A Fuel Cell Future?

Ryan O'Hayre

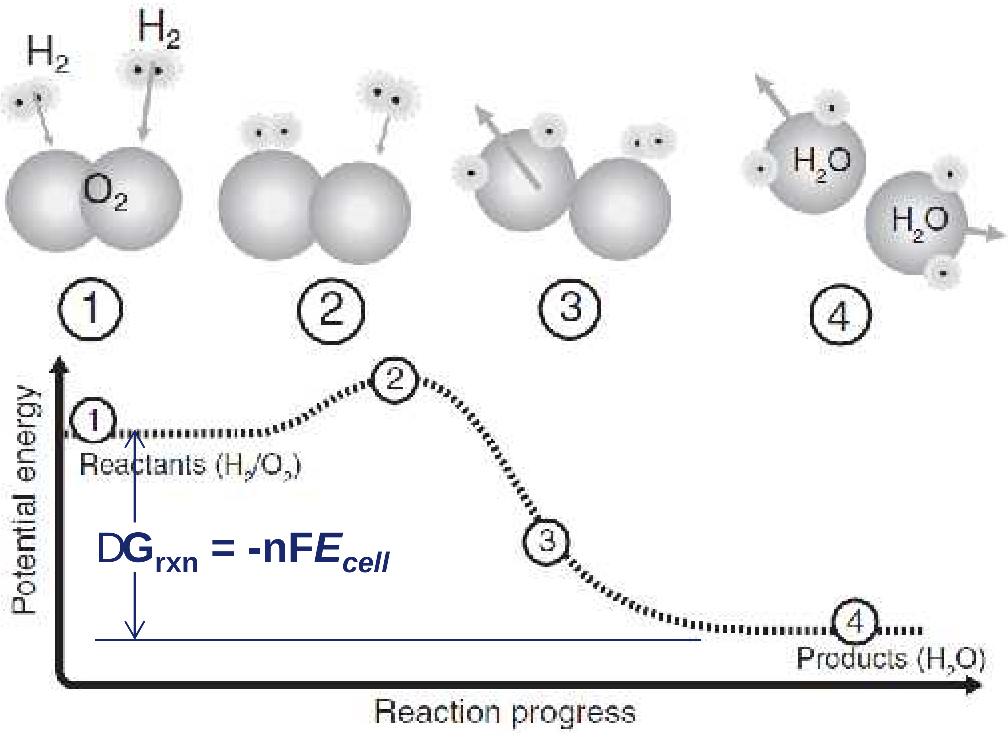
Fuel Cell Basics

What Is A Fuel Cell?

- Electrochemical energy conversion device
  - Directly converts chemical energy to electrical energy

How a Fuel Cell Works

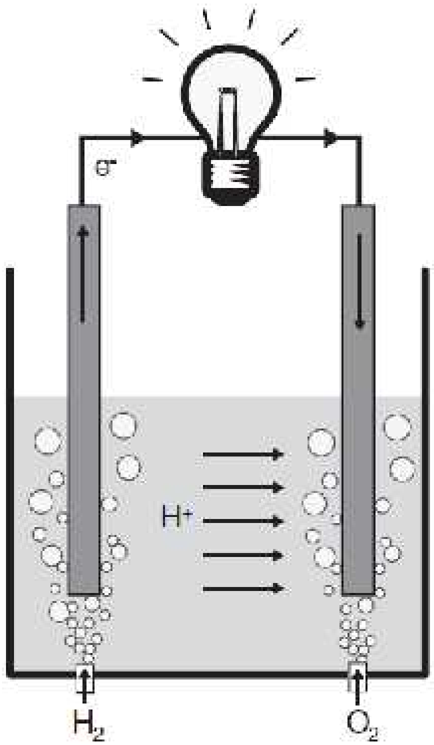
- Exploits electron bonding reconfigurations without thermalization



Ryan O'Hayre, Suk-Won Cha, Whitney Colella, Fritz B. Prinz, (2009). *Fuel Cell Fundamentals, 2nd Edition*. New York, New York: John Wiley and Sons, Inc.

How a Fuel Cell Works

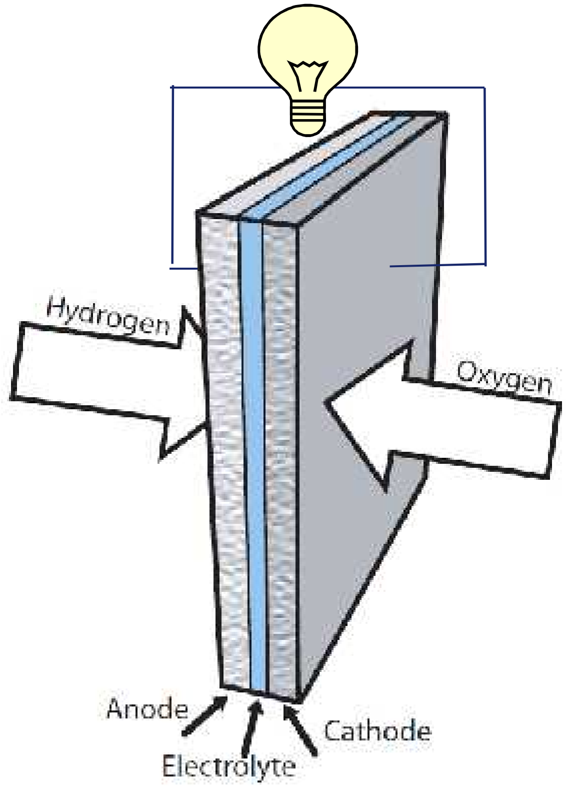
- Spatial and temporal separation of oxidation and reduction reactions



A Simple Fuel Cell

How a Fuel Cell Works

- Electrochemical energy conversion device
  - Directly converts chemical energy to electrical energy



Ryan O'Hayre, Suk-Won Cha, Whitney Colella, Fritz B. Prinz, (2009). *Fuel Cell Fundamentals, 2nd Edition*. New York, New York: John Wiley and Sons, Inc.

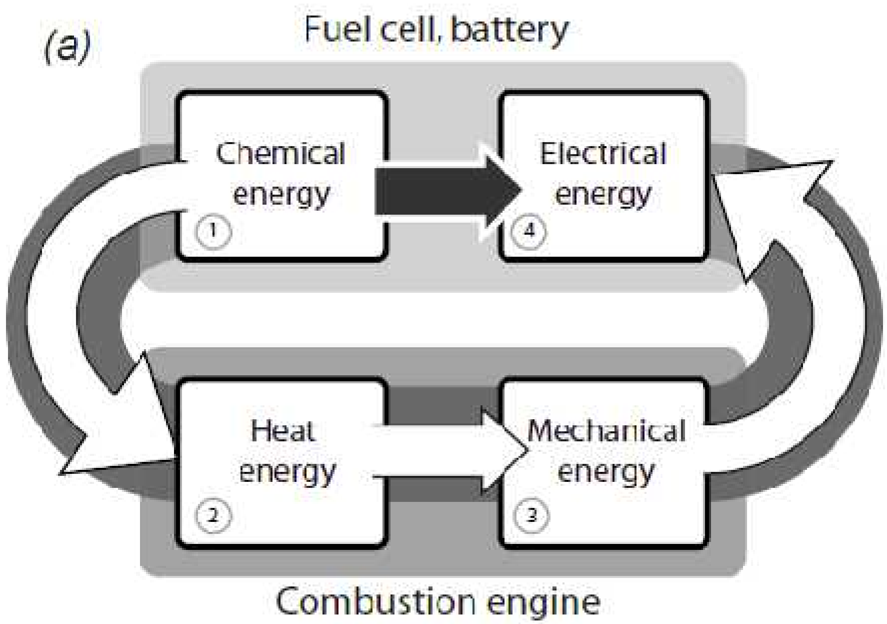
How a Fuel Cell Works

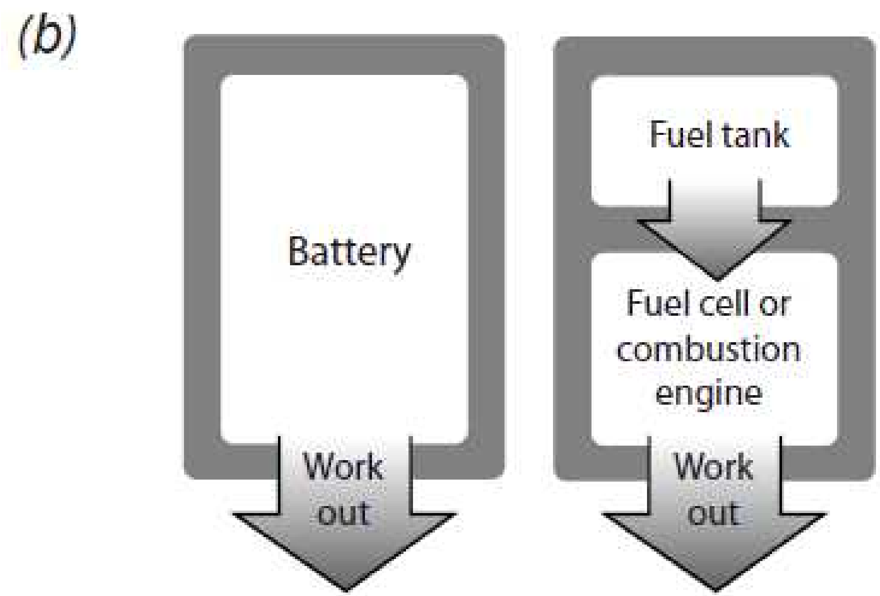
- Electrochemical energy conversion device
  - Directly converts chemical energy to electrical energy

Fuel Cells vs. Batteries vs. Engines

Isothermal energy conversion *vs.* Non-isothermal (Carnot-limited) conversion

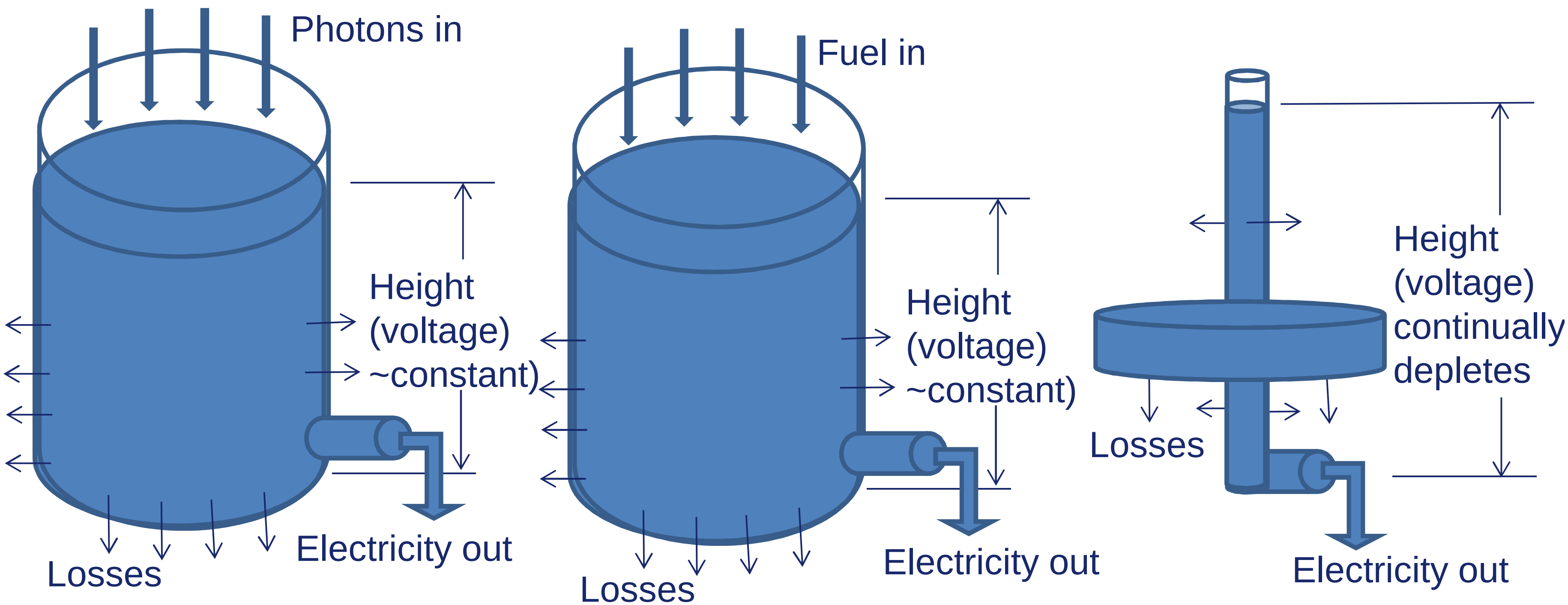
Closed *vs.* Open System





Fuel Cells vs. Batteries vs. PV

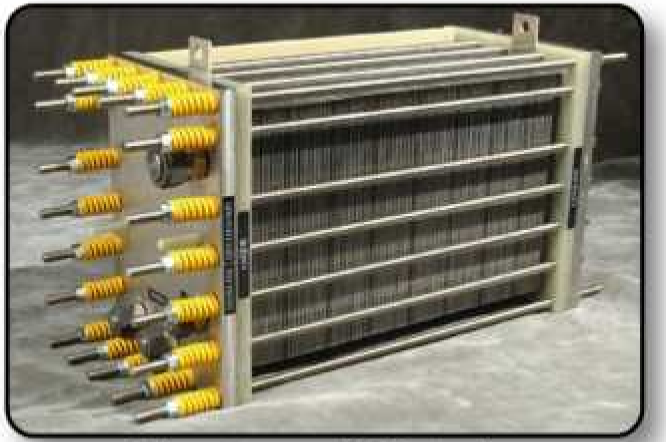
PV **Open System** | **Fuel Cell** **Open System** | **Battery** **Closed System**



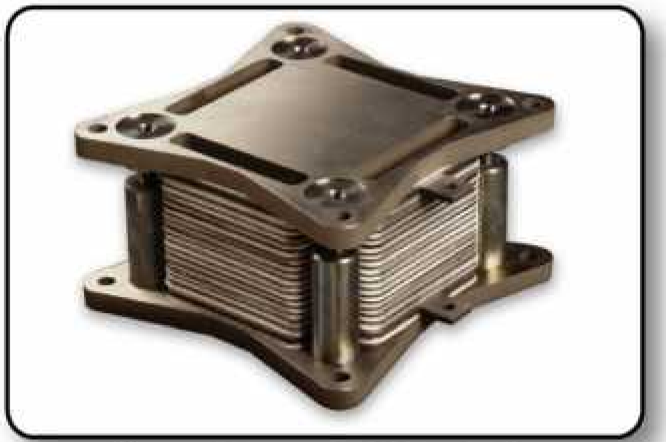
Typical conversion rates:

10-30 mA/cm² | **100-3000 mA/cm²** | **0.1-10 mA/cm²**

Main Focus: PEMFC and SOFC



Plug Power PEM stack

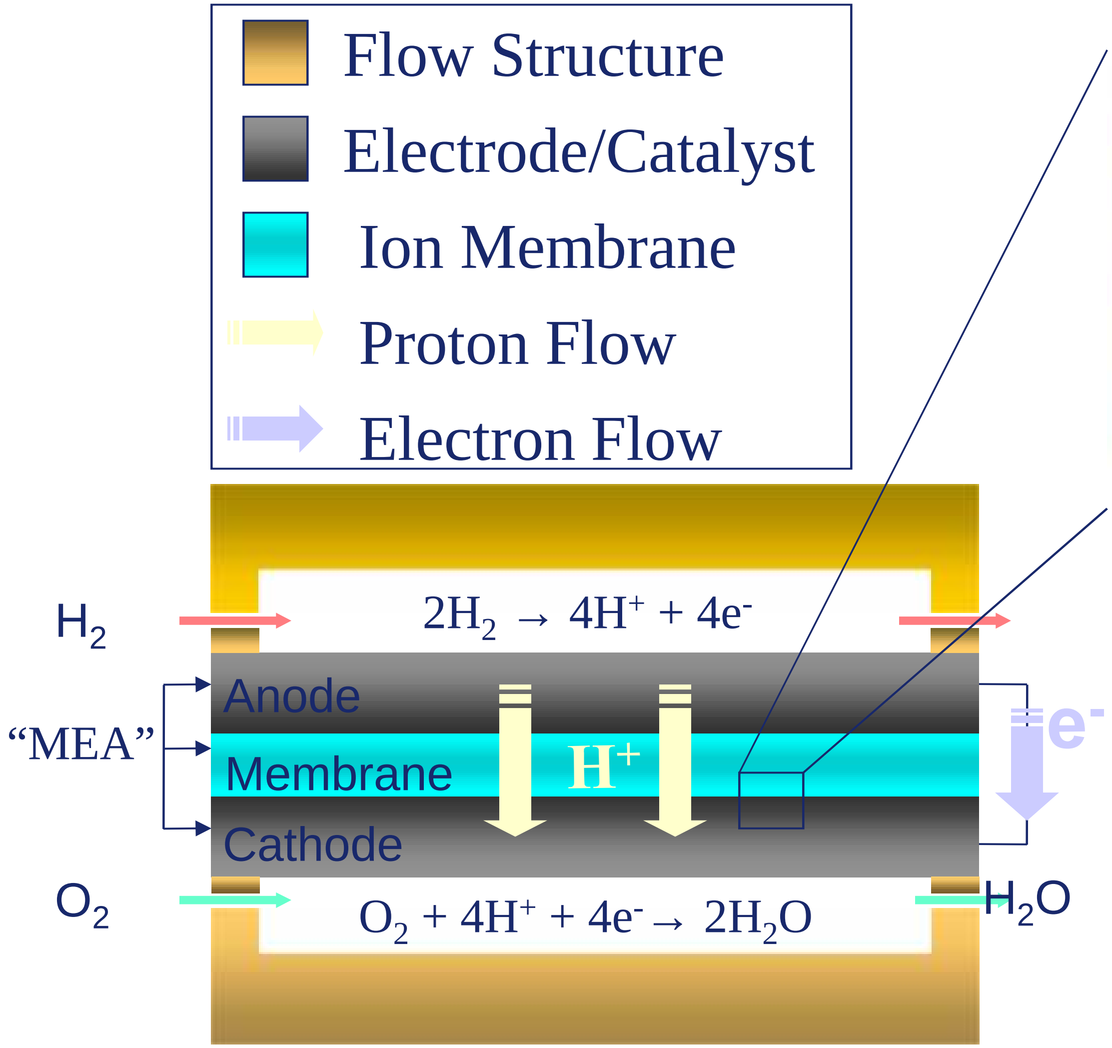


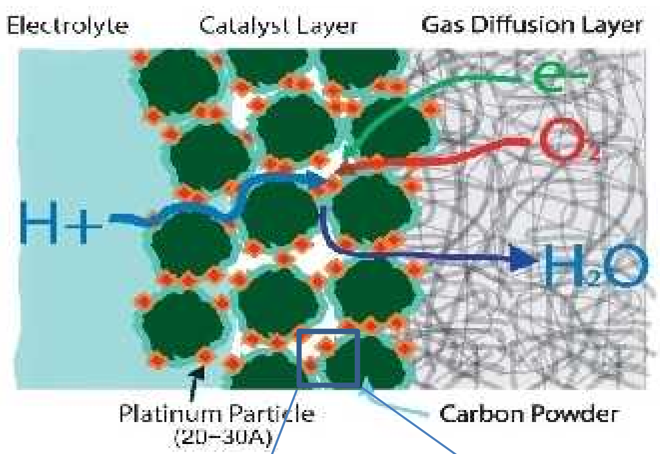
Versa-Power SOFC stack

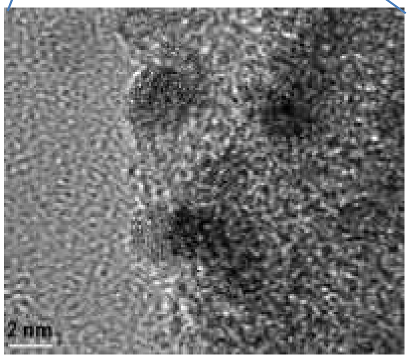
Polymer Electrolyte Membrane (PEM)
- High-temperature polymers
- CO-tolerant anodes
- Materials for bipolar plates
- Non-Pt cathode catalysts
- Nano-structructured carbon supports
- Materials characterization
- Systems testing
- Cost-effective manufacturing

Solid-oxide fuel cells (SOFC)
- Internal reforming kinetics
- Fuel processing (CPOX, reforming, ...)
- Alternative cell architectures
- Modeling and simulation
- On-cell diagnostics
- Ceramic-metal seals
- Materials characterization
- Cost-effective manufacturing

How a Fuel Cell Works: PEMFC







How a Fuel Cell Works: SOFC

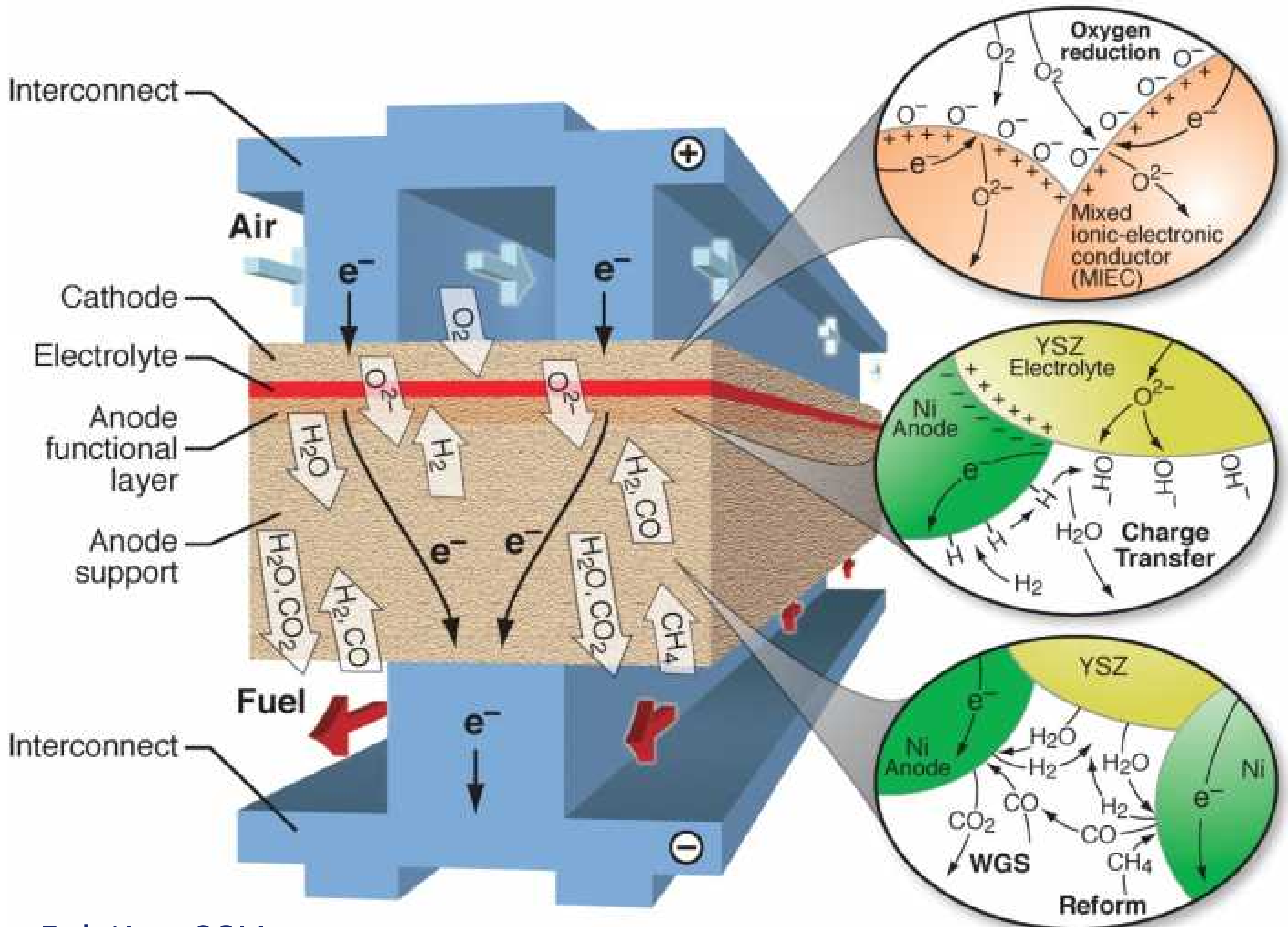
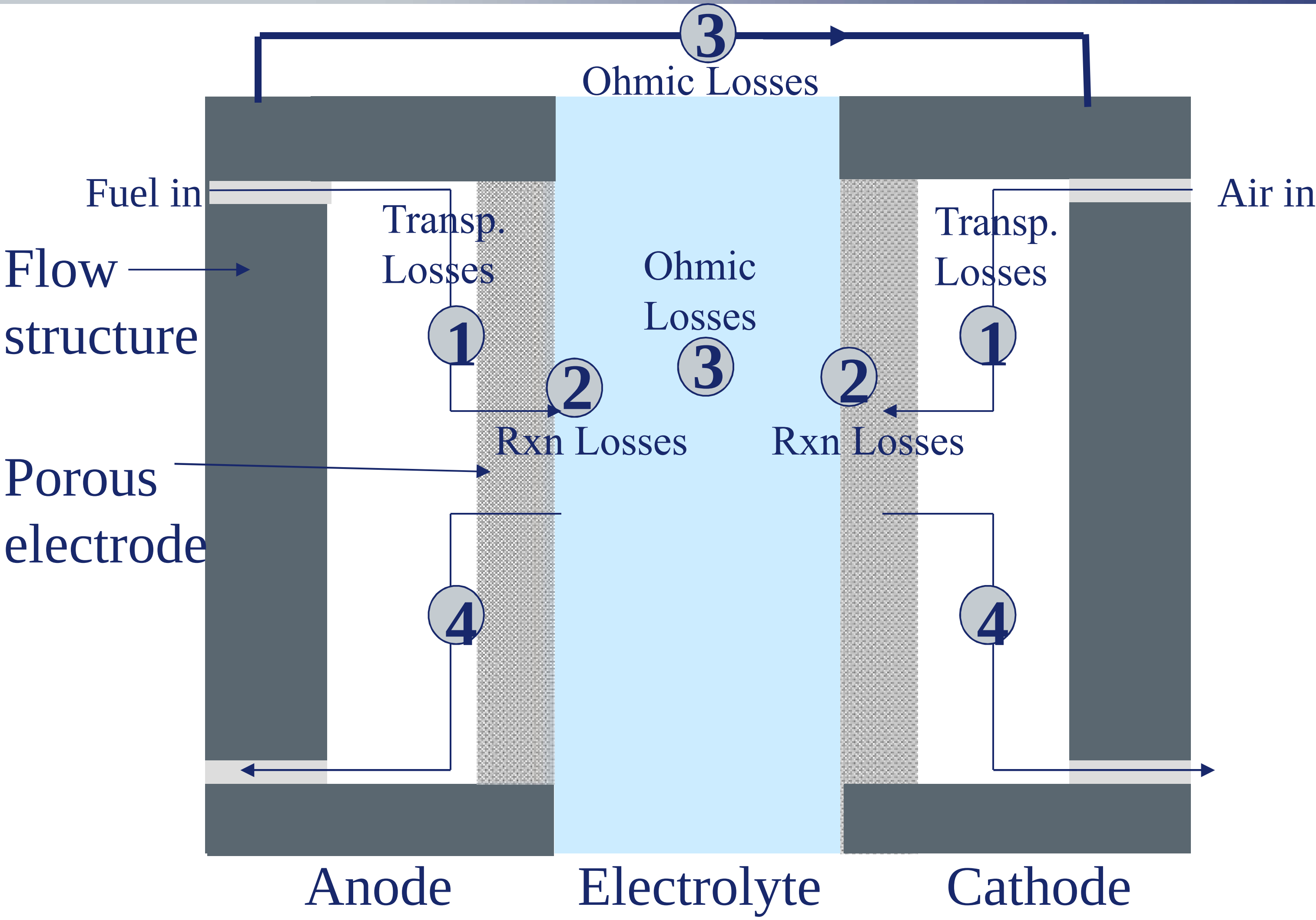
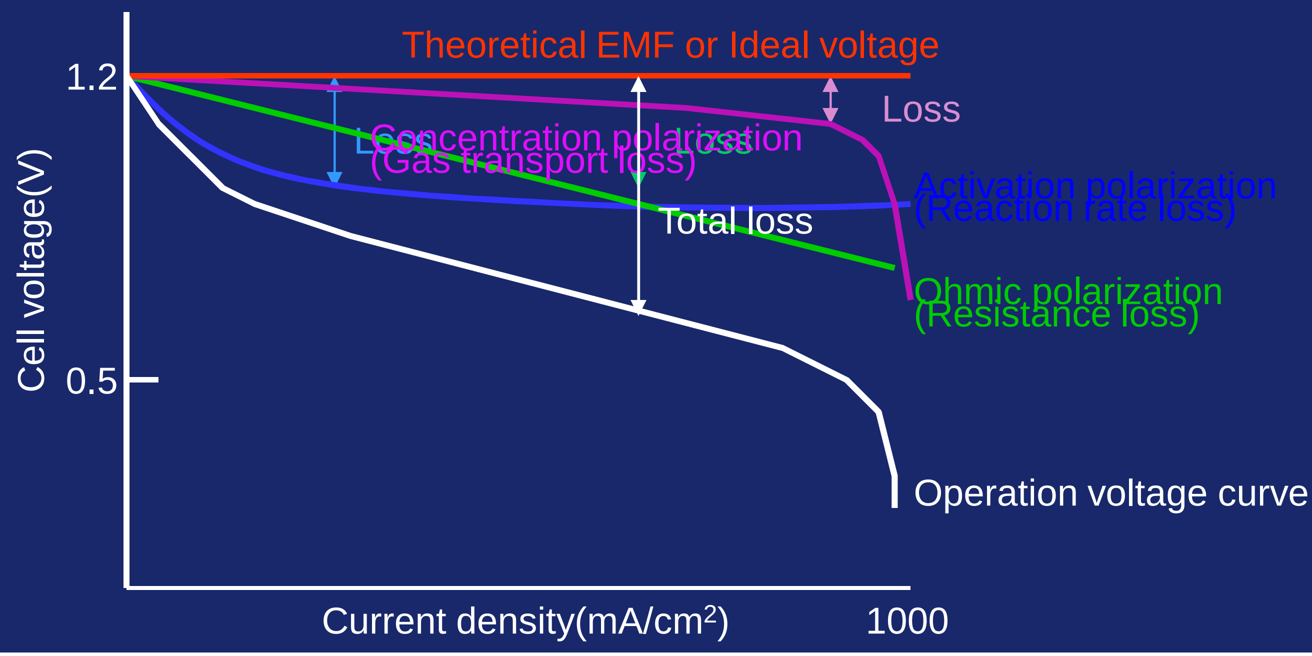


Image courtesy Bob Kee, CSM

How a Fuel Cell Works



Fuel Cell Kinetics

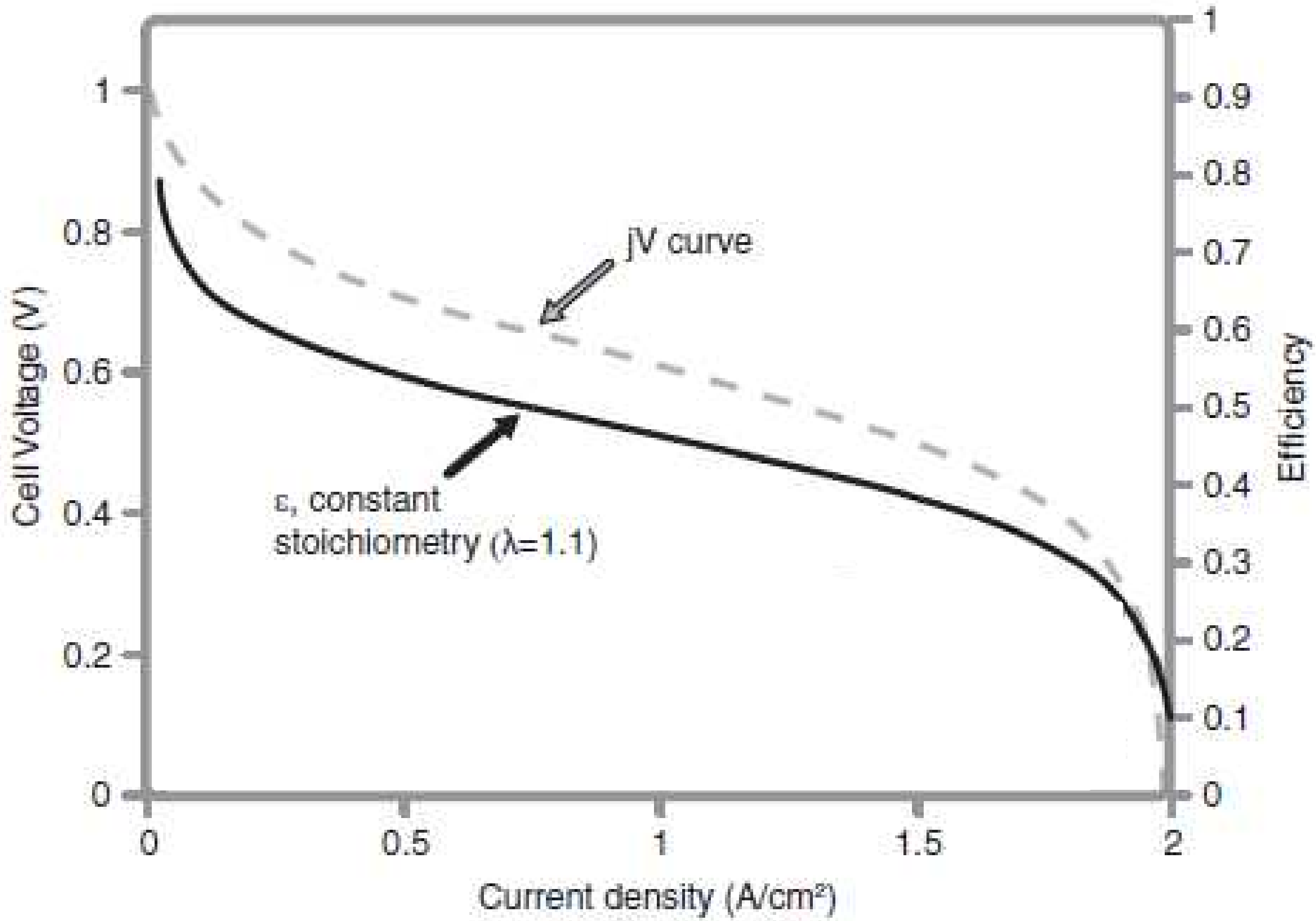


- Generalized polarization (kinetic) loss equation

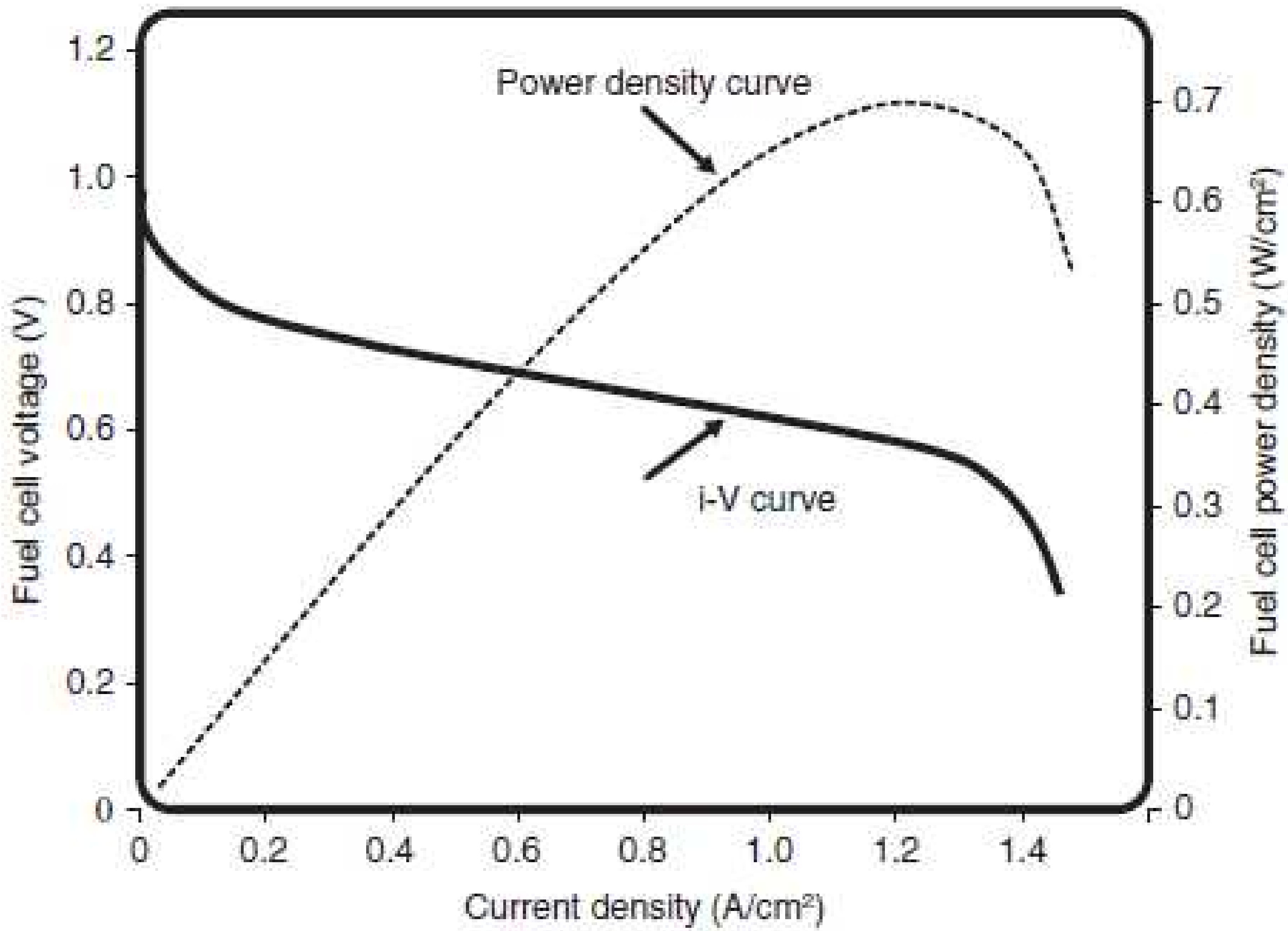
$$V = E_{cell} - A\ln\left(\frac{i+i_n}{i_0}\right) - (i+i_n)r - B\ln\left(1-\frac{i+i_n}{i_l}\right)$$

- Fuel Cell Kinetics
  - 1) $\eta_{activation}$ = Sluggish reaction kinetics, activation barrier
  - 2) η_{ohmic} = Resistance losses in electrode/electrolyte
  - 3) $\eta_{concentration}$ = Mass transport limitations (diffusion)

Efficiency

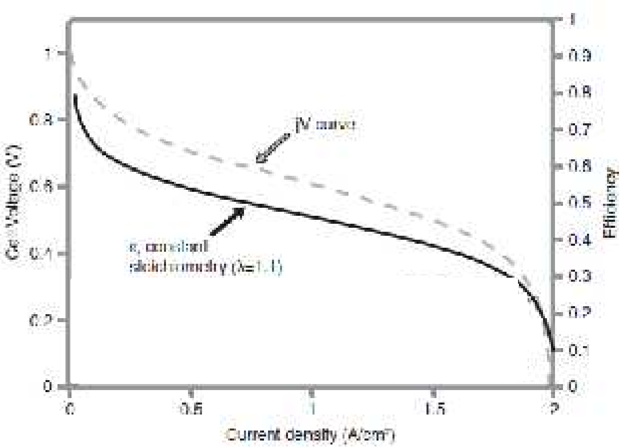

jV curve
ε, constant stoichiometry (λ=1.1)
Cell Voltage (V)
Efficiency
Current density (A/cm²)
0
0.5
1
1.5
2
0.2
0.4
0.6
0.8
0.1
0.3
0.5
0.7
0.9

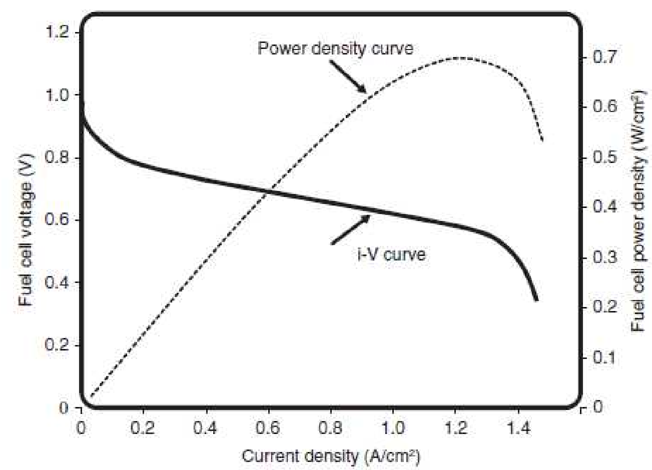
Power Density



Discussion Question:

What is the best operating voltage for a fuel cell?



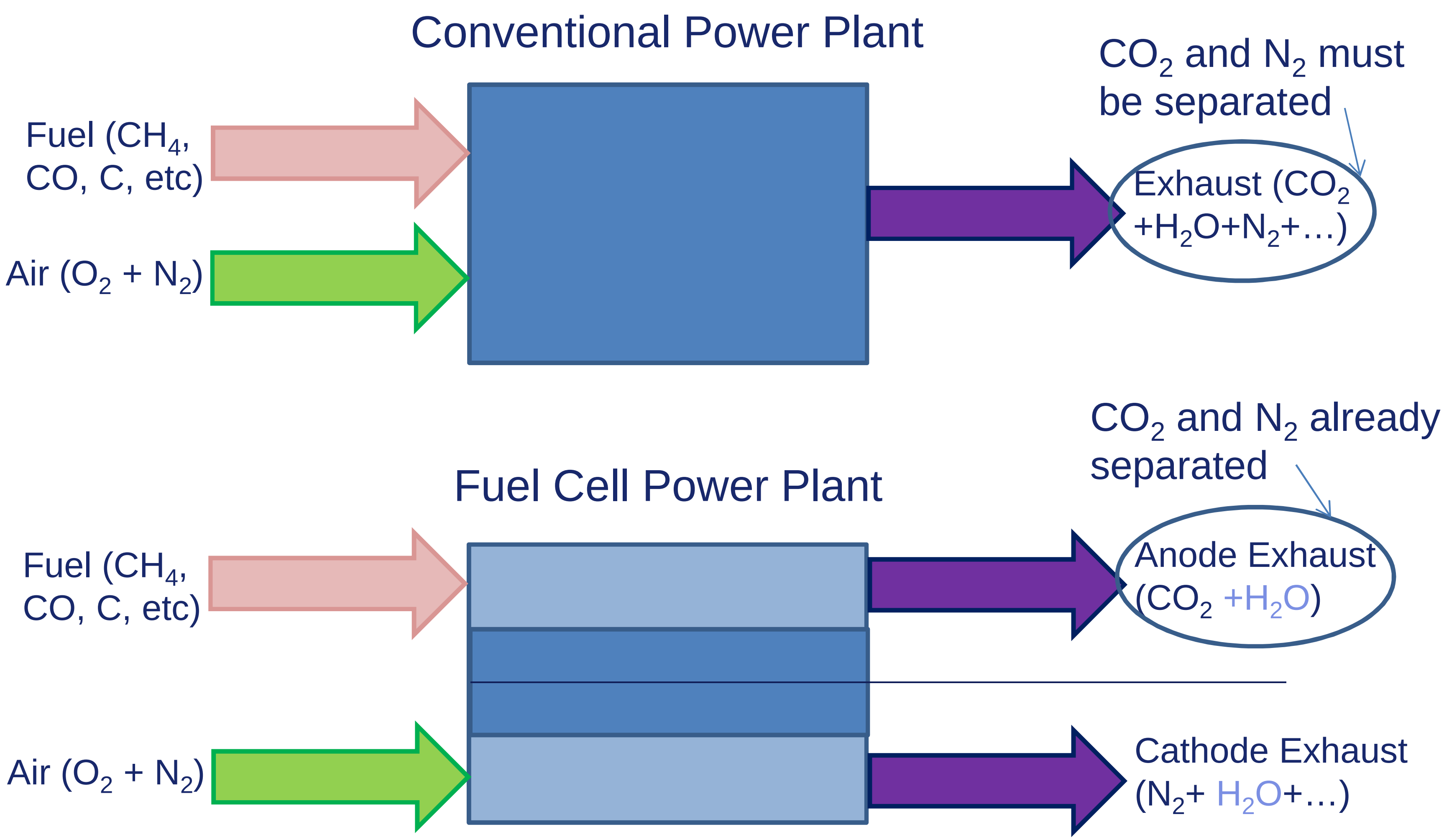


Fuel Cell Advantages

Clean, Lean, Green Machines

- Avoid carnot cycle limitations
- Higher potential efficiencies
- Lower particulate emissions
- Silent, mechanically robust
- Scaleable, dispatchable
- CO_2 sequestration “built-in”

Fuel Cell Advantages: CO_2 Separation



Fuel Cell Barriers

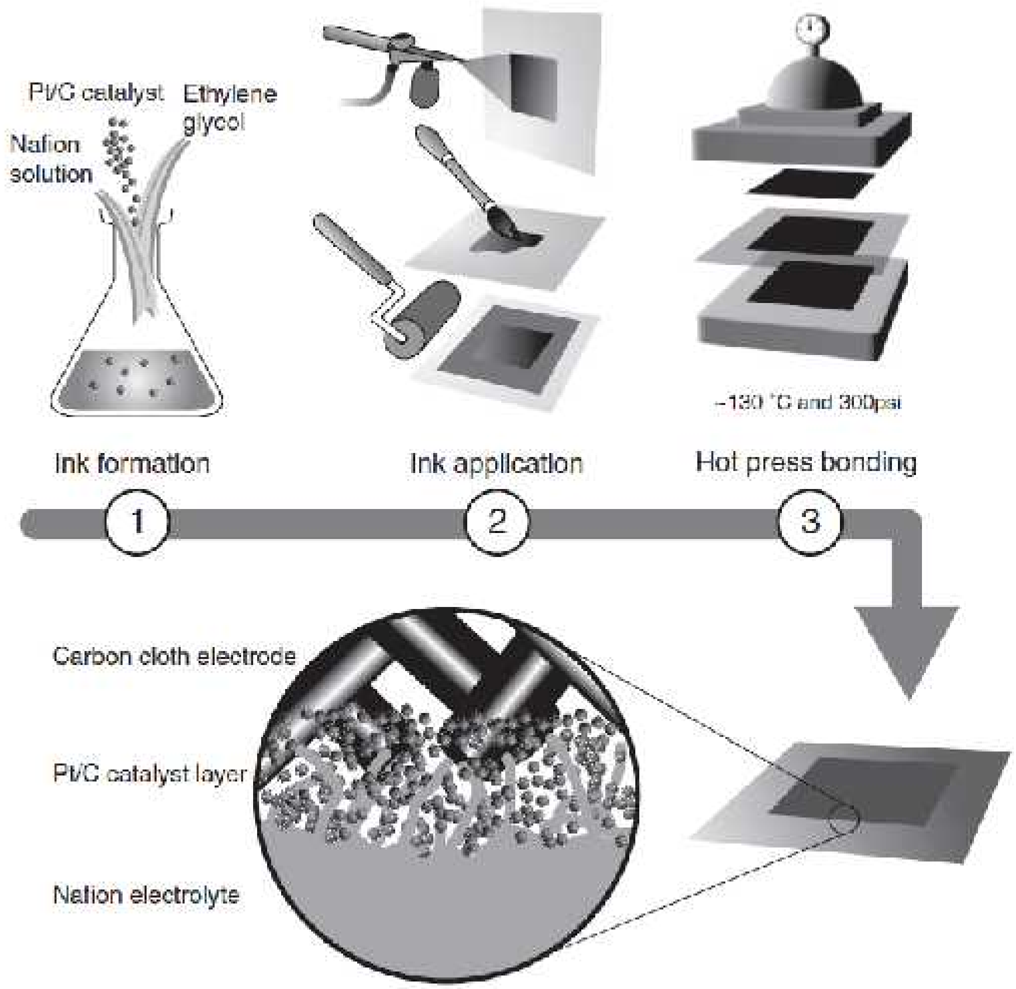
- **Cost**
- **Lifetime/Durability**
- **“Fuel Problem”**

Discussion Question:

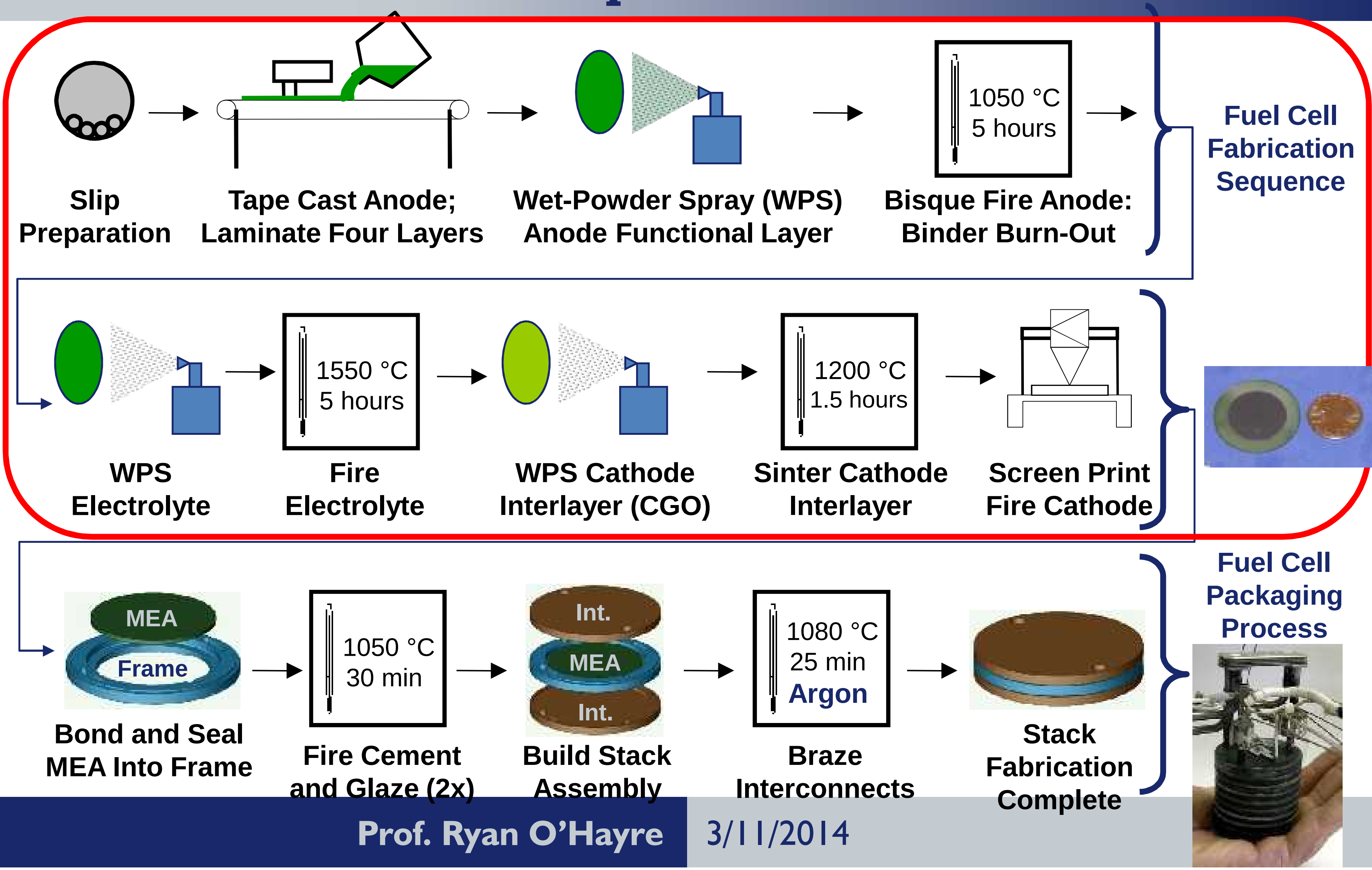
What is the biggest barrier to fuel cells?

Fuel Cell Technology

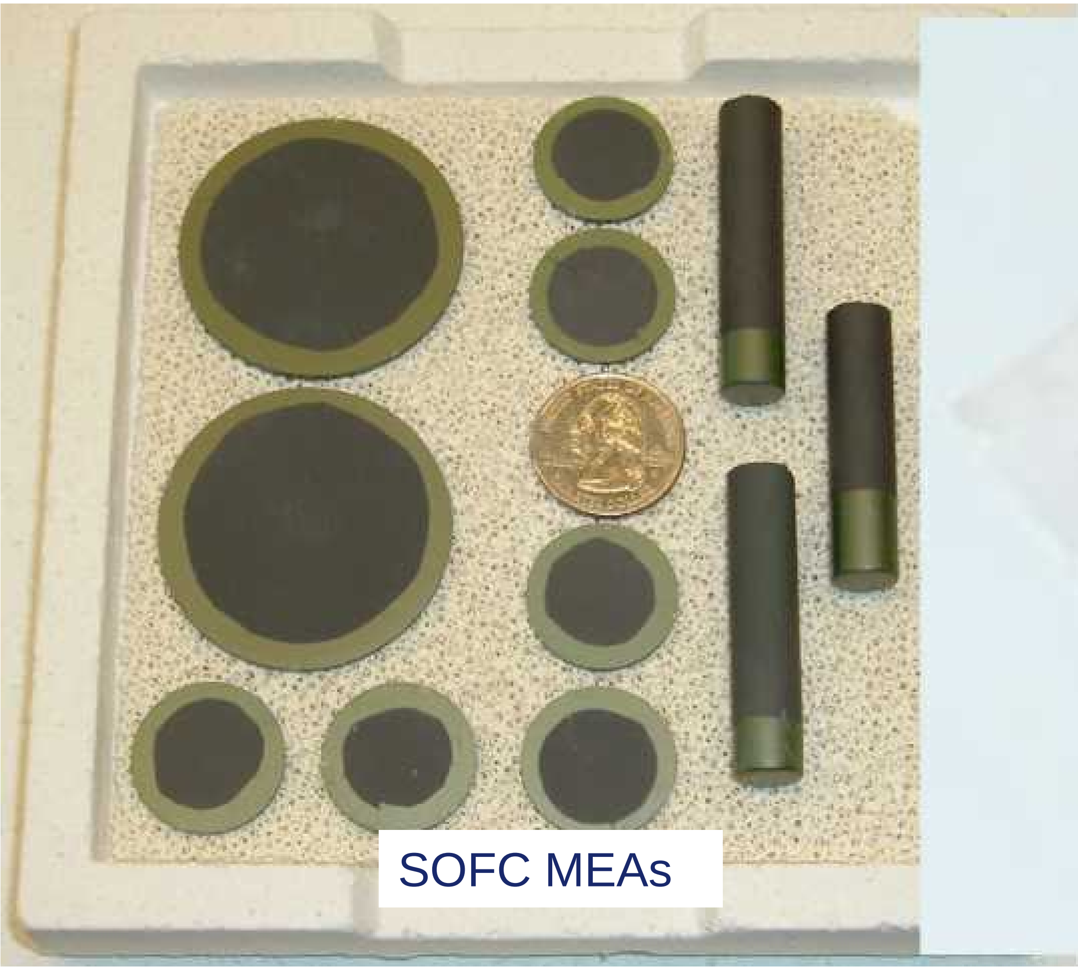
PEMFC Fabrication: From inks to stacks

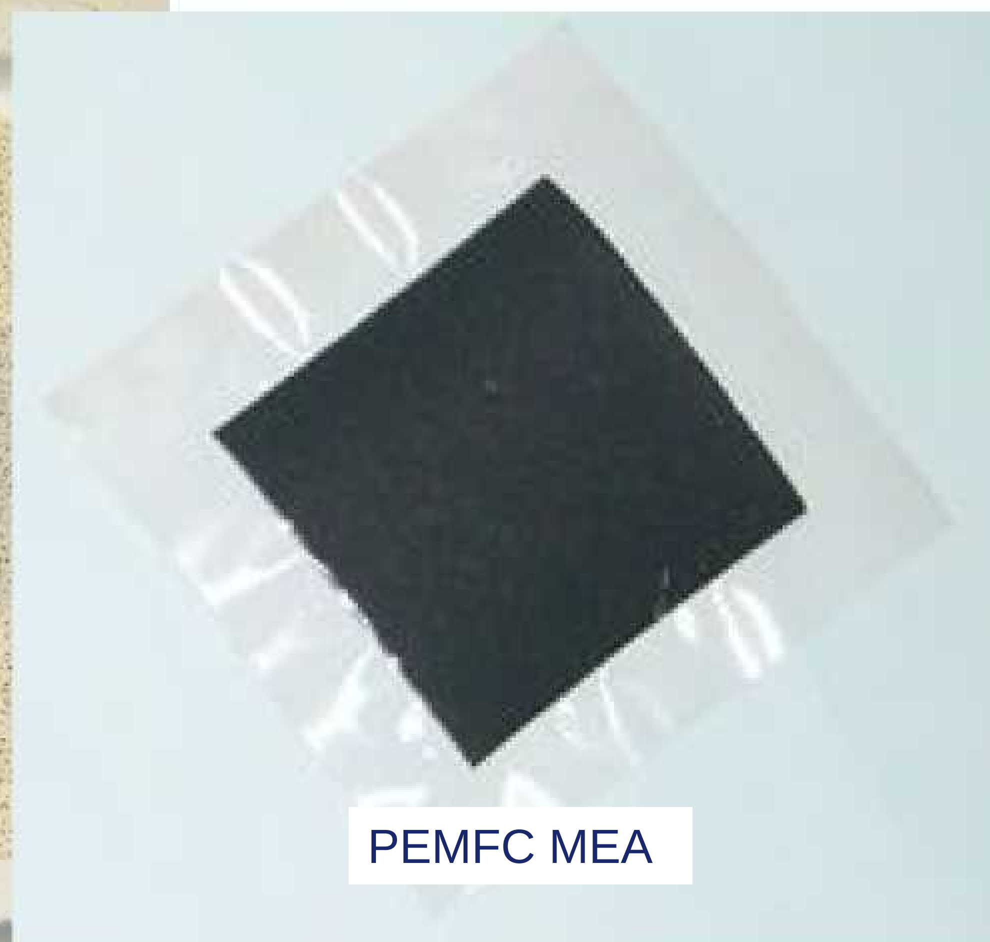


SOFC Fabrication: From powders to stacks



Example PEM and SOFC MEAs Fabricated at CFCC





The first step in scale-up and integration: STACKS

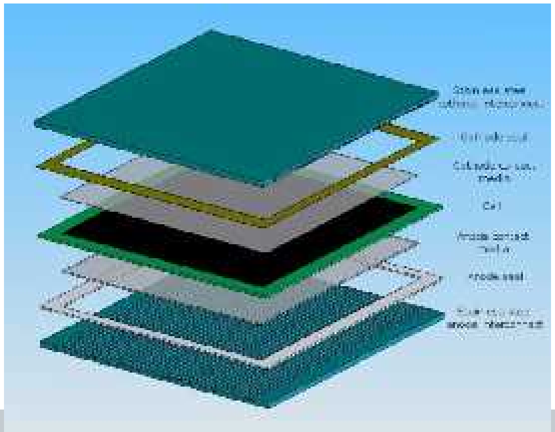
- Typical fuel cell operates at ~ 0.6 Volts
  - We live in a (minimum) 9-volt world, 240V would be nice too
  - To achieve target voltage, connect cells in series: STACK
    - We stack batteries to use flashlights

The Competition

- Stacking presents unique packaging challenges
  - PEMCs require water management
  - SOFCs operate at 600 - 800°C
  - Combustive gases are present

ITN's Fuel Cell Stack

VersaPower's Fuel Cell Stack



A complete power SYSTEM = Fuel cell + BoP

Air Blower

21 grams, 1 watt

Recuperator

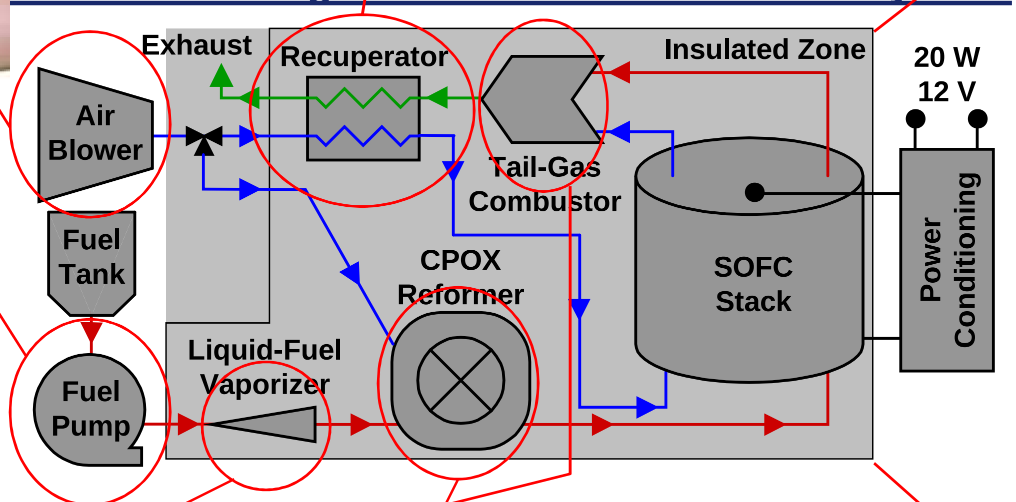
Air heat exchange
85% effectiveness

Nine-cell PP stack
with BOP hardware

Fuel Pump

17 grams
0.3 watt

ocess Flow Diagram for ITN's Palm Power System



Fuel Vaporizer

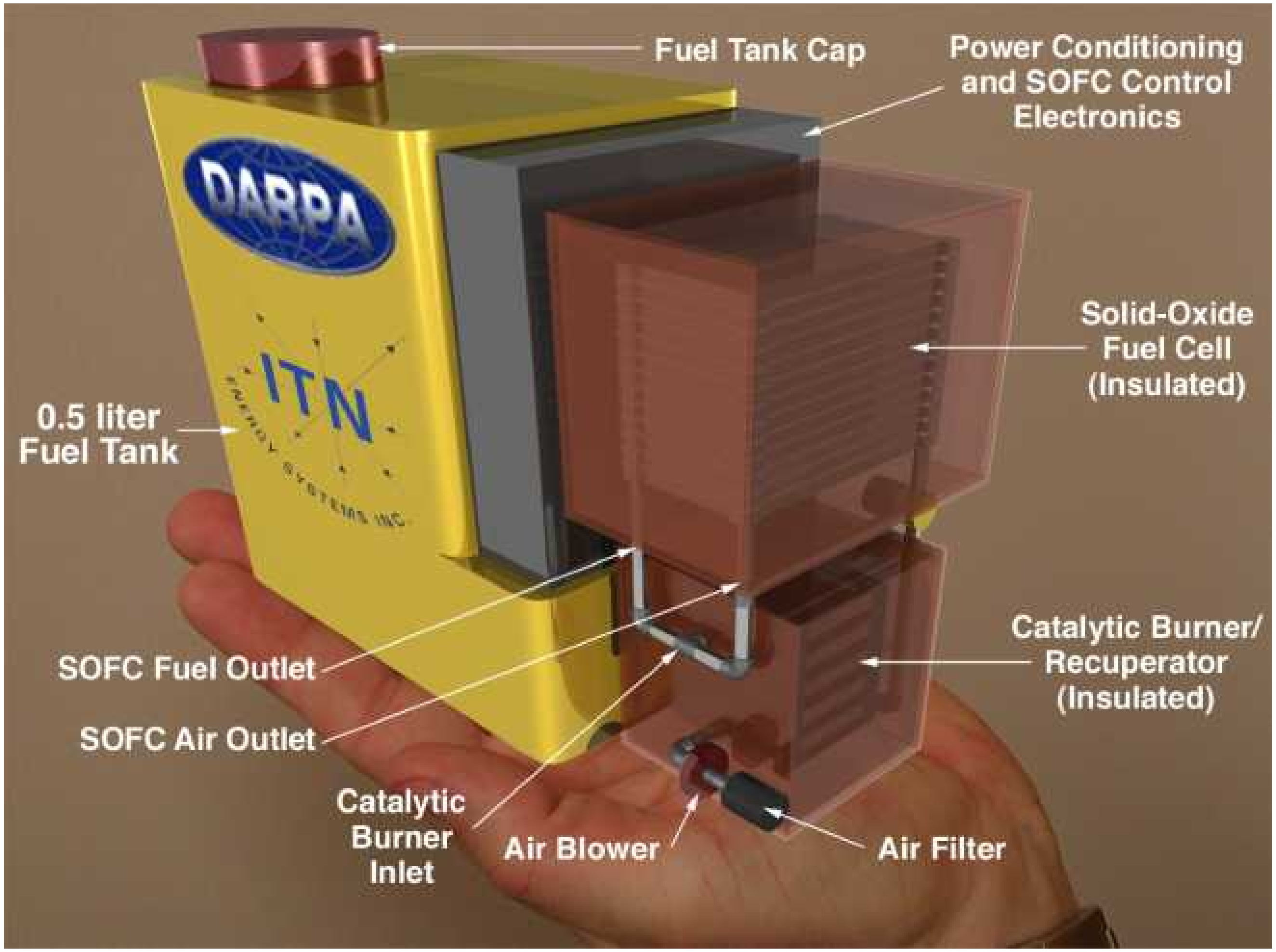
Combustor and CPOX unit

Multiple fuels:

- Propane
- Butane
- Kerosene

Complete System = Fuel Cell + Balance of Plant (BoP)

ITN's "Palm Power" SOFC Generator

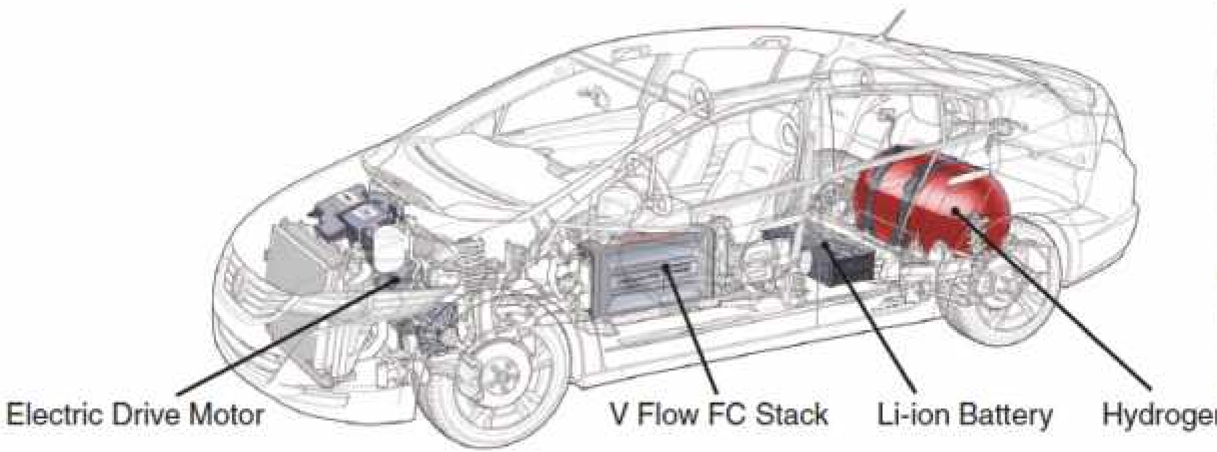


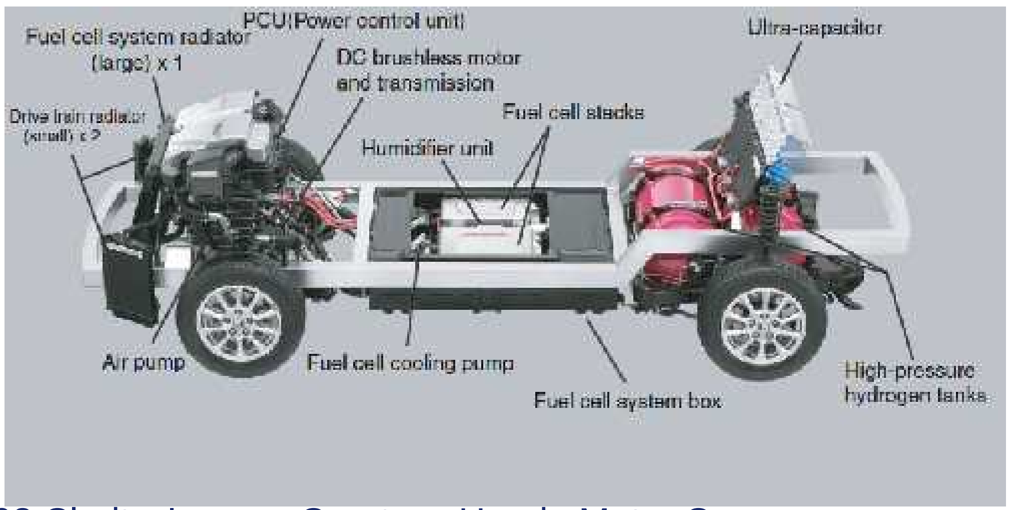
Complete System = Fuel Cell + Balance of Plant (BoP)

Siemens 220kW SOFC – Gas Turbine Hybrid

Fuel Cell Applications

Commercial Applications: Vehicular Power





2005 Honda FCX and 2008 Clarity. Images Courtesy Honda Motor Company

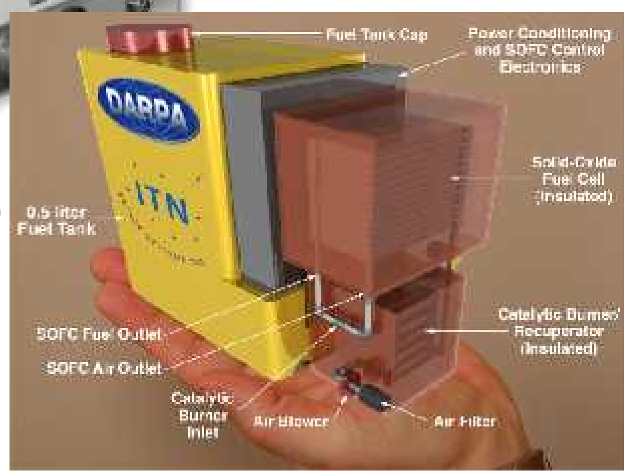
Commercial Applications: Portable Power

Samsung/Toshiba

- •Direct methanol fuel cells
- •Consumer electronics applications

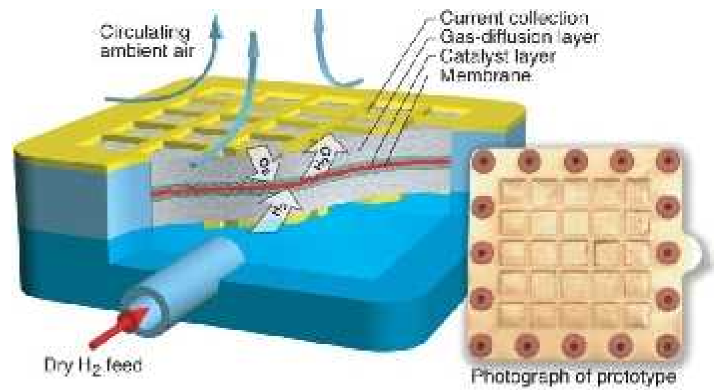
Protonex Corporation, ITN Energy

- Portable systems
- Battery chargers



Ardica Technologies

- •Fully passive air-breathing fuel cells
- •<10W portable applications

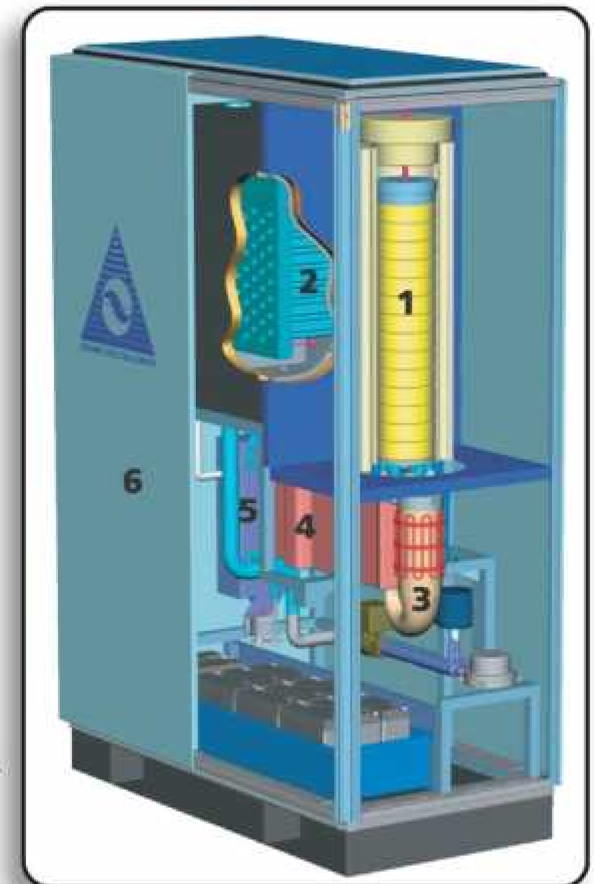


B. Babcock, A.J. Tupper, D. Clark, T. Fabian, R. O'Hayre, "Optimization of Air Breathing Fuel Cell Cathodes" *of Fuel Cell Technology,* **7**, 021017-1—021017-11 (2010)

Commercial Applications: Stationary/Residential/Auxiliary Power

Auxiliary power units
- Quiet power
- Logistics fuels

Combined Heat/Power
- Residential
- Natural gas



Images courtesy Bob Kee, CSM

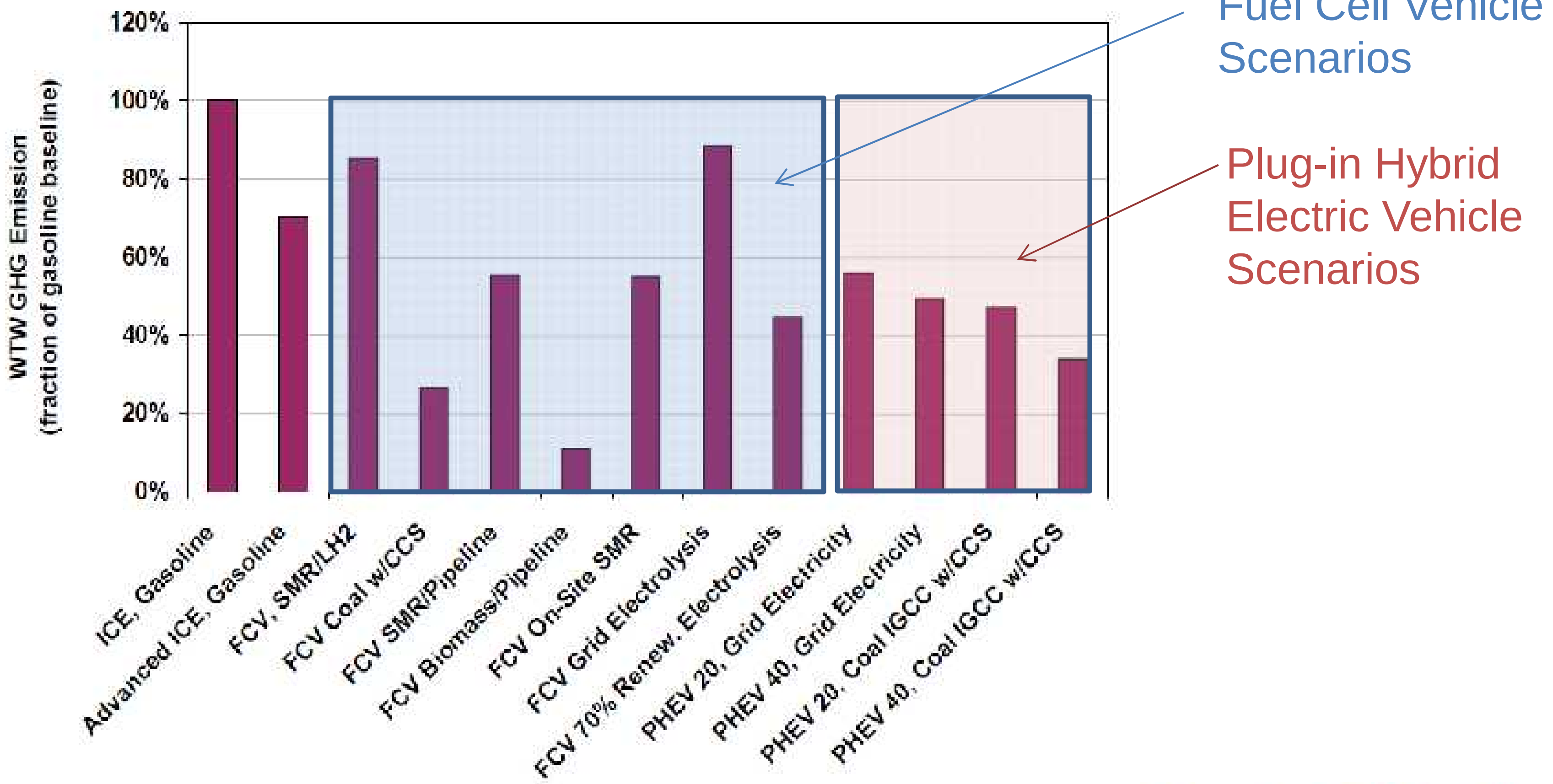
Commercialization Challenges

?

Cost (Current/ *Target*)
Lifetime (Current/ *Target*)
Fuel problem

Can FC Vehicles Compete?

Figure 1-6: Relative GHG Emissions, WTW[8]

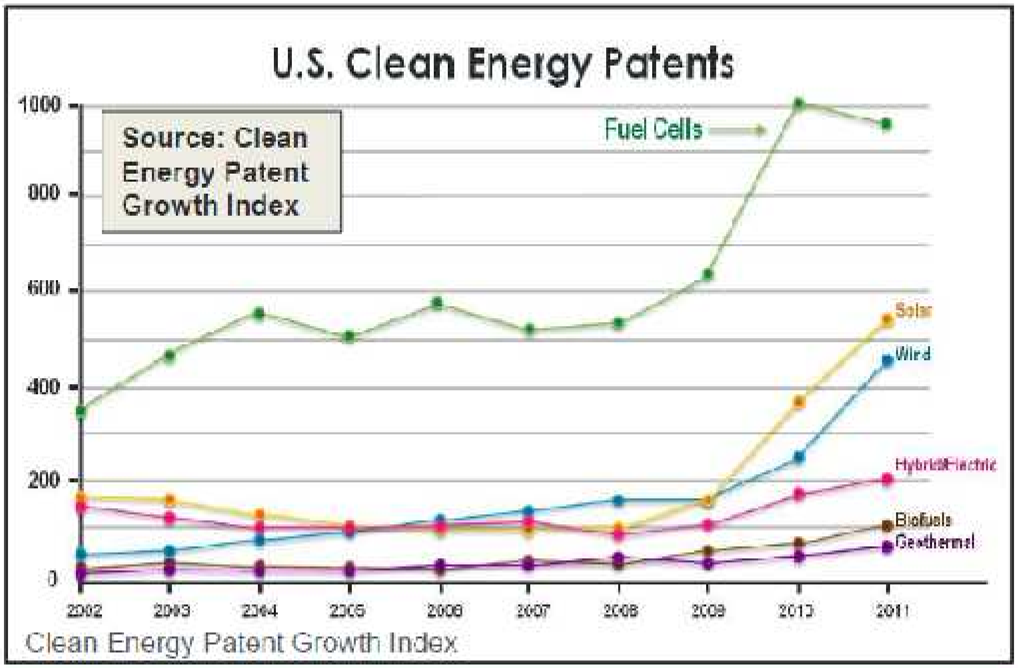


[8] AB1007, WTT Report, TIAX 2007

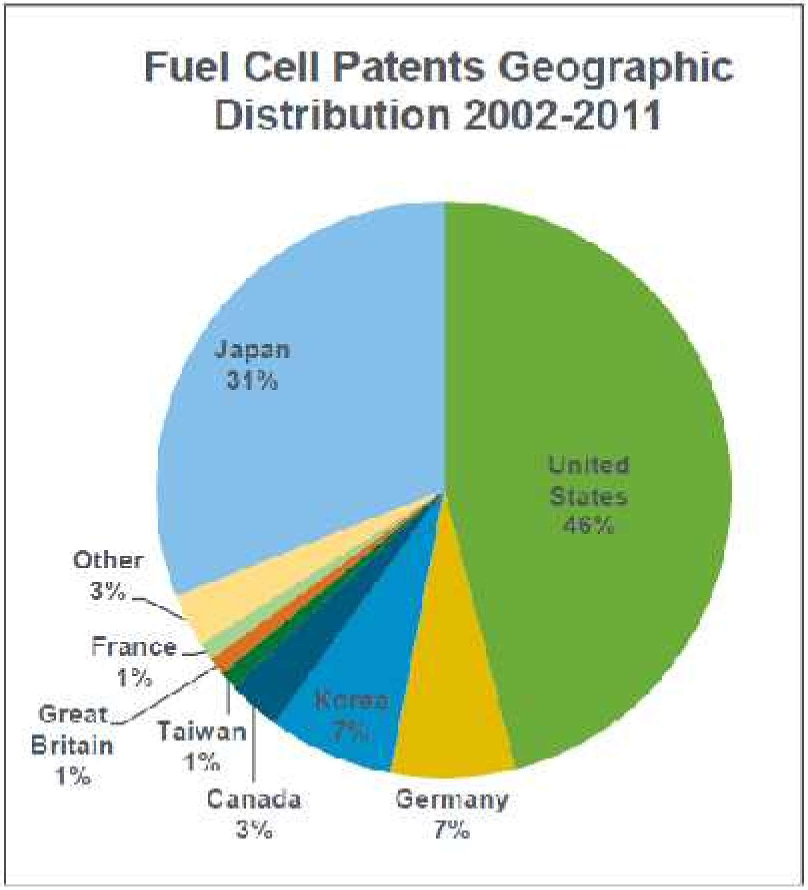
Discussion Question:

Can fuel cell vehicles compete?

Clean Energy Patents



Top 10 companies: GM, Honda, Samsung, Toyota, UTC Power, Nissan, Ballard, Plug Power, Panasonic, Delphi Technologies



Slide courtesy M. Penev, NREL

How Do Fuel Cell Vehicles Stack Up?

Kia Borrego
internal combustion (gasoline)

Kia Borrego
fuel cell (hydrogen)

	Gasoline	H_2 (SMR)	H_2 (SMR & Sequestration)	H_2 (Renewable)
MPG	18	57	57	57
CO_2 Emissions lb/mile	1.35	0.48	0.00	0.00
CO_2 Emissions Reductions %	N/A	64%	100%	100%

Slide courtesy M. Penev, NREL

How Do Fuel Cell Vehicles Stack Up?

Kia Borrego
internal combustion (gasoline)

Kia Borrego
fuel cell (hydrogen)

Driving range	400	426 miles
Acceleration 0-60	7.8 sec	12.8 sec
Cost MSRP	$34,000	(speculation: $50,000)

The driving experience is the same other than a lack of engine noise.

Slide courtesy M. Penev, NREL

FCEV Production Outlook

Manufacturer	Launch
Ford	~2017
GM	~2015
Honda	~2015
Hyundai	2013-2015
Daimler	~2017
Nissan	~2017
Toyota	~2015

Slide courtesy M. Penev, NREL

March 2013: Hyundai begins FCEV production

2013-2015: production run ~1000 vehicles

Most vehicles are expected for fleet deployments

Slide courtesy M. Penev, NREL

Hydrogen Bus Transportation

Multiple manufacturers already produce hydrogen powered busses

Slide courtesy M. Penev, NREL

Hydrogen Station in Torrance, CA

Refueling very similar to CNG (Compressed Natural Gas)

Slide courtesy M. Penev, NREL

Hydrogen Station in Torrance, CA

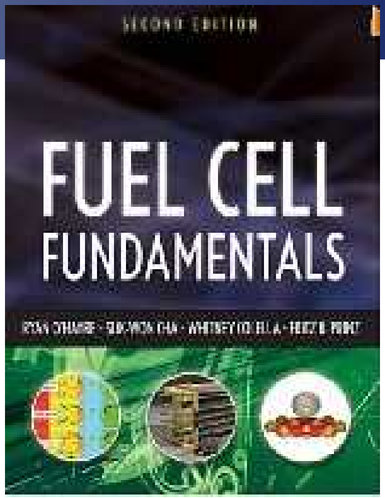
Slide courtesy M. Penev, NREL

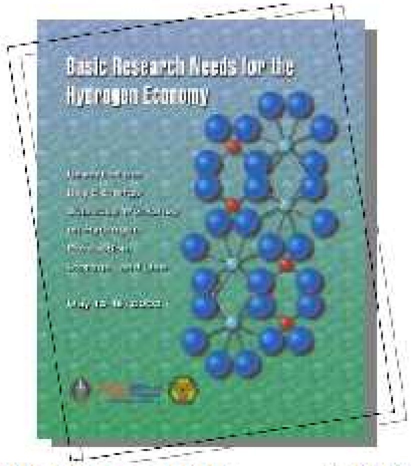
Hydrogen Refueling at NREL

NREL recently outfitted the hydrogen dispensing station at the National Wind Technology Center near Boulder with cascading storage tanks, which decrease the time required for refueling. The station has a 130 kg storage capacity at 413 bar (6,000 psi), so filling a car takes about 2-5 minutes.

Further Reading

1. Ryan O'Hayre, Suk-Won Cha, Whitney Colella, Fritz B. Prinz, (2009). *Fuel Cell Fundamentals, 2nd Edition*. New York, New York: John Wiley and Sons, Inc.
2. J. H. Hirschenhofer, D. B. Stauffer, R. R. Engleman, and M. G. Klett. *Fuel Cell Handbook* (6th ed), U.S. Department of Energy, Morgantown, WV, 2003. (**AVAILABLE FREE ON THE WEB)**
3. J. Larminie and A. Dicks. *Fuel Cell Systems Explained. John Wiley and Sons, New York,* 2000.
4. M. Dresselhaus (Chair). Basic research needs for the hydrogen economy: Report of the basic energy sciences workshop on hydrogen production, storage, and use. Technical report, Workshop on Hydrogen Production, Storage, and Use, Rockville, MD, 2003. (**AVAILABLE FREE ON THE WEB)**
5. BCH Steele and A. Heinzel, "Materials for fuel-cell technologies", Nature, **414** (6861), pp 345-352 (2001).





Millie Dresselhaus (MIT)
George Crabtree (ANL)
Michelle Buchanan (ORNL)

Acknowledgements

Prof. Robert Kee (CSM)
Dr. Yingke Zhou (CSM)
Mr. Michael Sanders (CSM)
Ms. Ann Deml (CSM)
Dr. Bryan Pivovar (NREL)
Dr. Michael Penev (NREL)

Facility Support

NREL

CFCC Colorado Fuel Cell Center

Renewable Energy Materials Research Science and Engineering Center REMRSEC

Funding

Army Research Office

National Science Foundation

ACS PRF

Air Force Office of Scientific Research

CoorsTek Amazing Solutions.