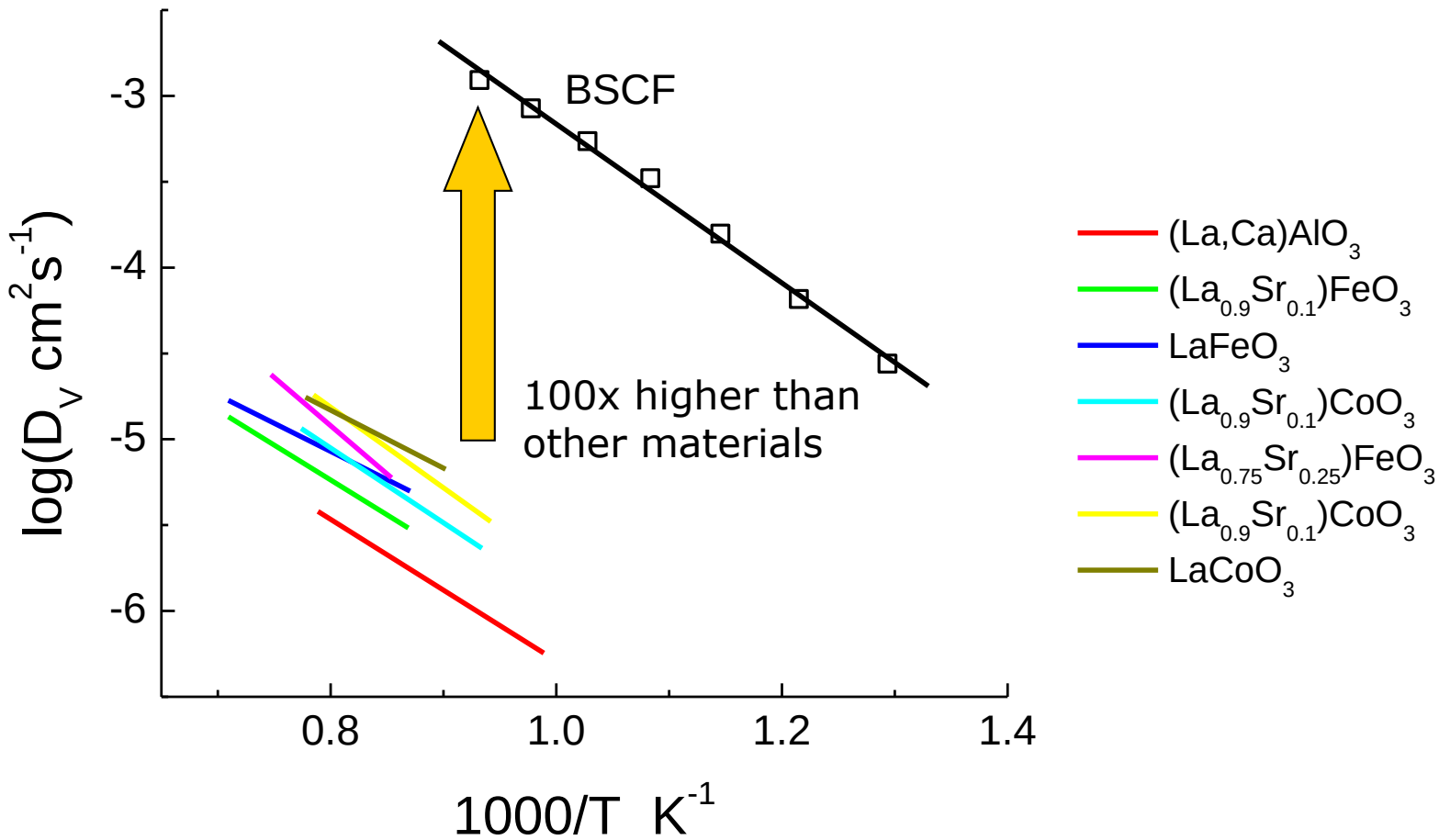
Ba,Sr

almost 1 in 5 vacant





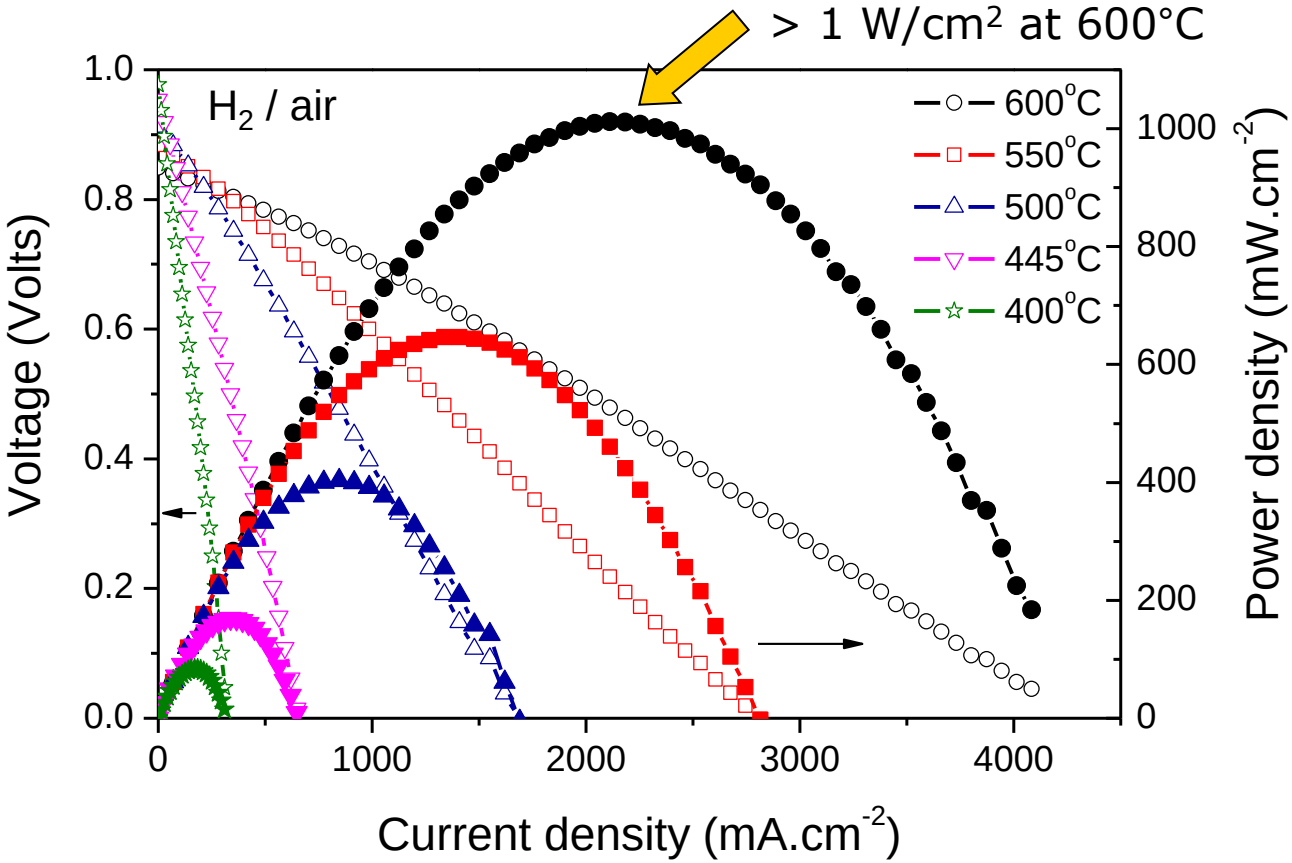
Vacancy Diffusion Coefficient



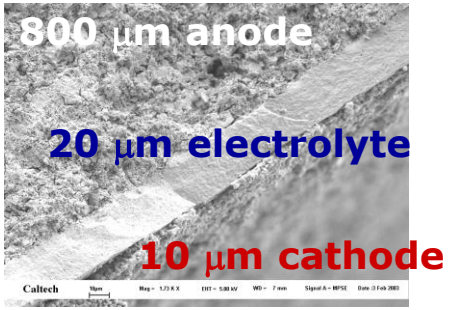
similar enhancement in k_{surf}

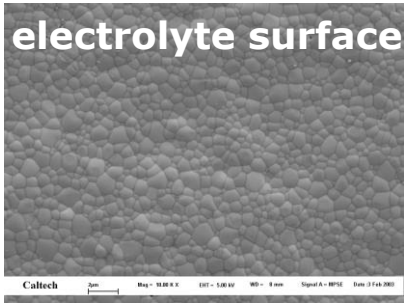
Record Performance

Conventional powder processing



Ni-SDC | SDC | BSCF





High power density reproduced in other labs

Z. Shao and S. M. Haile, *Nature* **431**, 170-173 (2004).

Impact

Cooler Material Boosts Fuel Cells

SOFC cathode is hot stuff…

Next generation of fuel cells…

TRN
The Latest Technology Research News

Cooler material boosts fuel cells

By Kimberly Patch, Technology Research News

Finding a way to reduce the operating temperature requirements for solid oxide fuel cells, which now require temperatures of 800 to 1,000 degrees Celsius to use fuel other than pure hydrogen, is a key step toward widespread adoption of fuel cells.

Solid oxide is one of five basic types of fuel cells, and is a promising type for municipal, home and mobile electricity generators.

Researchers from the California Institute of Technology have devised a cathode that allows solid oxide fuel cells to operate at 500 to 700 degrees Celsius. This temperature range is high enough to support a variety of fuels, but low enough that the fuel cell components need not be made from costly high-temperature materials, said Sossina Haile, an associate professor of materials science and chemical engineering at the California Institute of Technology.

The method promises to lower the cost of fuel cells, which could spur broader adoption of the technology.

Fuel cells extract chemical energy from fuel rather than burning it like combustion engines. Like batteries, fuel cells contain a pair of electrodes, and supply a flow of electricity by pushing electrons from the anode to the cathode. This happens when oxygen reacts with electrons at the cathode to form oxygen ions, which then migrate through the electrolyte to the anode where they react with fuel to produce water and release electrons. Some fuels also produce carbon dioxide at this step.

The researchers' fuel cell looks much like existing cells, said Haile. "It's like developing a recipe for a cake that bakes at 150 degrees Fahrenheit rather than 325 degrees Fahrenheit," she said. "The oven still looks pretty much the same, but it's a lot cheaper because it doesn't have to withstand such high temperatures."

Until the researchers' new cathode, all known cathode materials have been effective only at temperatures near 1,000 degrees Celsius at catalyzing, or speeding up the reaction of the oxygen gas molecule with electrons to form negatively-charged oxygen ions, said Haile.

Haile's research colleague Zongping Shao developed the material, made from barium, strontium, cobalt, iron and oxygen, and dubbed BSCF, for a different application -- oxygen purification membranes.

It was natural that the researchers test the material as a fuel cell cathode because some of the properties that make the material useful as an oxygen purification membrane also tend to make it good as a fuel cell cathode, said Haile.

But the chemical formula was different enough from typical fuel cell cathodes

Tech Research News

R&D FOCUS

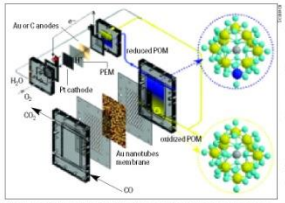
A survey of cutting-edge research, development and innovation.

Energy shuttle exploits nanocatalysis

Madison, WI: An unwanted and damaging by-product of fuel-cell operation could be removed and put to good use via a reaction pathway that also generates electricity, according to research presented in the journal *Science* (27 August, p1280).

Won Bae Kim and colleagues at the University of Wisconsin, Madison, US, have come up with a way of oxidizing CO by reacting it with water and a reducible polyoxometalate (POM) compound at room temperature in the presence of a gold nanotube or nanoparticle catalyst. POM compounds such as $H_3PMo_{12}O_{40}$ serve as strong oxidizing agents for CO and as storage agents for electrons and protons. Gold nanoparticles are excellent catalysts for the oxidation of CO, particularly in the presence of water.

A key feature of the Wisconsin approach is that the oxidizing agent exhibits reversible behaviour. The reducible POM compound facilitates CO [illegible] while the reduced form of the POM then serves as a fuel to generate electricity when it undergoes oxidation at the fuel cell's anode. Furthermore, the anode does not have to include precious metals: the researchers found that good current densities can [illegible] carbon anode.



Cleaning up: Wisconsin's CO oxidation reactor with gold nanocatalyst.

CO is a by-product when hydrocarbons or oxygenated hydrocarbons are broken down to yield the hydrogen that is necessary to fuel proton-exchange-membrane (PEM) fuel cells. This causes problems, because even small quantities of CO [illegible] catalyst in these cells. The current method for removing CO is the water-gas shift (WGS) reaction, which converts CO and water to carbon dioxide and hydrogen. However, this exothermic reaction is a major bottleneck in the production of hydrogen because it is slow at the low temperatures (around 500 K) required to achieve favourable conversions.

By contrast, the Wisconsin approach shows oxidation rates for CO that are an order of magnitude greater than the rates observed with the WGS reaction. The use of the gold catalyst also enables the POM reaction to take place at room temperature. "This [new] process is especially promising for the production of electrical energy from renewable, biomass-derived oxygenated hydrocarbons because these reactants have CO stoichiometric ratios equal to 1:1, and they therefore generate H_2 and CO in nearly equal amounts during catalytic decomposition," write the [illegible]

SOFC cathode is hot stuff at lower temperatures

Pasadena, CA: A new cathode material [illegible] high power densities in solid-oxide fuel cells (SOFCs) even when they are operated at temperatures as low as 500 °C. This is significant because cathode performance is one of the main limiting factors in lowering the operating temperatures of SOFCs. Today's SOFC systems generally operate at 800–1000 °C, which results in high costs and challenges in finding materials that can cope with these temperatures.

When the cathode material, $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF), was incorporated into a thin-film-doped ceria fuel cell it exhibited peak power densities of 1010 mW/cm^2 and 402 mW/cm^2 at temperatures of 600 °C and 500 °C respectively. At both temperatures, the fuel was humidified hydrogen and the cathode gas was air. "These values are more than twice those measured in our laboratory for a similar cell but with [illegible] samaria-doped ceria] as the cathode," write Zongping Shao and Sossina M Haile in the journal *Nature* (9 September, p170).

Beyond the high power density, BSCF is expected to provide benefits for single-chamber fuel cells. In conventional SOFCs, the anode and cathode reactions occur in different physical chambers, but there is growing interest in operating systems where the anode and cathode are in the same chamber. For this design to work, however, the cathode must be able to facilitate the electrochemical reduction of oxygen but be inactive towards oxidation of the fuel.

The team, which is based at California Institute of Technology, has shown that BSCF has a lower activity towards propane oxidation than other cathode materials. Under stoichiometric conditions at [illegible] version rate of just 5.3%. In contrast, the competing cathode materials LSCF [$La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$] and SSC gave propane conversion rates of 35.5% and 16.1%.

The new cathode material also yielded good power densities in a single-chamber configuration with a propane:oxygen:helium mixture (4:9:36 volumetric ratio) as the feed gas. In fact, once the BSCF cathode was modified to incorporate 30 wt% SDC, the cell gave a peak power density of around 440 mW/cm^2 when the furnace was set to 500 °C. The apparently higher power density than that seen in the dual-chamber system at the same temperature is attributed to the heat released during partial oxidation of the fuel at the anode. This heat release means that the actual temperature of the fuel cell is about [illegible] °C higher than the furnace temperature.

The Caltech scientists have high hopes for BSCF. They claim that, even at temperatures as low as 500 °C, around 74% of the overall cell resistance in a dual-chamber configuration arises from the 20 μm-thick electrolyte rather than the cathode. The next step is to try to halve the electrolyte resistance by optimizing its composition.

If this effort is successful, the researchers predict that a peak power density of more than 600 mW/cm^2 could be achieved at temperatures of 500 °C. They note that "additional increases in power density may be achieved through precise control of the cathode architecture using advanced preparation methods to maximize the surface area over which the oxygen-exchange reaction can occur".

The Fuel Cell Review | October/November 2004 | FCR.IOP.ORG

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R & D Focus

FUEL CELL WORKS

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Next generation of fuel cells addresses major design problem

Publication Date: [illegible] ember 2004
Source: Science Letter

For several years now the U.S. Department of Energy (DOE) has been urging the fuel cell commur to solve a major problem in the design of solid oxide fuel cells (SOFCs): heat. Such fuel cells could someday provide reliable power for homes and industry, dramatically cutting greenhouse gas emissions as well as other pollutants.

But SOFCs run hot, at temperatures as high as 1000 degrees C (about 1800 degrees F). They're efficient at such temperatures, but only a few costly materials can withstand the heat. Using such materials makes things expensive, and is the reason for the push for lower temperatures by the D

Sossina Haile, an associate professor of materials science and chemical engineering at the Californ Institute of Technology, is an expert in fuel cells, and she has been whittling away at the heat prol for years. Now she and her colleagues have not only solved the problem, they've smashed it. They brought the temperature down to about 600 degrees C (1100 degrees F), while achieving more po output than others are achieving at the higher temperatures - about 1 watt per square centimeter fuel cell area.

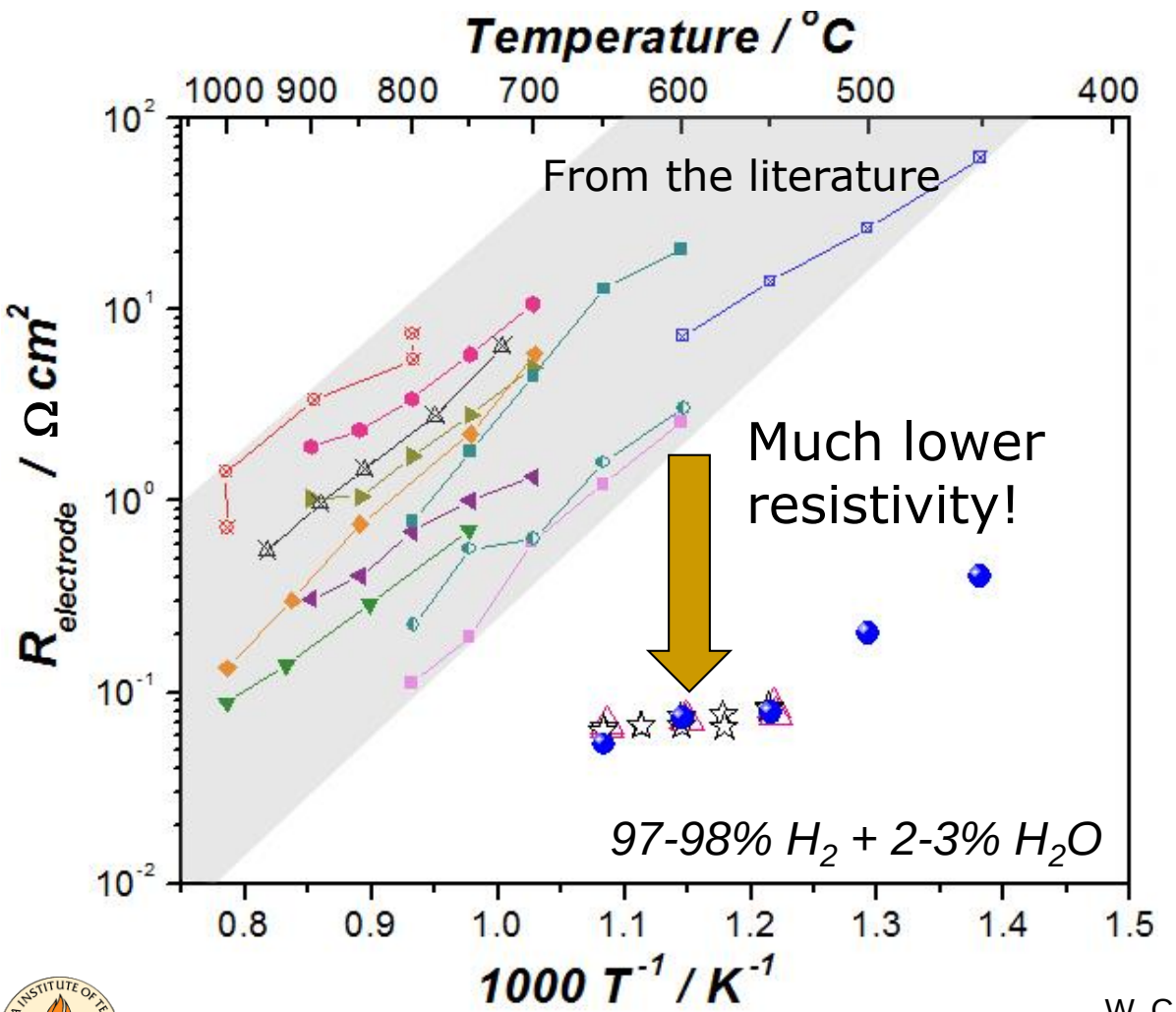
They accomplished this by changing the chemical composition of one component of a fuel cell calle the cathode. The cathode is where air is fed in to the fuel cell, and it's where the oxygen is electrochemically reduced to oxygen ions. The oxygen ions then migrate across the electrolyte (wh conducts electricity), to react with fuel at the anode, another fuel cell component. The electrochem reduction of oxygen is an essential step in the fuel cell's process of generating power. But the prot with running solid oxide fuel cells at 500-700 degrees C is that the cathode becomes inactive wher temperature is less than about 800 degrees C.

Haile and postdoctoral scholar Zongping Shao's insight was to switch out the conventional cathode and replace it with a compound that has a long chemical formula guaranteed to strike fear into the heart of every undergraduate, but is abbreviated as "BSCF".

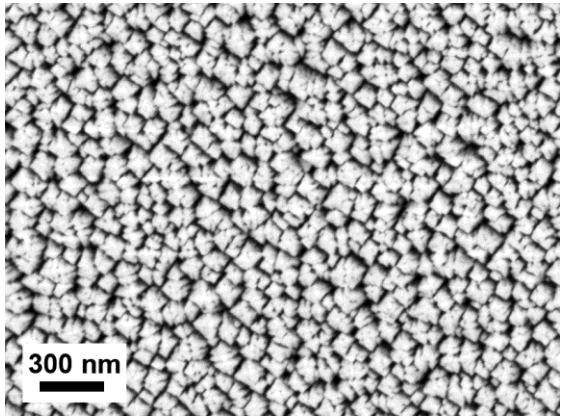
What BSCF can do that standard cathodes can't is to allow the oxygen to diffuse through it very rapidly. "In conventional cathodes, the oxygen diffuses slowly, so that even if the electrochemical reaction is fast, the oxygen ions are slow in getting to the electrolyte," said Haile. "In BSCF the electrochemical reaction is fast and the oxygen ion transport is fast. You have the best combinatio properties." This combination is what gives the very high power outputs from Haile's fuel cells.

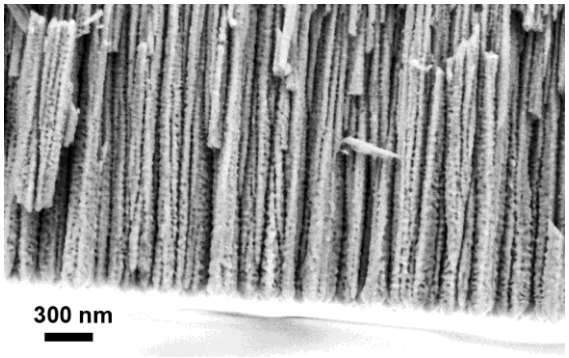
Fuel Cell Works

How to Do Even Better



Nanostructured fuel electrode

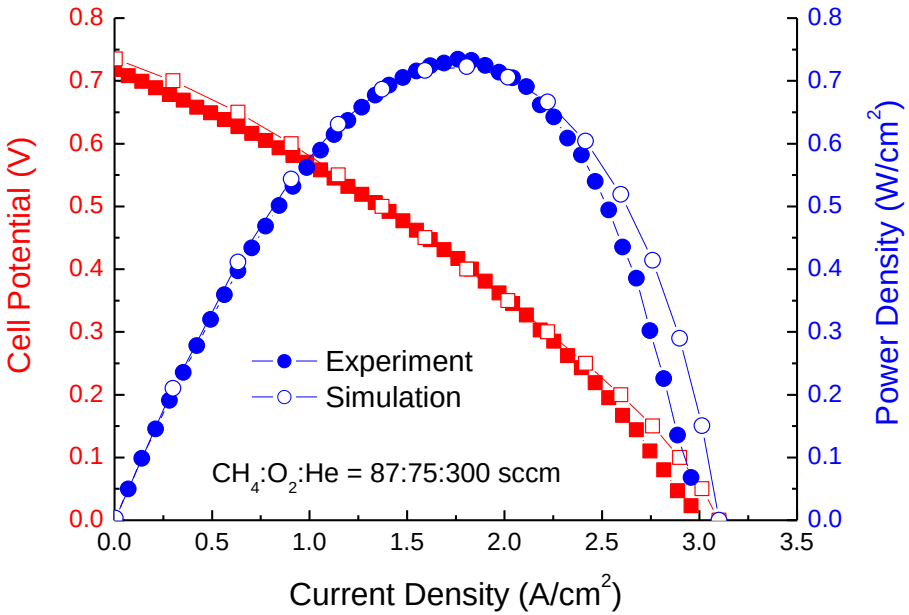




W. C. Chueh, Y. Hao, WooChul Jung and S. M. Haile, *Nat. Mat.*. (2011) doi:10.1038/nmat3184.

What Are the Limits?

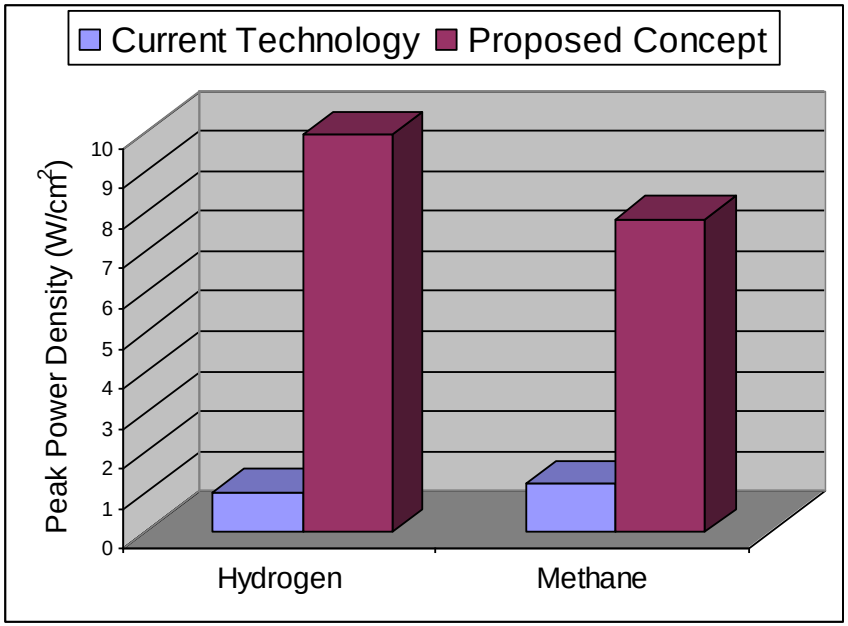
Model validation



- Parameters obtained independently
- Model predicts experimental results

Model predictions

- 10x increase in power



Based on fundamentals

Y. Hao, Z. Shao, J. Mederos, W. Lai, D. G. Goodwin and S. M. Haile, *Solid State Ionics* **177**, 2013-2021 (2006).

Summary & Conclusions

- Sustainable energy is the 'grand challenge' of our century
  - Fuel cells can play an important role
  - Effective at all size scales – relevant for developing nations
- Solid acid fuel cells
  - Radical alternatives to state-of-the-art
  - Viability demonstrated; spin-off company established
- Solid oxide fuel cells
  - Excellent alternative cathode (air electrode) discovered
  - Increased activity of anode (fuel electrode) ten-fold
  - Exceptional performance on the horizon
- Still plenty of need for fundamental research

"The stone age didn't end because of a shortage of stones"

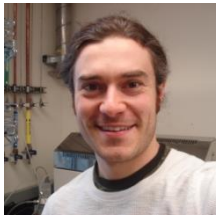
-Sheik Ahmed Zaki Yemani, Saudi Oil Minister, 1973

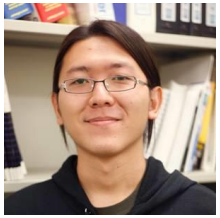
The People

- Current Students

Carolyn

Danien


Rob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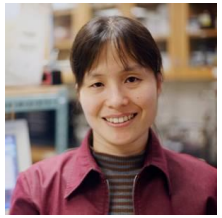
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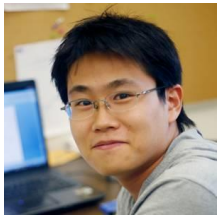
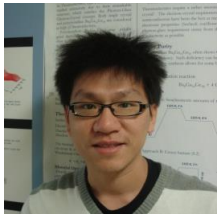

Tae-Sik

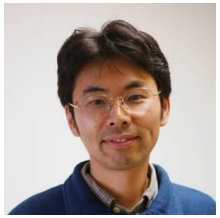
Vanessa

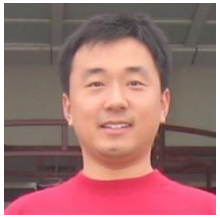
B.G.


Chih-Kai

Áron

- Associates & Post-docs


Yoshi


Yong

Jaemin

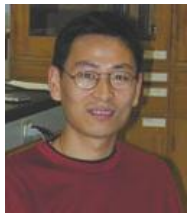
Woo-Chul

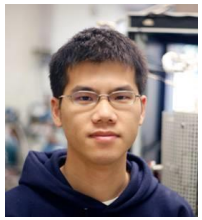
- Former, who contributed to results

Calum

Tetsuya

Dane


Zongping


William

Wei

- Collaborator: Prof. David Goodwin