


How to Progress on Low Temperature PEM Fuel Cells

outlook, challenges, future research directions and needs, and future developments

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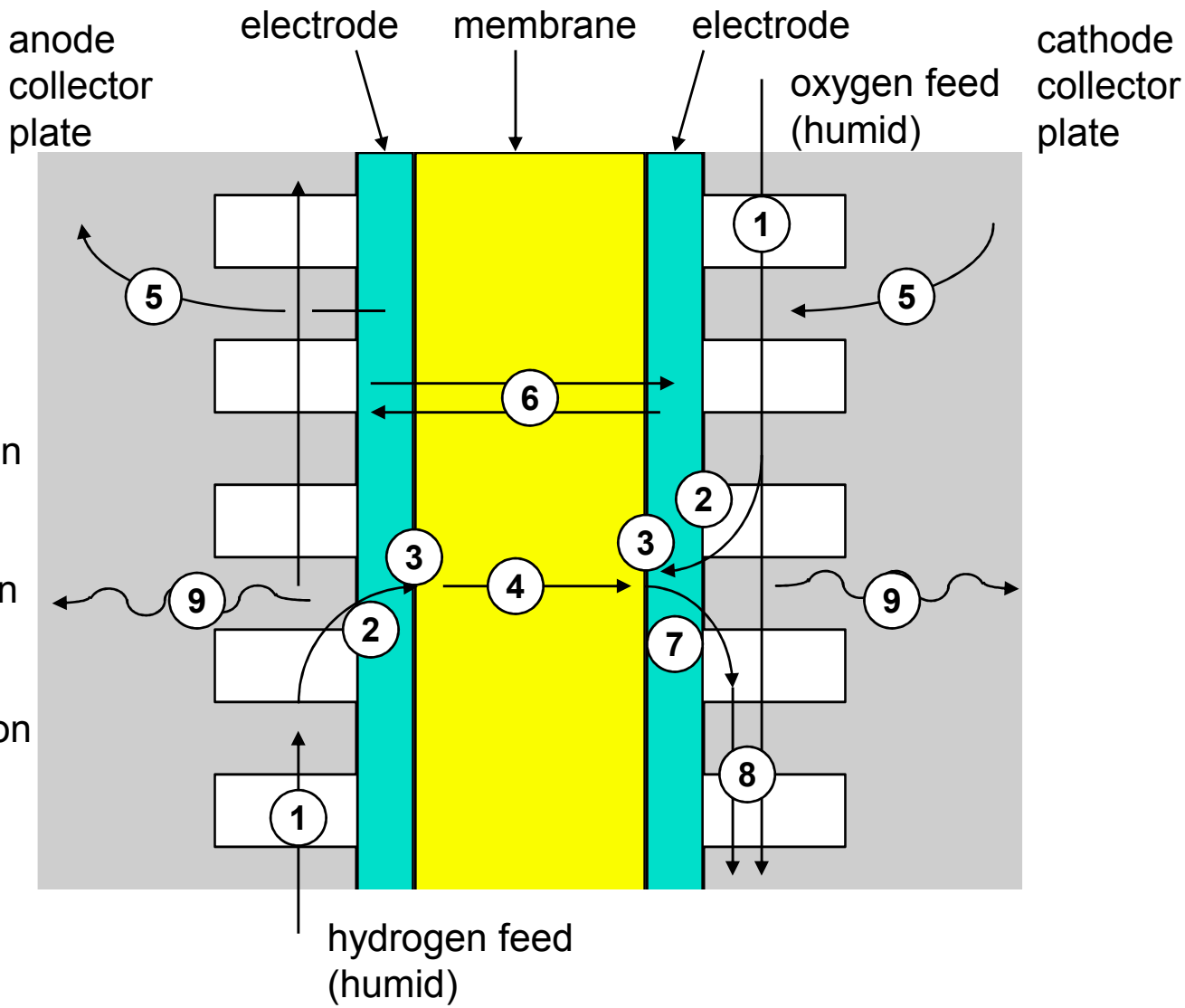
Joint European Summer School for Fuel Cell and Hydrogen Technology

Outline

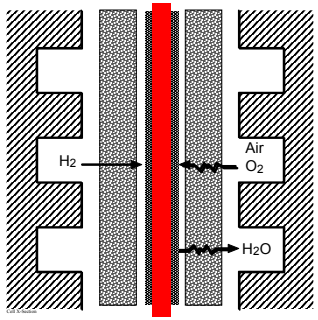
- Status (what do we know, what has been done so far)
- Why don’t we have more fuel cell products on the market
- Trends (what still needs to be done, what we still have to learn)
- Bigger picture

PROCESSES INSIDE A FUEL CELL

1 gas flow
2 gas diffusion
3 electrochemical reaction
4 proton conduction
5 electron conduction
6 water drag and diffusion
7 water flow
8 2-phase flow
9 heat transfer (convection and conduction)



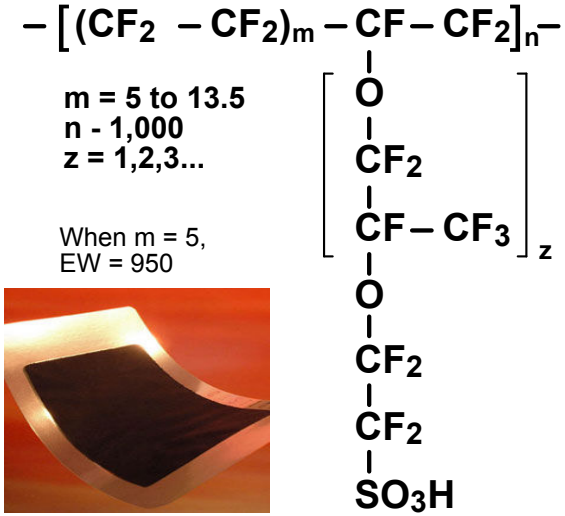
Membrane



Functions
- Conducts protons
- Does not conduct electrons
- Separates H_2 and O_2

Properties
- Proton conductivity
- Water content
- Electroosmotic drag
- H_2 and O_2 permeability
- Mechanical strength
- Chemical stability

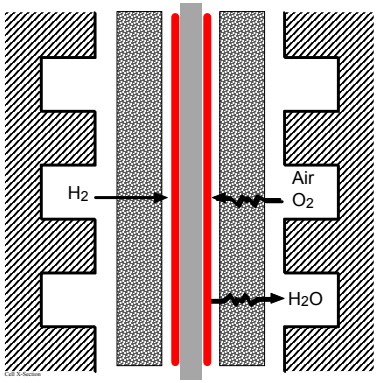
Material
- Nafion™
- Copolymer of tetrafluoroethylene ("Teflon") and various perfluorosulfonate monomers.
- Thickness 0.025-0.125 mm
- Roughly 1 nm diameter hydrophilic pores.



m = 5 to 13.5
n - 1,000
z = 1,2,3...

When m = 5,
EW = 950

Catalyst/Catalyst Layer

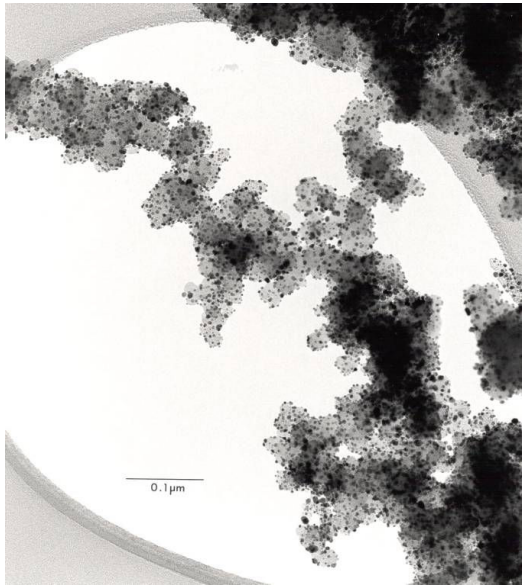


Functions
Oxygen reduction
Hydrogen oxidation
Conducts electrons

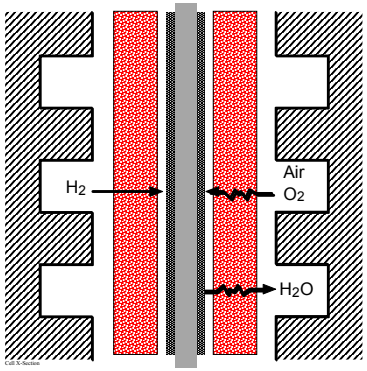
$H2 \rightarrow 2e^- + 2H^+$
$O2 + 2e^- + 2H^+ \rightarrow H2O$

Properties
Good catalyst
Chemical stability
Electrical conductivity

Material
Platinum
Finely dispersed (3-5 nm) on high surface area carbon
Loading: 0.1-1.0 mg/cm^2



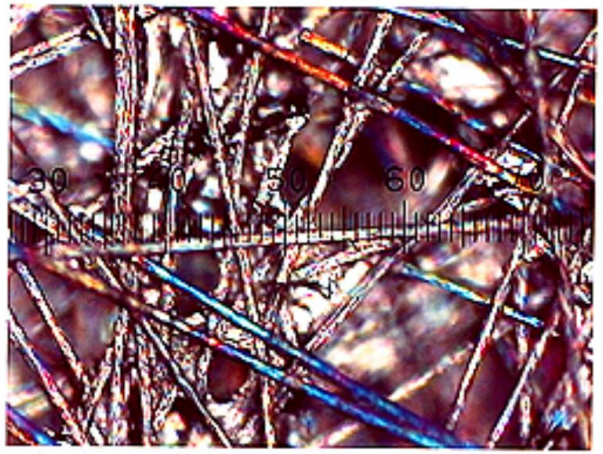
Gas Diffusion Layer



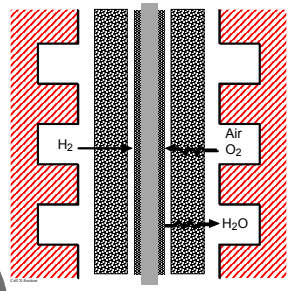
Functions
- Supplies reactants to the catalyst site
- Conducts electrons
- Electrical contacts
- Takes the product water away
- Structural support to the membrane

Properties
- Porosity
- Electrical conductivity
- Hydrophobicity
- Mechanical strength
- Compressibility
- Chemical stability

Materials
- Carbon fiber paper
- Carbon cloth
- Non-woven materials
- Metallic screens
- Foams



Bi-polar plates



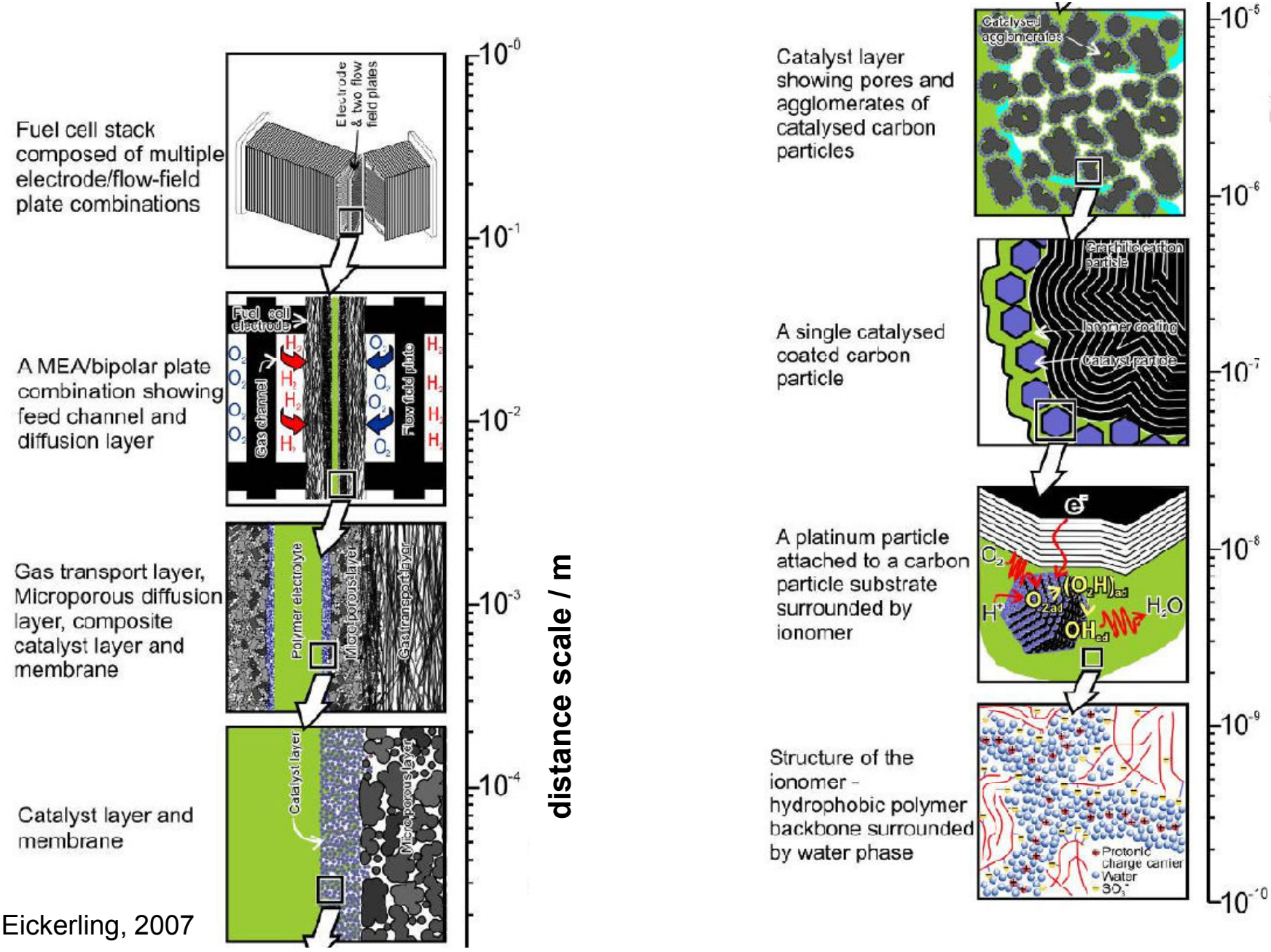
Functions
- separates gases
- connects cells electrically
- houses flow fields
- supports MEAs
- seals
- provides structural rigidity
- conducts heat

Properties
- permeability
- electrical conductivity
- comformability
- manufacturability
- mechanical strength
- chemical stability
- thermal conductivity

Materials
- graphite
- graphite/polymer mixtures
- graphoil
- metallic with coating
- composite

Processes
- machining
- compression molding
- injection molding
- embossing
- stamping

Hierarchy of structures in PEM fuel cells



M. Eickerling, 2007

Tehnological challenges in fuel cell development

science

- Membrane material
- Catalyst
- Catalyst layer structure
- Interactions between layers
- Water management

engineering

- Heat transfer
- …
- Cell and stack design
- …
- System design
- …
- Manufacturing processes

→

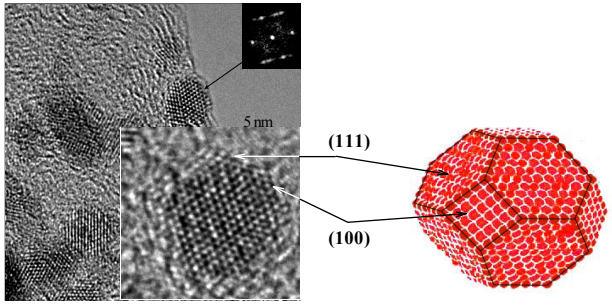
Performance

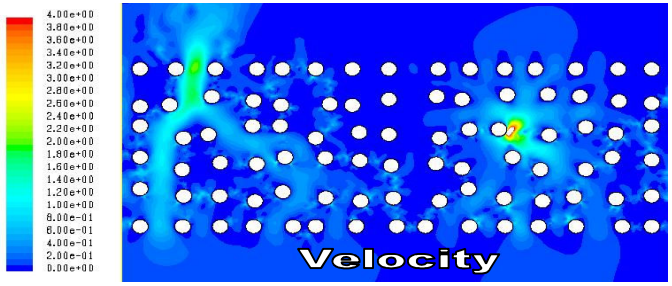
Durability

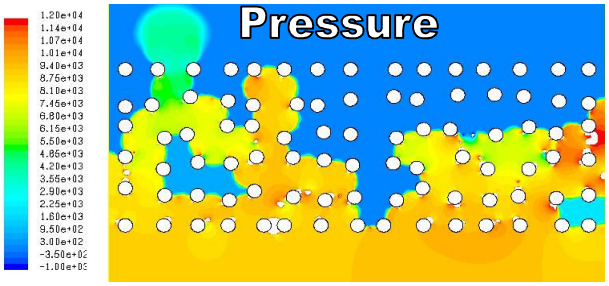
Cost

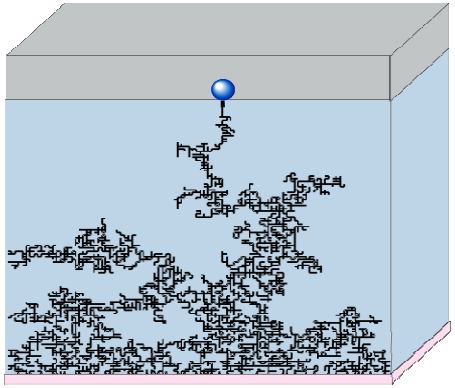
Technological Challenges in PEM Fuel Cells

- **Membrane material**
  - other (non-PSA) cheaper materials
  - high temperature membranes
- **Catalyst**
  - reduced loadings
  - binary & ternary alloys
  - non precious metal catalysts
- **Catalyst layer & GDL structure**
  - improved water removal









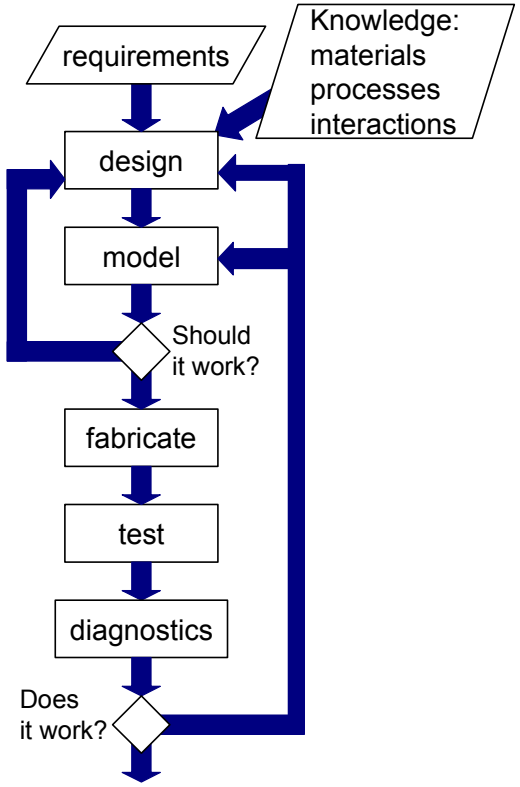
Stack engineering/design

Goals

- Uniform reactant distribution to each cell
- Uniform reactant distribution inside each cell
- Required temperature distribution inside each cell

Methods

- Modeling of processes
- Experiments with single cell
- Diagnostics
- Experiments with short stack
- Evaluation of full size stack



Modeling of processes in fuel cells

Fluid flows
Diffusion
Migration

Gas flow
Gas fluid – 2-phase flow

Conservation of mass
Conservation of moment
Conservation of energy
Conservation of species
Conservation of charge

Droplet formation
Droplet behavior
Surface tension
Capillary flow

Electrochemical reactions
Butler Volmer equation
- Sink for reactants
- Source for products
- Heat source

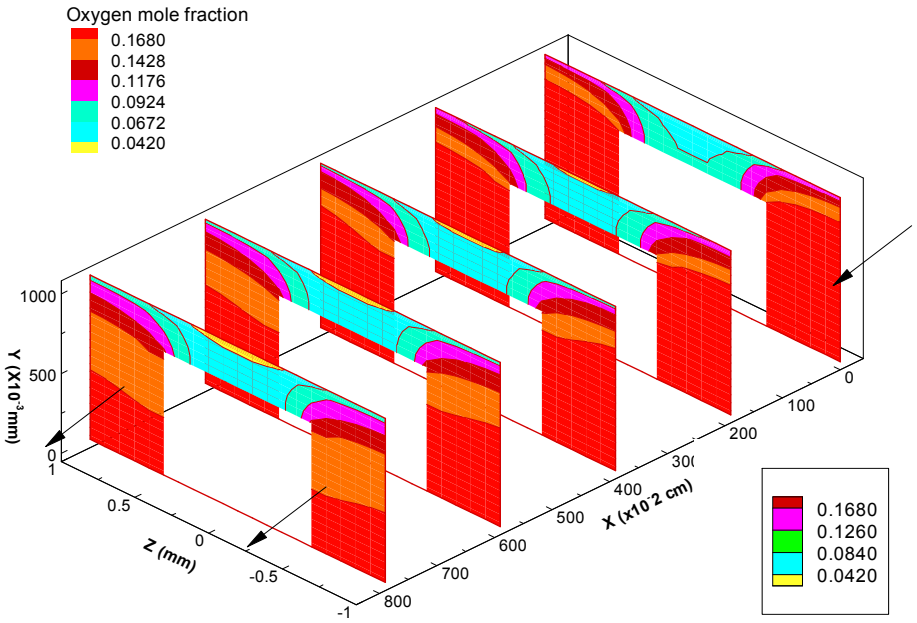
In open spaces/channels
In porous media
In liquid
In solids

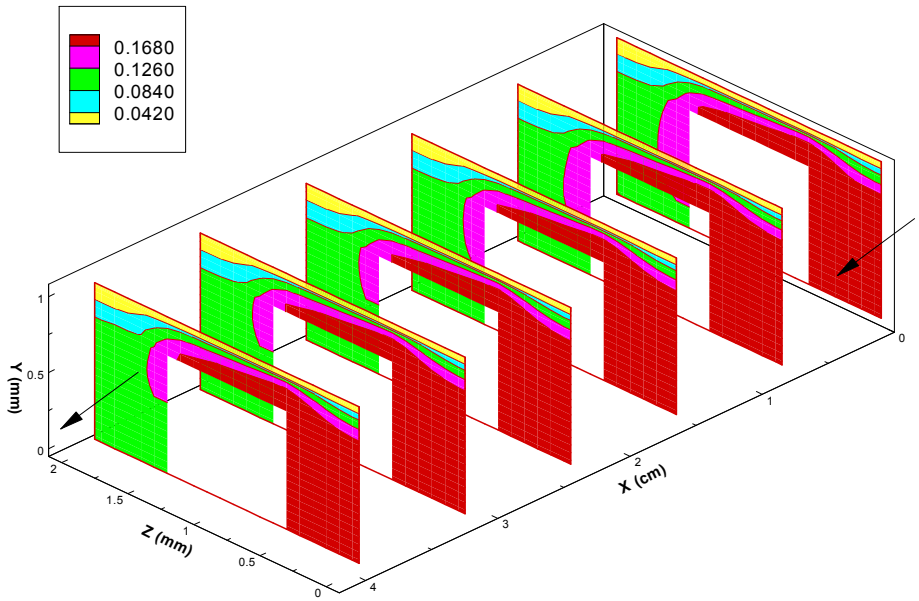
Phase change
- Evaporation
- Condensation

1-D (y)
2-D (x-y or z-y)
2 2-D (x-y and z-y)
3-D models (x-y-z)

Oxygen molar fraction

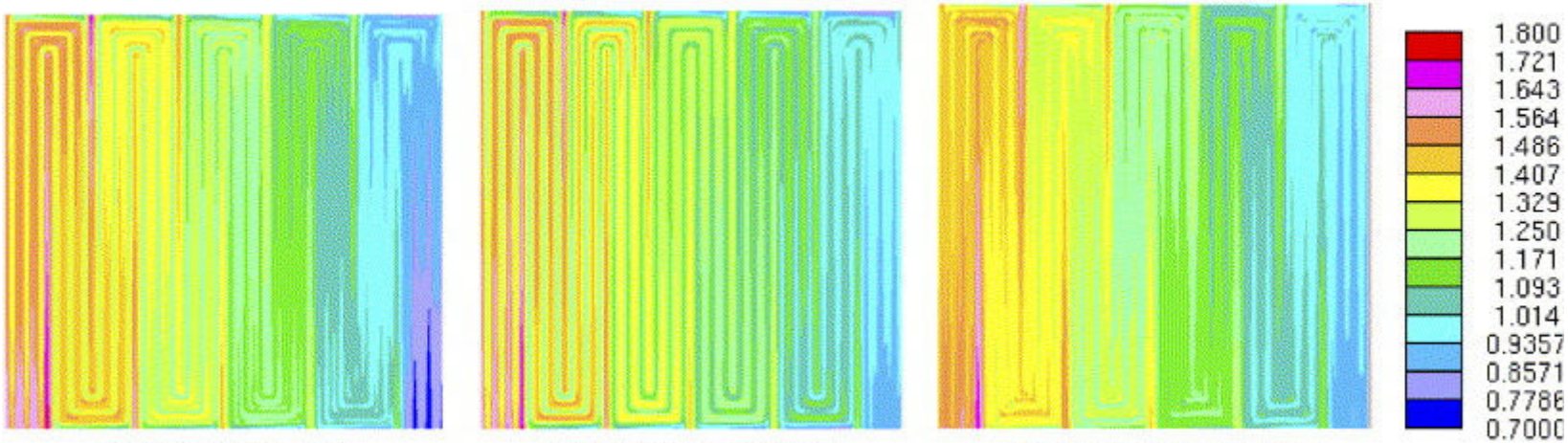
conventional flow field vs. interdigitated flow field





H. Liu, T. Zhou and L. You, NSF Workshop on Engineering Fundamentals of Low-Temperature PEM Fuel Cells, Arlington, VA, November 14-15, 2001

Current density (A/cm^2) distributions at I_{avg} = 1.2 A/cm^2; stationary conditions

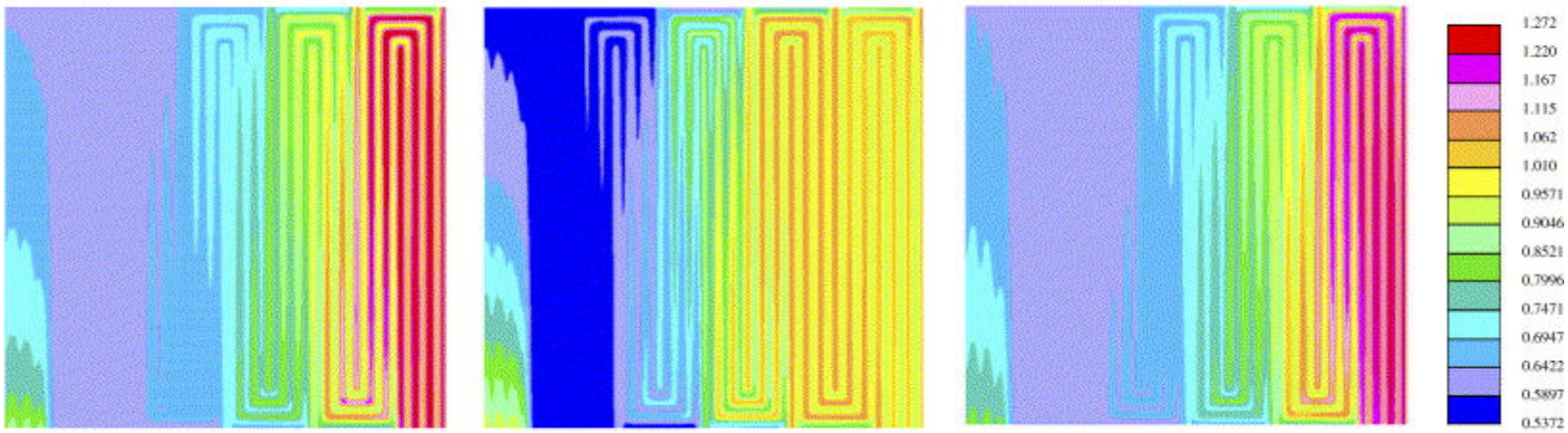


Base case 0.9 mm/0.9 mm
Vcell = 0.521 V

Channel wide 1.0 mm/0.7 mm
Vcell = 0.522 V

Channel narrow 0.7 mm/1.0 mm
Vcell= 0.5365 V

Current density (A/cm^2) distributions at I_{avg} = 0.8 A/cm^2; automotive conditions



Base case 0.9 mm/0.9 mm
Vcell = 0.672 V

Channel wide 1.0 mm/0.7 mm
Vcell = 0.707 V

Channel narrow 0.7 mm/1.0 mm
Vcell = 0.677 V

S. Shimpalee, J.W. Van Zee, Numerical studies on rib & channel dimension of flow-field on PEMFC performance, *Int. J. of Hydrogen Energy*, *Volume 32, Issue 7*, *2007*, *Pages 842-856*

Fuel Cell Diagnostic Methods

Electrochemical techniques

- Polarization curve
- Current interruption
- Electrochemical Impedance Spectroscopy
- Cyclic Voltammetry
- CO Stripping Voltammetry
- Linear Sweep Voltammetry

Species Distribution Mapping

- Pressure Drop Measurements
- Gas Composition Analysis
- Neutron Imaging
- Magnetic Resonance Imaging
- X-ray Imaging
- Optically Transparent Fuel Cells
- Embedded Sensors

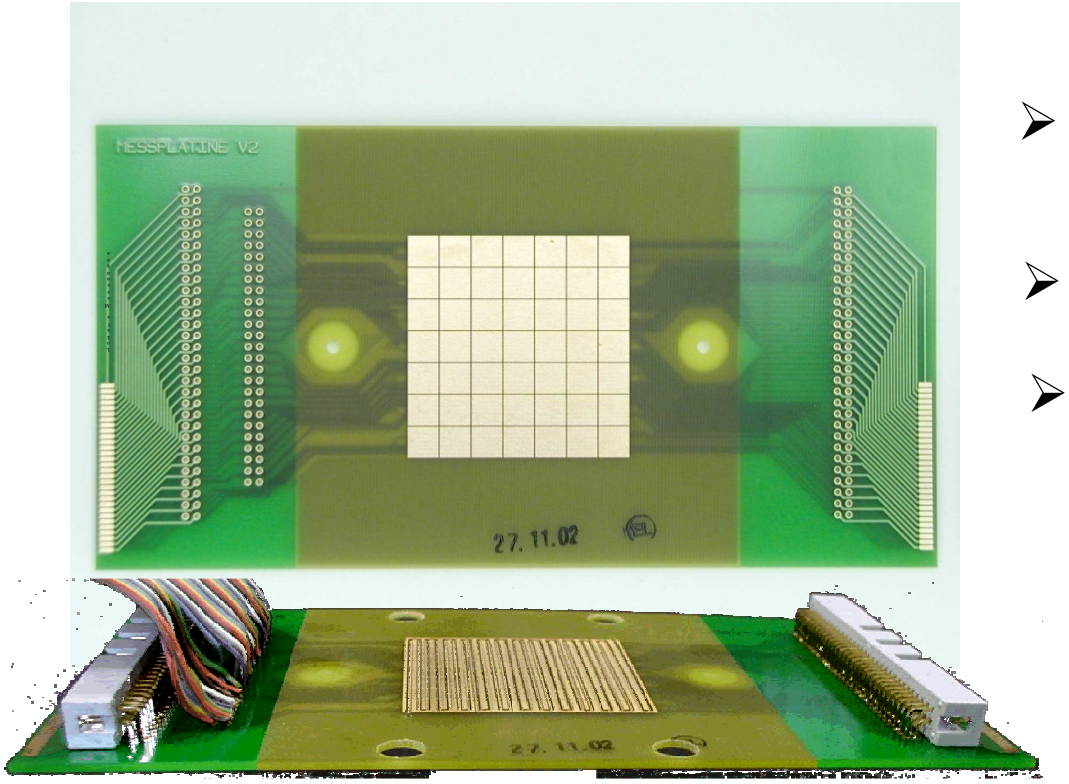
Current Distribution Mapping

- Partial MEA
- Segmented Cells

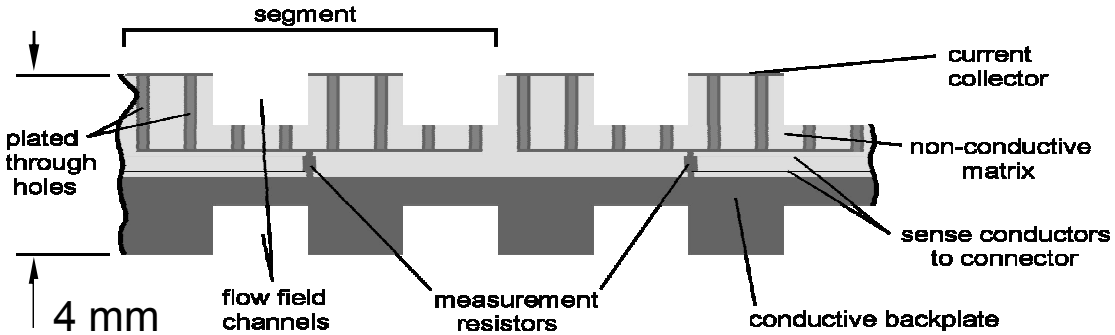
Temperature Distribution Mapping

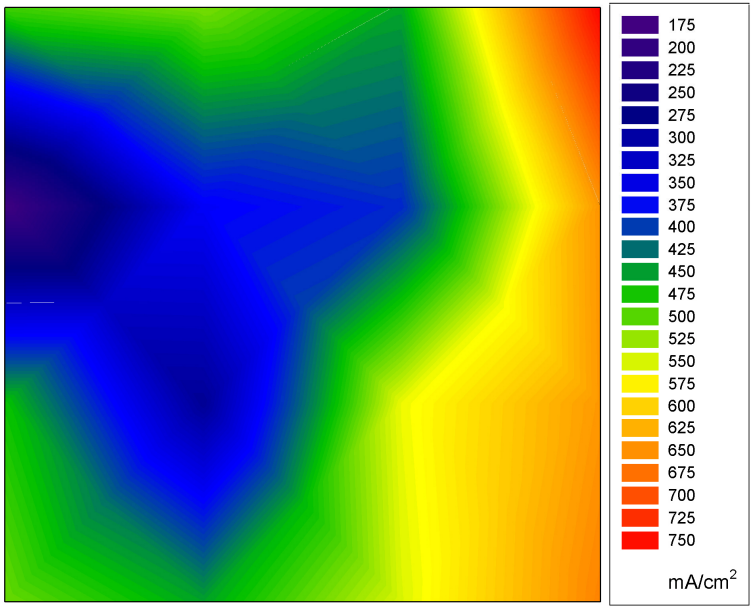
- IR Transparent Fuel Cells
- Embedded Sensors

Segmented bipolar plates



- local current density measurement dynamic > 2000 measurement /s
- local temperature measurement
- local electrochemical impedance spectroscopy (EIS)

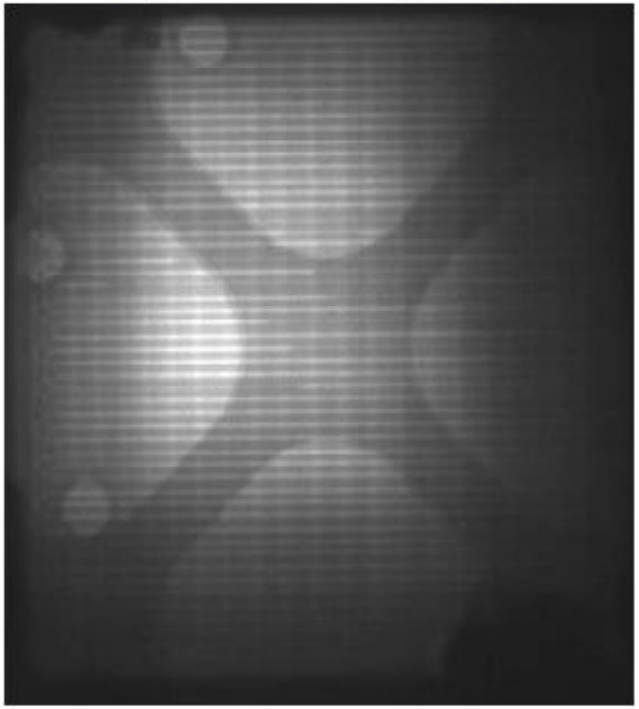




neutrons can 'see' water in fuel cells

normalization of images: water distribution map

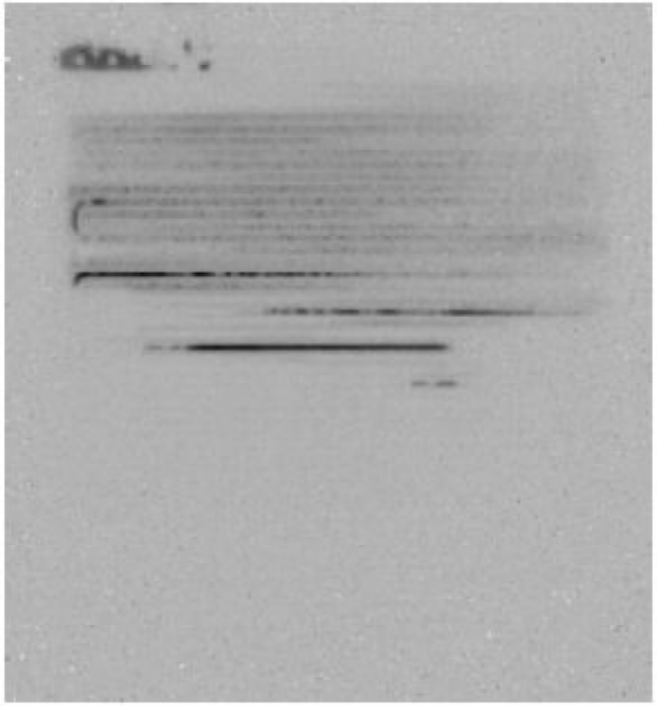
original radiography



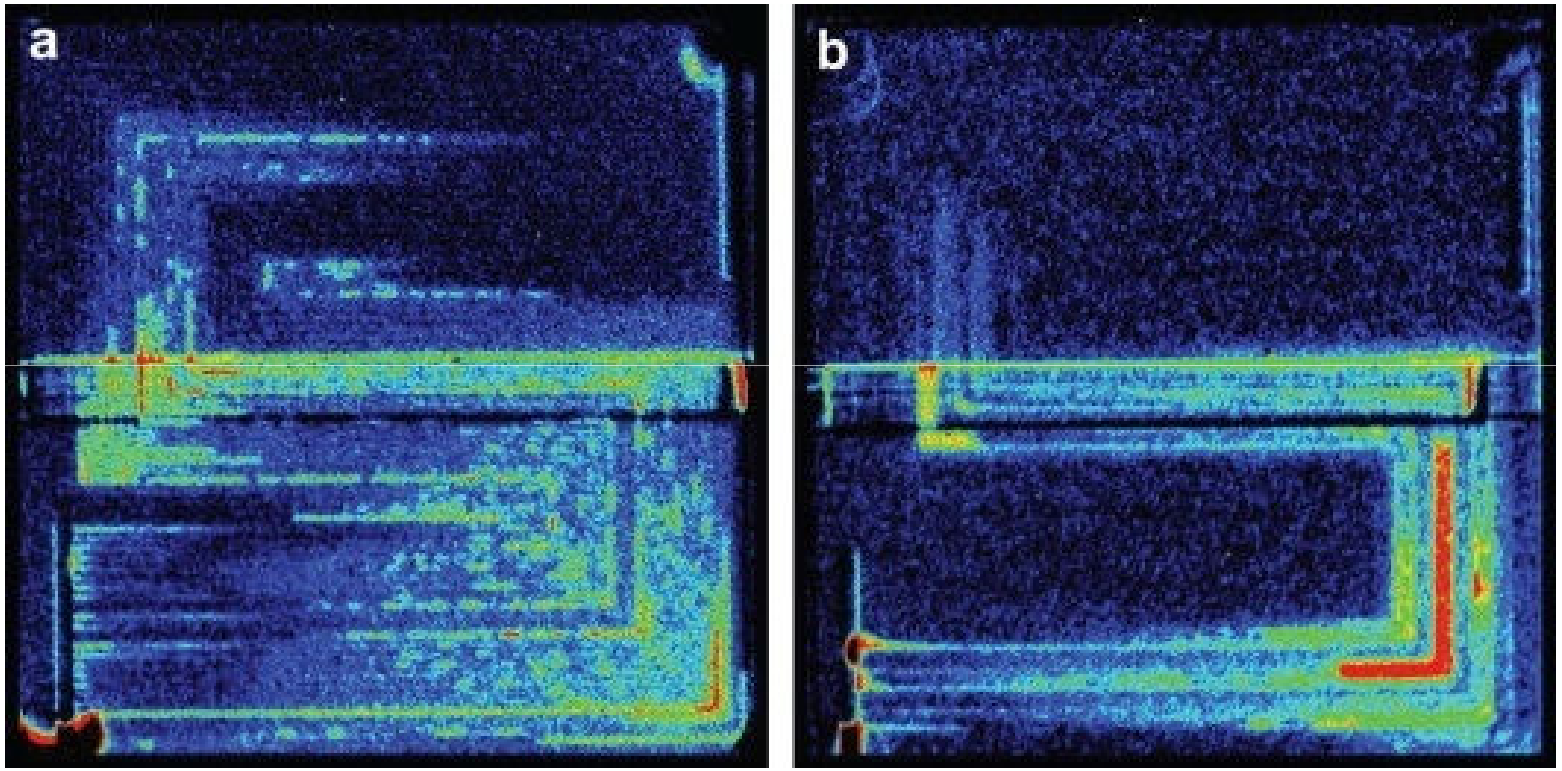
100 mm

ratio:
water filled
cell
/empty cell

water distribution



Liquid water distribution in PEMFC by neutron imaging
at Penn State University



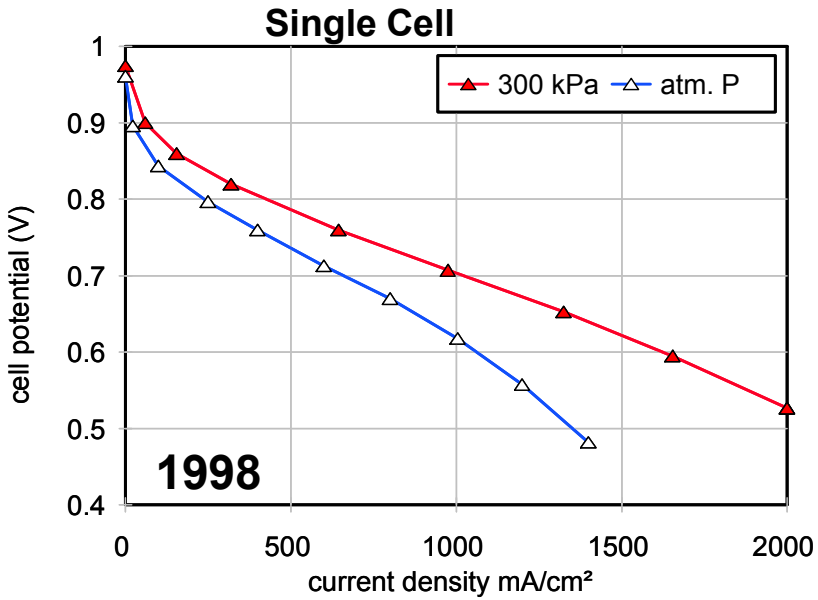
A. Turhan, K. Heller, J.S. Brenizer and M.M. Mench, Passive control of liquid water storage and distribution in a PEFC through flow-field design, *Journal of Power Sources* **180** (2) (2008), pp. 773–783.

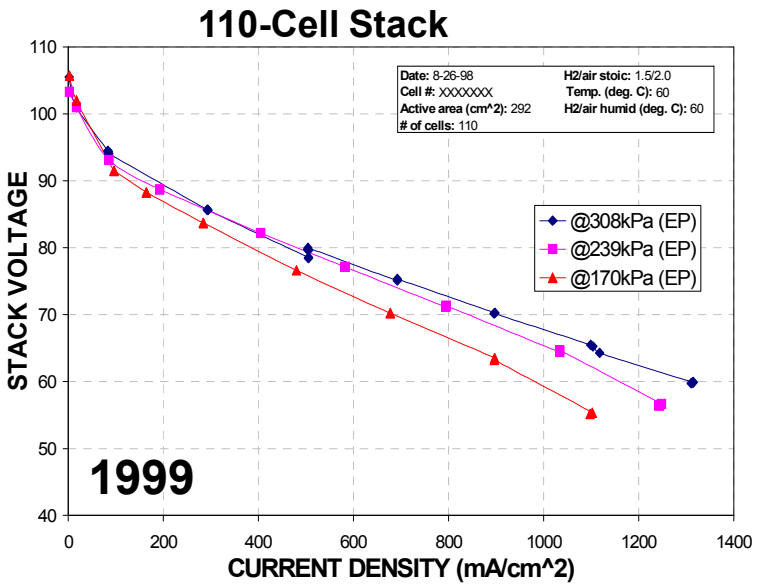
Stack engineering/design

Goals

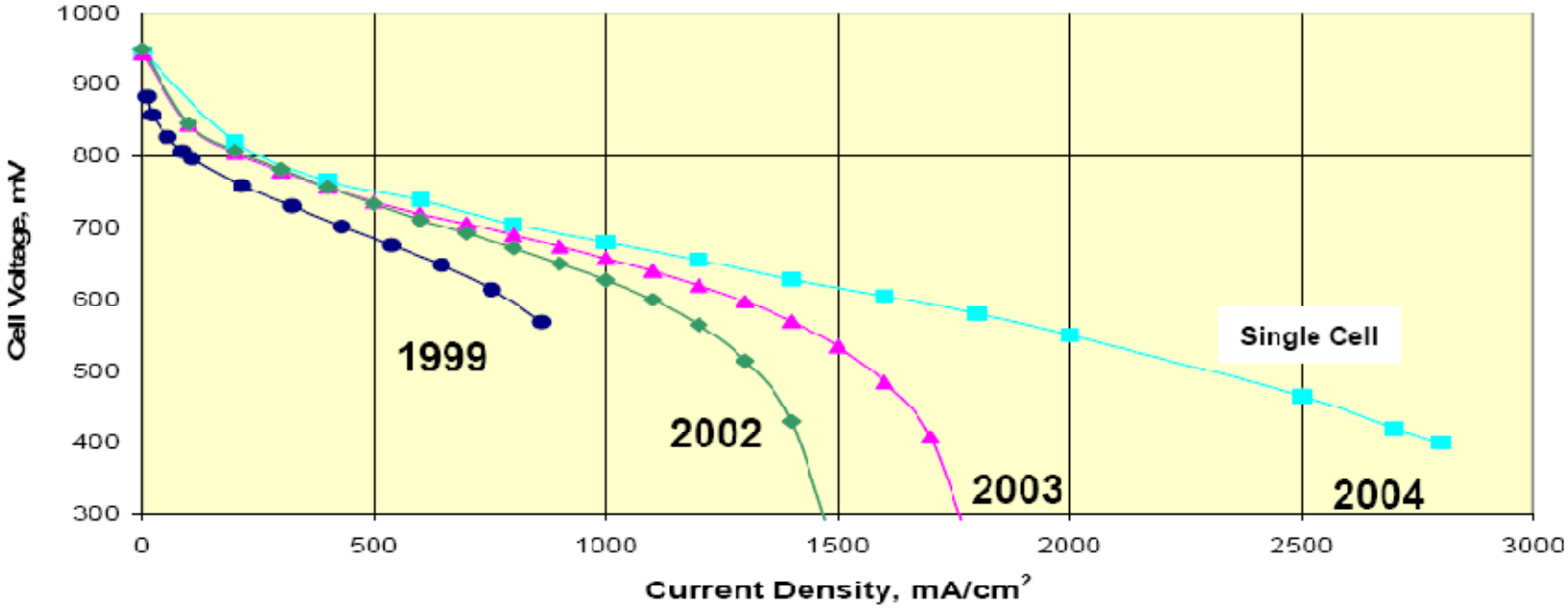
- Uniform reactant distribution to each cell
- Uniform reactant distribution inside each cell
- Required temperature distribution inside each cell
- **Minimal resistive losses**
  - **good electrical contacts**
  - **choice of materials**
- **Take into account thermal expansion**
- **No hydrogen or oxygen leaks**
- **Minimal required pressure drop (reactanats and coolant)**
- **Eliminate possibility for water accumulation**
- **Design for manufacturing/design for assembly**

energypartners





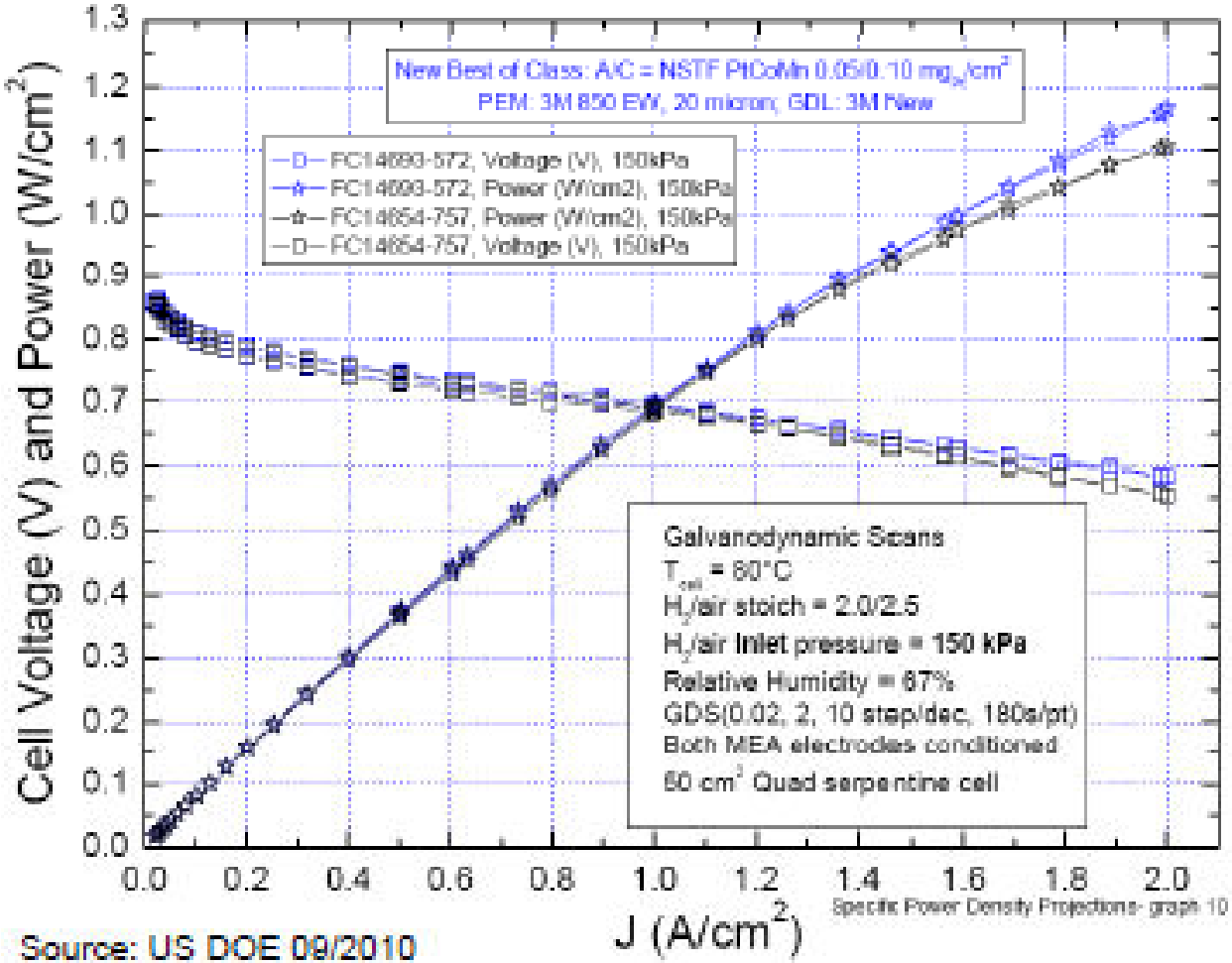
UTC Fuel Cells
A United Technologies Company



2010 Progress & Accomplishments

U.S. DEPARTMENT OF ENERGY

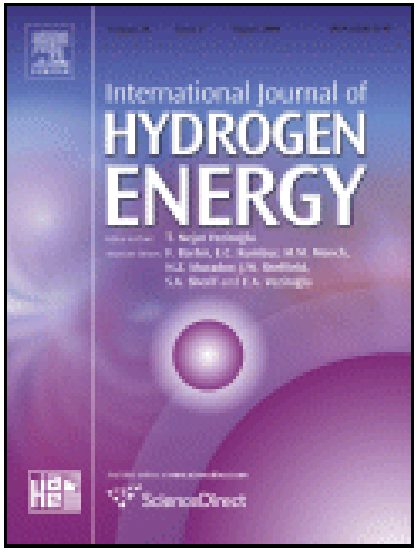
MEAs demonstrate high performance under non-ideal (cool, wet) conditions



Source: US DOE 09/2010

Recent Trends in Fuel Cell R&D

- High temperature membrane
- Self-humidifying membrane
- Alternative non-noble metal catalysts
- Gas diffusion layer characterization
- Corrosion and properties of bi-polar plates
- Diagnostics and modeling
- Understanding of water transport
- Miniature fuel cells
- Direct-borohydride fuel cells
- Bio fuel cells
- Flow field configuration
- System simplification and optimization
- Durability
- Application-specific topics



Fuel Cell R&D - *Metrics*

U.S. DEPARTMENT OF ENERGY

Fuel Cell R&D is focused on a broad range of applications, using a variety of technologies and fuels.

KEY TARGETS:

Distributed Power*:

- $750/kW by 2011
- 40,000-hour durability by 2011
- 40% efficiency by 2011

Transportation:

- $45/kW by 2010; $30/kW by 2015*
- 5,000-hour durability by 2015
- 60% efficiency

APUs:

- Specific power of 40 W/kg by 2015
- Power density of 35 W/L by 2015

Portable Power*:

- Energy density of 1,000 W-h/L by 2013

Performance metrics being tracked will help form materials handling and backup power targets

*Targets are currently under review

Source: US DOE 09/2010

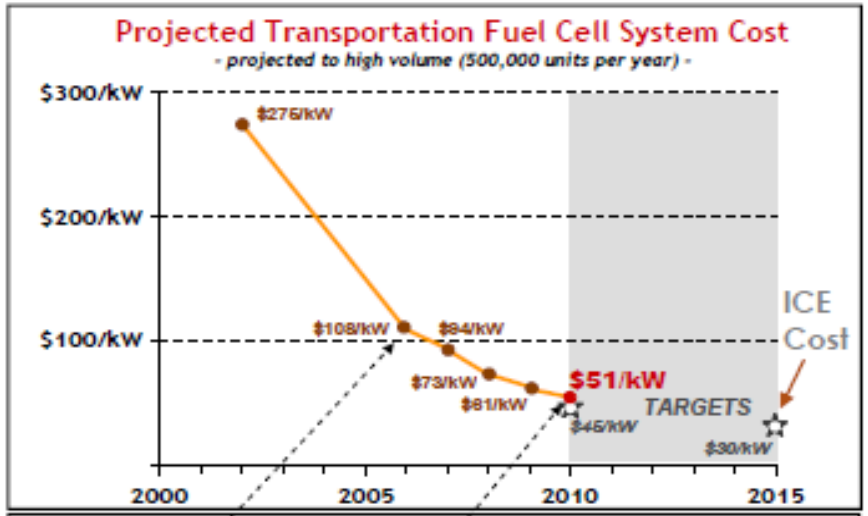
Fuel Cell R&D — *Progress: Cost*

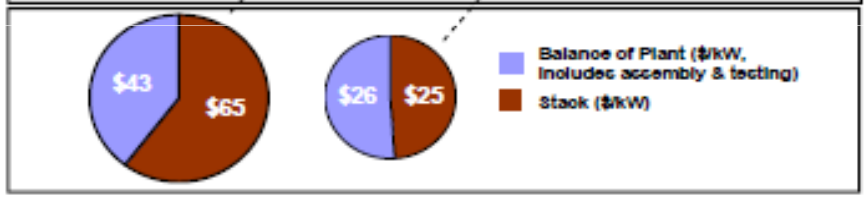
U.S. DEPARTMENT OF ENERGY

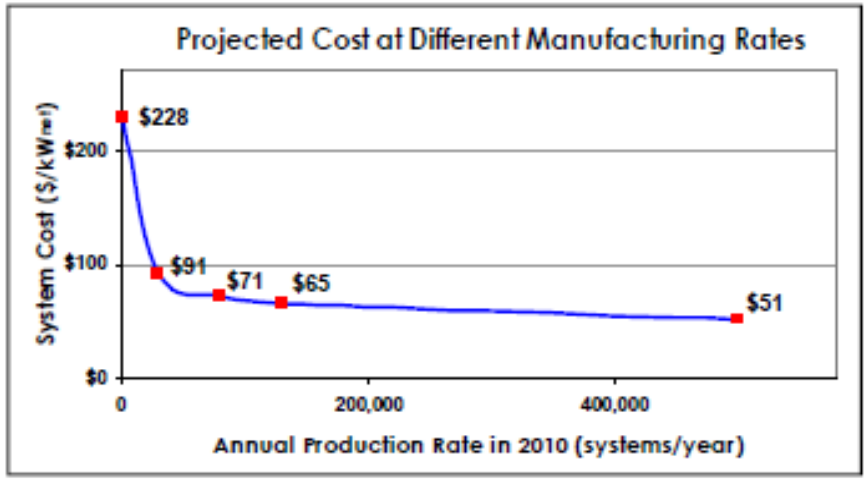
Projected high-volume cost of fuel cells has been reduced to $51/kW (2010)*

- *More than 15% reduction since 2009*
- *More than 80% reduction since 2002*
- *2008 cost projection was validated by independent panel***

As stack costs are reduced, balance-of-plant components are responsible for a larger % of costs.







*Based on projection to high-volume manufacturing (500,000 units/year).

**Panel found $60 – $80/kW to be a "valid estimate": http://hydrogendoedev.nrel.gov/peer_reviews.html

Source: US DOE 09/2010

Catalysts and Supports

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

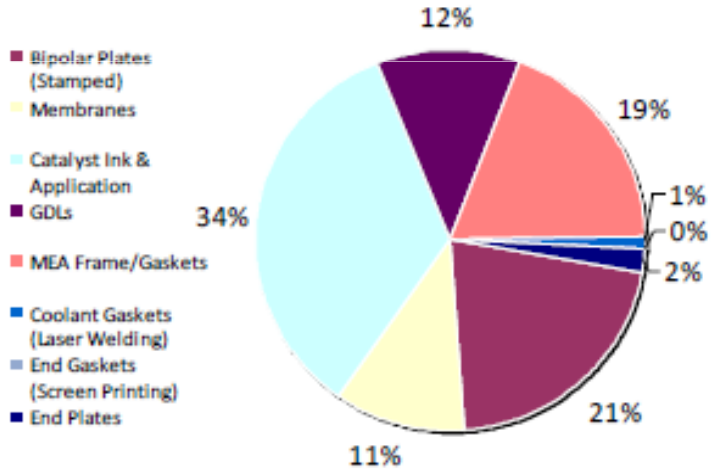
Challenges:

- **Platinum (Pt) cost is ~34% of total stack cost**
- **Catalyst durability needs improvement**

Four Strategies for Catalysts & Supports R&D:

- Lower PGM Content
  - Improved Pt catalyst utilization and durability
- Pt Alloys
  - Pt-based alloys with comparable performance to Pt and cost less
- Novel Support Structures
  - Non-carbon supports and alternative carbon structures
- Non-PGM catalysts
  - Non-precious metal catalysts with improved performance and durability

Stack Cost - $26/kW

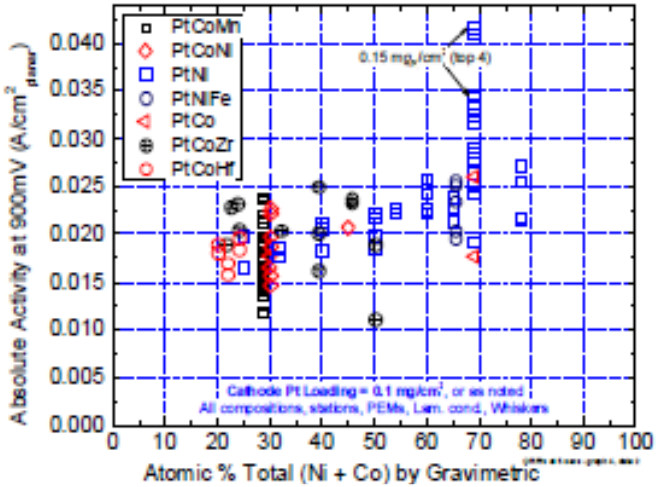


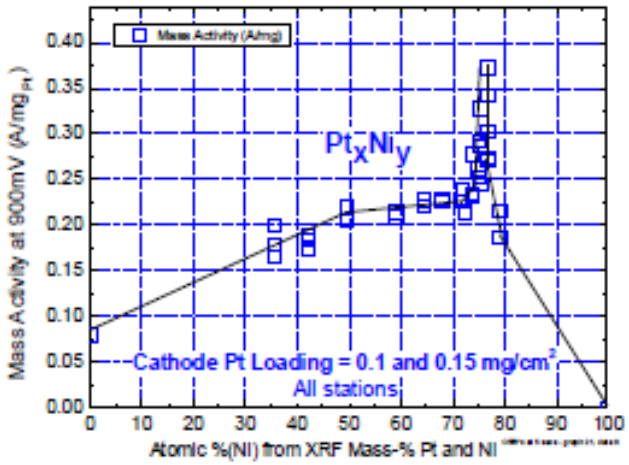
DTI, 2009 analysis, scaled to high volume production of 500,000 units/yr

Used $1100/Troy Ounce for Pt Cost

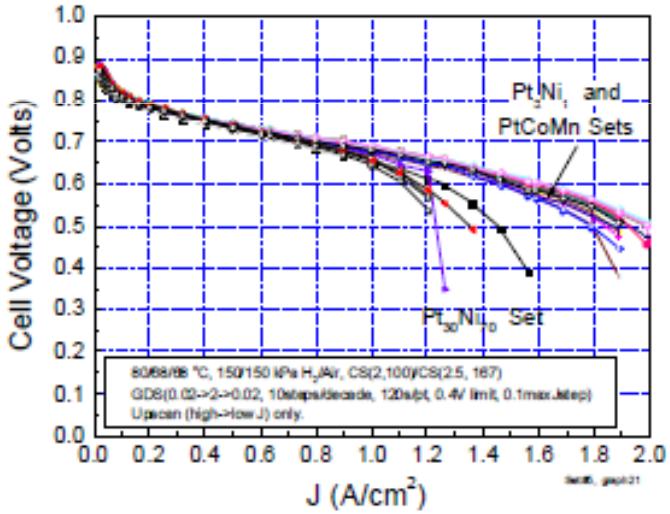
Source: US DOE 09/2010

High-Activity Binary PtNi Alloy Catalyst





- Screening of multiple new alloys at 3M revealed anomalously high ORR activity for Pt_xNi_y at high Ni content
- Dramatic and sharp mass activity peak at Pt_3Ni_7 (gravimetric) vs 60at% Ni and 76at% Ni by EMP and XRF respectively
- Definite gains in kinetic performance but not a practical catalyst yet due to performance limitations above 1 A/cm²



Next Steps: Improve high current density performance

M. Debe, 2010 DOE Hydrogen Program Review

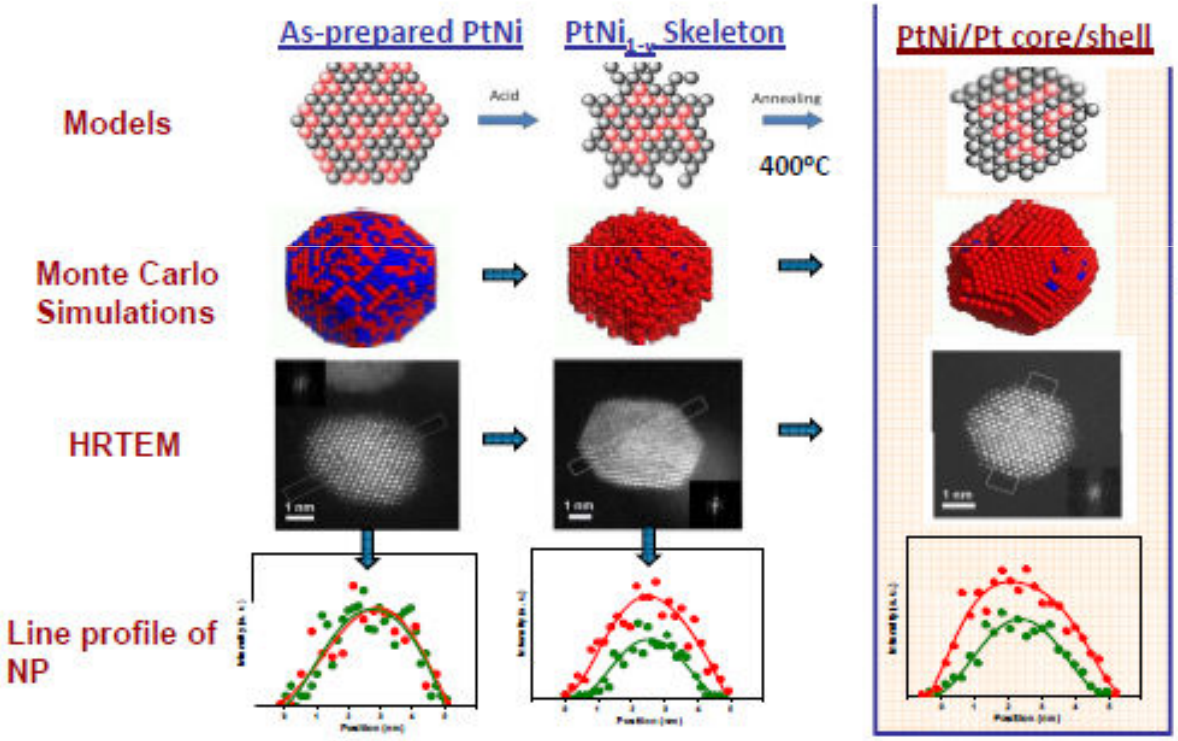
Source: US DOE 09/2010

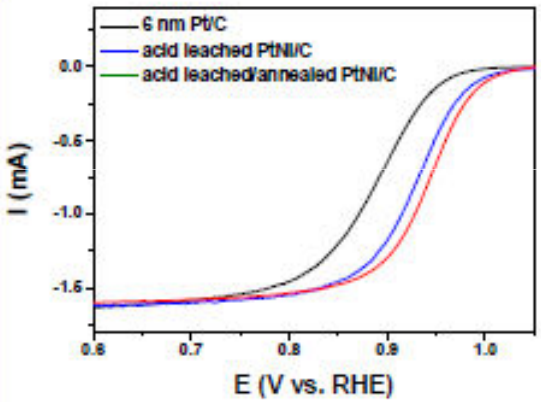
3M

Nano-segregated Cathode Catalysts

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Argonne National Laboratory approach: Materials by design to characterize, synthesize, and test nanosegregated multi-metallic nanoparticles and nanostructed thin metal films





PtNi/Pt core/shell catalyst has 7X activity over same size Pt/C

Next Steps: Evaluate in-cell durability, scale-up

N. Markovic, 2010 DOE Hydrogen Program Review

Argonne

Source: US DOE 09/2010

2010 Progress & Accomplishments

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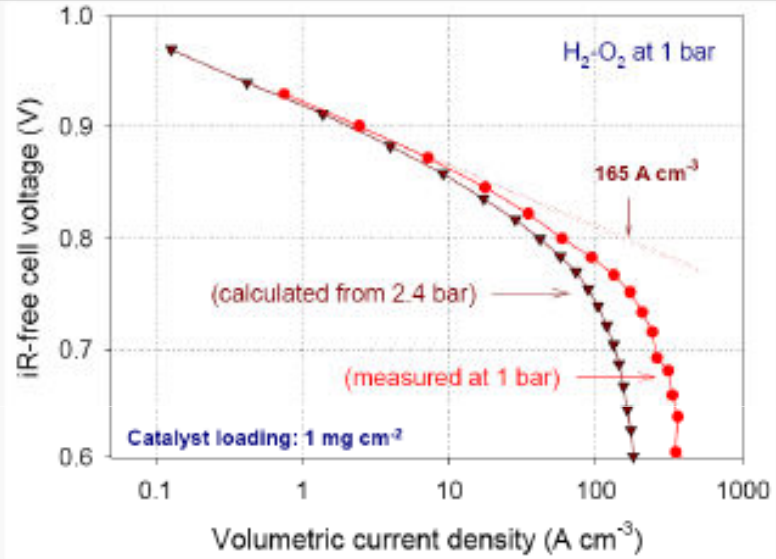
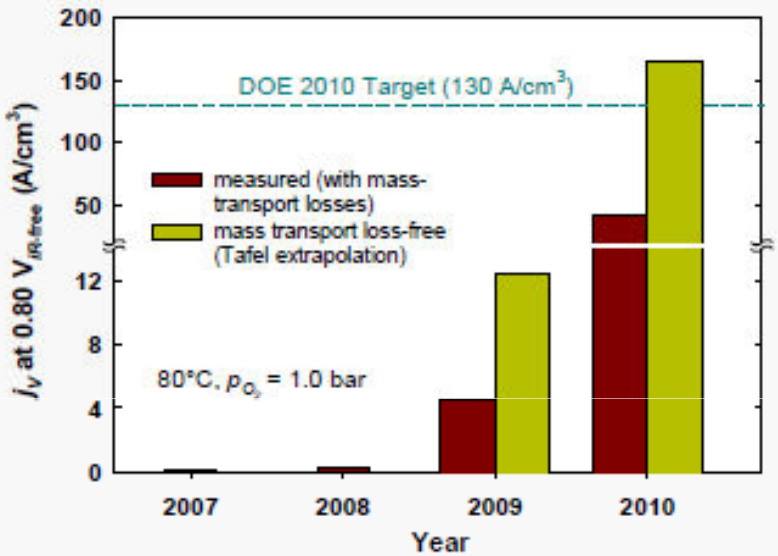
Non-PGM catalyst activity increased





- **High ORR activity reached with several non-PGM catalysts by LANL, including cyanamide-Fe-C catalyst (shown)**
- **Fuel cell performance improved by more than 100× since 2008**
- **Catalyst activity exceeds DOE 2010 activity target of 130 A/cm^3 at 0.80 V**

Source: US DOE 09/2010

Membranes

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Challenges:

- Membranes account for 48% of stack cost at low volume
- Limits on operating range
- Chemical and mechanical durability

Membrane R&D:

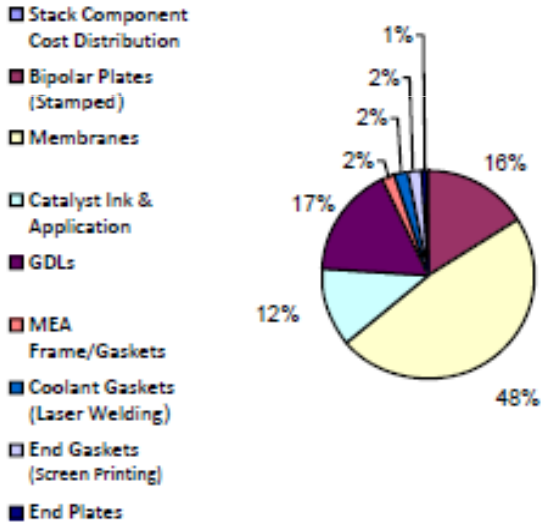
High-Temperature, Low Humidity Conductivity

- Phase segregation (polymer & membrane)
- Non-aqueous proton conductors
- Hydrophilic additives

High Conductivity and Durability Across Operating Range with Cycling

- Mechanical support or membrane reinforcement
- Chemical stabilization (additives, end-group capping)
- Polymer structure (side chain length, grafting, cross-linking, backbone properties, blends, EW)
- Processing parameters (temperature, solvents)
- New materials

Stack Cost - $137/kW



DTI, 2009 analysis, production of 1,000 units/yr

Used $453/m^2 for membrane Cost

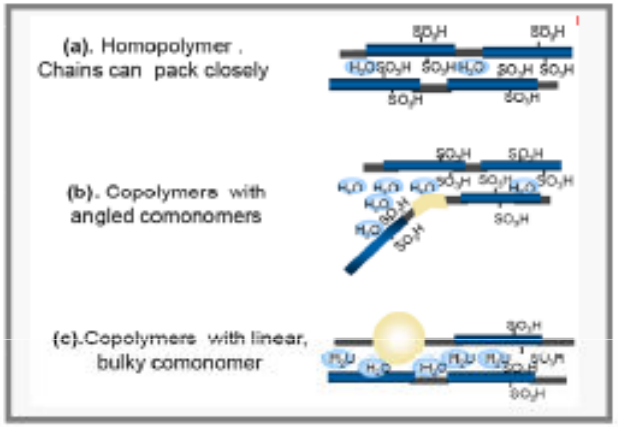
Source: US DOE 09/2010

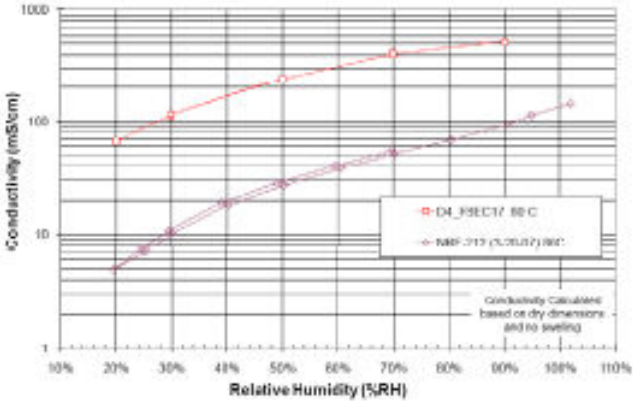
2010 Progress & Accomplishments

U.S. DEPARTMENT OF ENERGY

Membranes achieve high conductivity for high temperature applications

CWRU: Frozen-in Free Volume

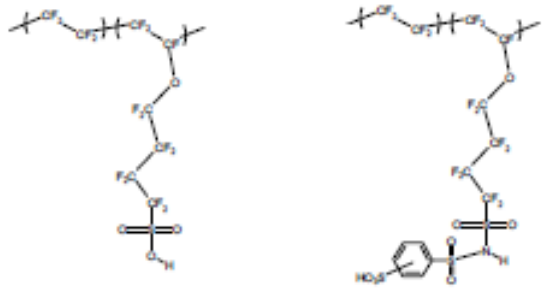


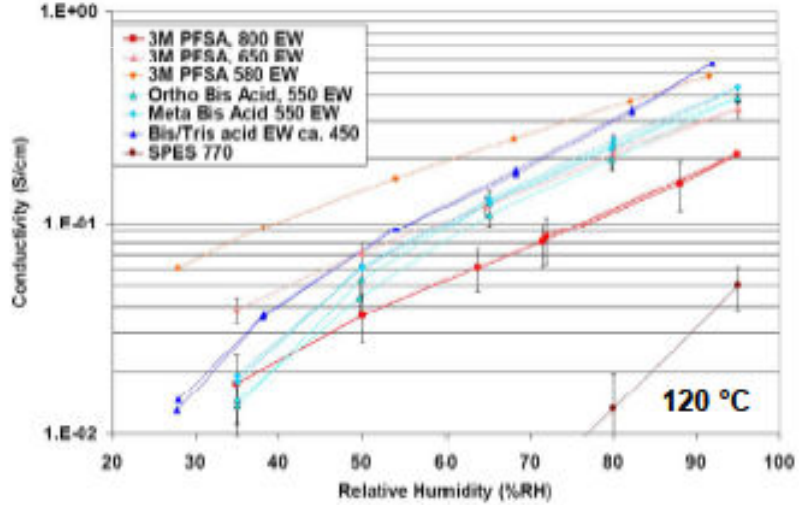


- Latest rigid-rod polyelectrolytes show outstanding conductivity at 80 °C
- 120 °C testing in progress

Source: US DOE 09/2010

3M: Low-EW PFSAs and Multi-Acid Side Chains





Low-EW PFSA has highest conductivity, but poor mechanical properties

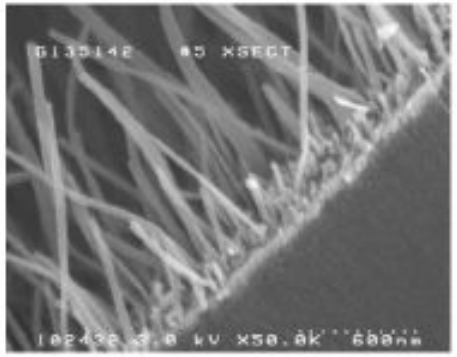
Multi-acid side chain ionomer achieves high conductivity while retaining better mechanical properties

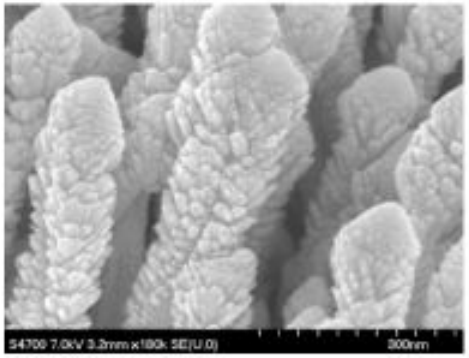
2010 Progress & Accomplishments

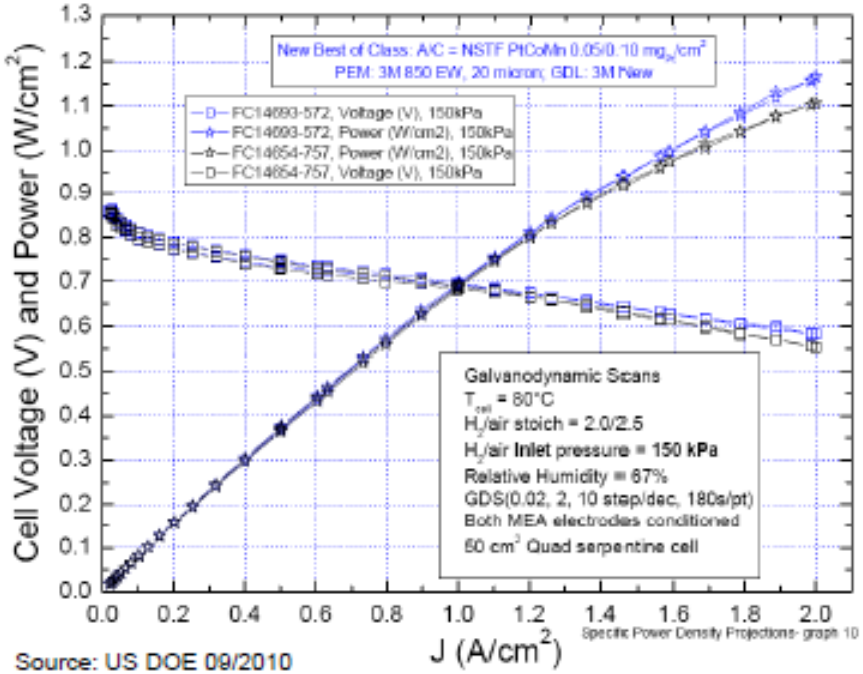
U.S. DEPARTMENT OF ENERGY

MEAs demonstrate high performance under non-ideal (cool, wet) conditions

3M Nanostructured Thin Film (NSTF) catalyst

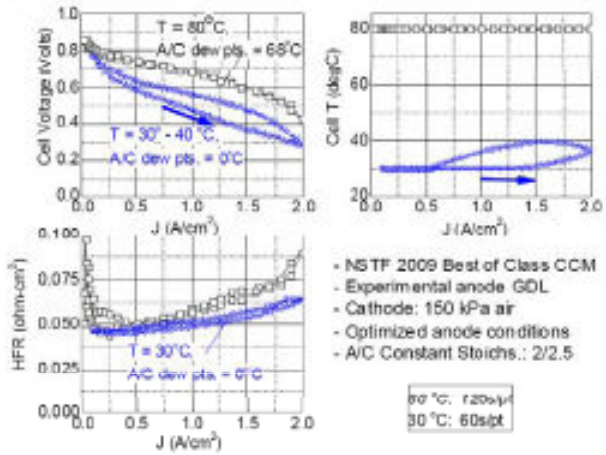






Source: US DOE 09/2010

First time standard NSTF CCM has ever hit 1.5 to 2 A/cm² at 30 to 35°C



3M's use of specific anode operating conditions and modification of anode diffusion media allows high performance operation under challenging conditions – temperature as low as 30 °C

NSTF meets major performance and durability targets

- High power at low PGM loading – 0.18 g_{PGM}/kW (single cell), 0.19 g_{PGM}/kW (stack) – *DOE 2010 target: 0.3 g_{PGM}/kW*
- Membrane Durability Test - 5000 hours with cycling (single cell) – *DOE 2010/2015 target: 5000 hours*

Fuel Cell R&D – *Progress: Durability*

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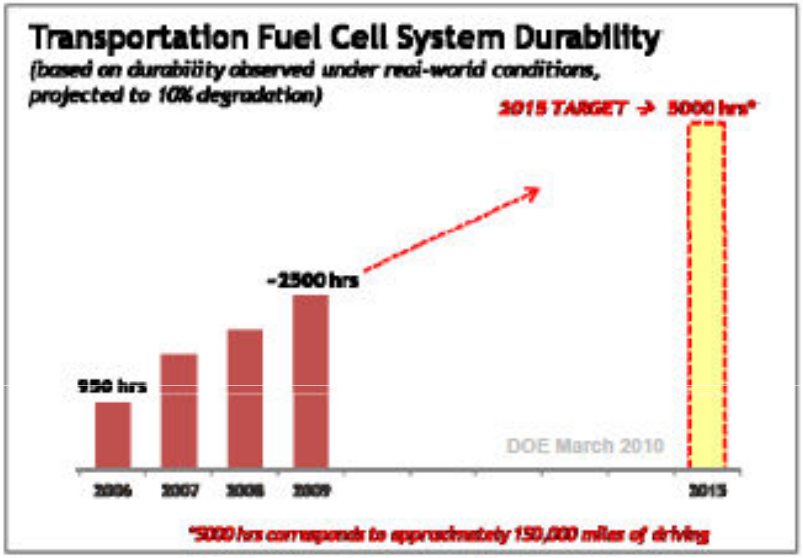
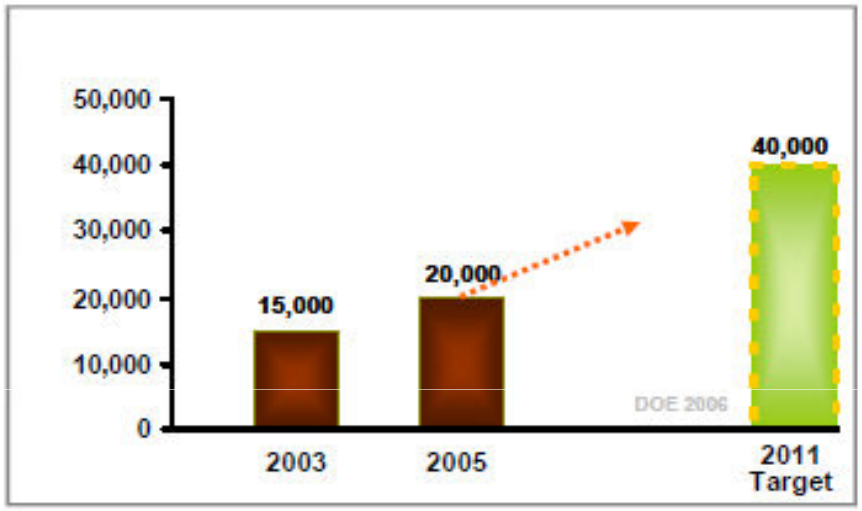
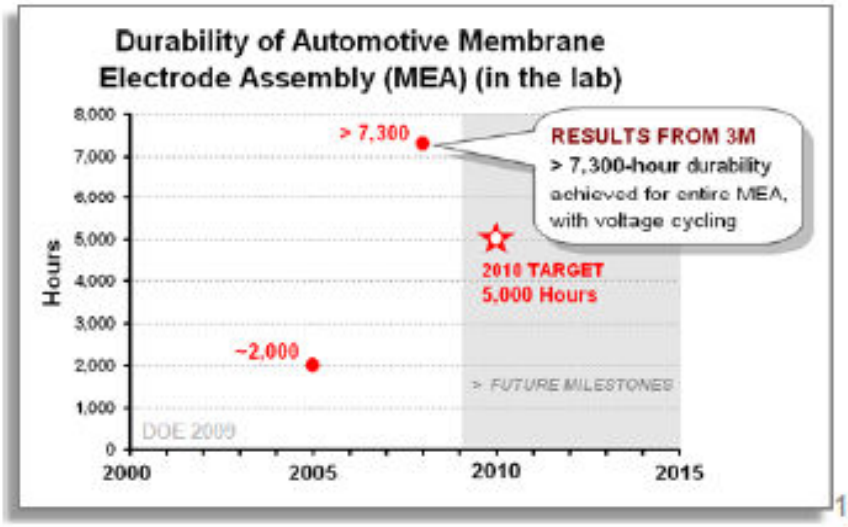
We've greatly increased durability—including more than doubling the demonstrated durability of transportation fuel cells.





Demonstrated >7,300-hour durability →

This exceeds our target for MEA durability, in single-cell testing—and has the potential to meet the 2010 target for MEAs in a fuel cell system



Source: US DOE 09/2010

Technology Validation
2010 Vehicles Progress & Accomplishments

U.S. DEPARTMENT OF ENERGY

Demonstrations are essential for validating the performance of technologies in integrated systems, under real-world conditions.

RECENT ACCOMPLISHMENTS

Vehicles & Infrastructure

- Fuel cell durability
  - 2,500 hours projected (nearly 75K miles)
- Over 2.8 million miles traveled
- Over 114 thousand total vehicle hours driven
- Fuel cell efficiency 53-59%
- Vehicle Range: ~196 – 254 miles
- Over 134,000 kg- H_2 produced or dispensed*
- 152 fuel cell vehicles and 24 hydrogen fueling stations have reported data to the project

Buses

- DOE is evaluating real-world bus fleet data (DOT collaboration)
  - H_2 fuel cell buses have a range of 39% to 141% better fuel economy when compared to diesel & CNG buses

Forklifts

- Forklifts at Defense Logistics Agency site have completed more than 18,000 refuelings

Recovery Act

- NREL is collecting operating data from deployments for an industry-wide report

*Not all hydrogen produced is used in vehicles

Source: US DOE 09/2010

Summary – Key Performance Metrics

U.S. DEPARTMENT OF ENERGY

Vehicle Performance Metrics	Gen 1 Vehicle	Gen 2 Vehicle	2009 Target
Fuel Cell Stack Durability			**2000 hours**
Max Team Projected Hours to 10% Voltage Degradation	**1807 hours**	**2521 hours**	
Average Fuel Cell Durability Projection	821 hours	1062 hours	
Max Hours of Operation by a Single FC Stack to Date	2375 hours	1261 hours	
Driving Range	**103-190 miles**	**196-254 miles**	**250 miles**
Fuel Economy (Window Sticker)	42 – 57 mi/kg	43 – 58 mi/kg	no target
Fuel Cell Efficiency at ¼ Power	51 - 58%	53 - 59%	60%
Fuel Cell Efficiency at Full Power	30 - 54%	42 - 53%	50%

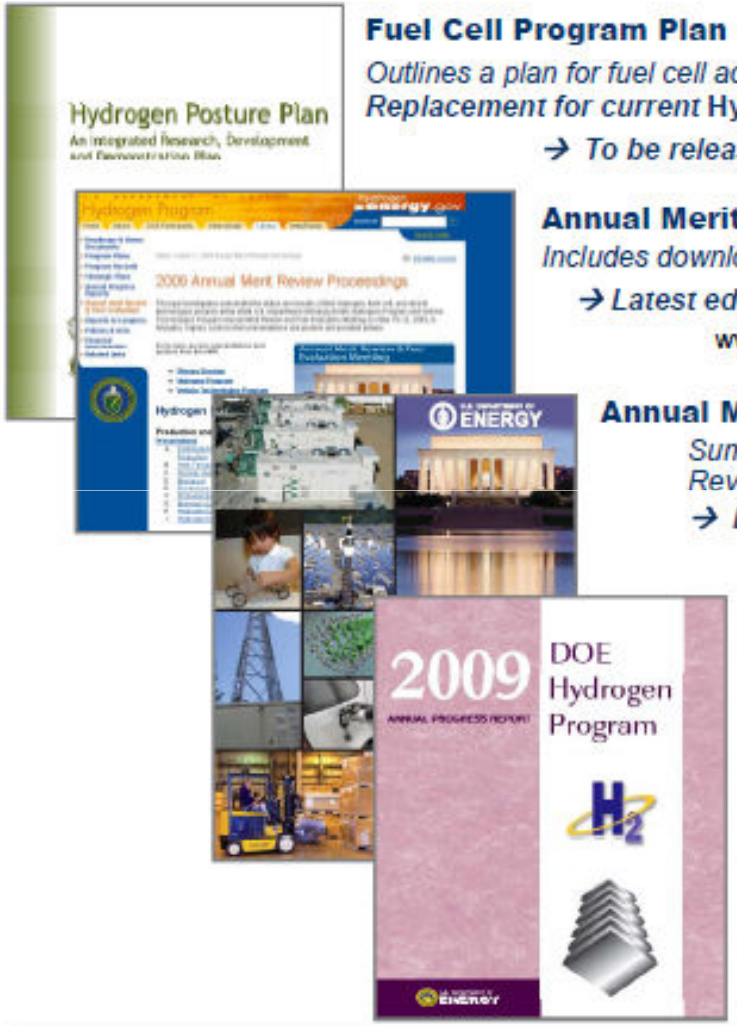
Infrastructure Performance Metrics			2009 Target
H_2 Cost at Station (early market)*	On-site natural gas reformation **$7.70 - $10.30**	On-site Electrolysis **$10.00 - $12.90**	**$3/gge**
Average H_2 Fueling Rate	0.77 kg/min		1.0 kg/min

*DOE independent panels concluded at 500 replicate stations/year:
Distributed natural gas reformation at 1500 kg/day: $2.75-$3.50/kg (2006)
Distributed electrolysis at 1500kg/day: $4.90-$5.70 (2009)

Source: US DOE 09/2010

For More Information

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Fuel Cell Program Plan

Outlines a plan for fuel cell activities in the Department of Energy
Replacement for current Hydrogen Posture Plan

→ *To be released in 2010*

Annual Merit Review Proceedings

Includes downloadable versions of all presentations at the Annual Merit Review

→ *Latest edition released June 2009*

www.hydrogen.energy.gov/annual_review09_proceedings.html

Annual Merit Review & Peer Evaluation Report

Summarizes the comments of the Peer Review Panel at the Annual Merit Review and Peer Evaluation Meeting

→ *Latest edition released October 2009*

www.hydrogen.energy.gov/annual_review08_report.html

Annual Progress Report

Summarizes activities and accomplishments within the Program over the preceding year, with reports on individual projects

→ *Latest edition published November 2009*

www.hydrogen.energy.gov/annual_progress.html

2010Annual Merit Review & Peer Evaluation Report and Annual Progress Report will be issued in November 2010

www.hydrogenandfuelcells.energy.gov* and *www.hydrogen.energy.gov

Source: US DOE 09/2010

Fuel Cell Technology:

Obstacles for Commercialization

Application	Key Obstacle(s)
Space	reliability
(Sub)marine	reliability
Marine (propulsion)	cost, fuel
Automotive, cars	cost, fuel availability
Automotive, buses	durability, cost
Niche transportation	
Stationary Power	durability, cost
Portable Power	
Battery Replacement	cost, fuel practicality



Summary about fuel cells:

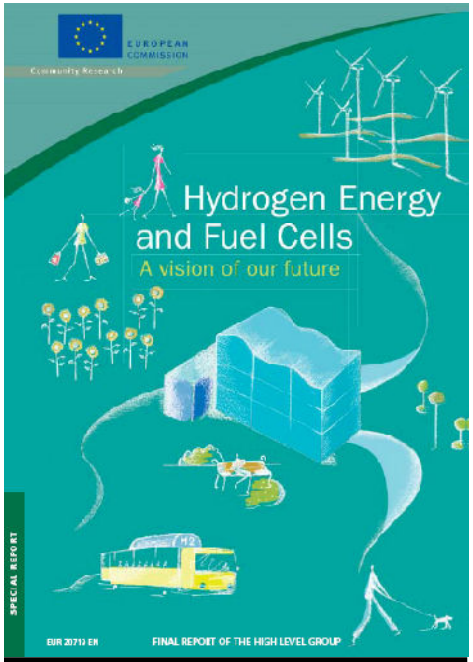
- Fuel cells are:
  - versatile (many possible applications)
  - efficient
  - clean (when use hydrogen as fuel)
  - modular
- Fuel cells are close to commercialization
  - niche market opportunities
- Few technical challenges, but no show-stoppers
  - performance
  - durability
  - cost
- There is a room and need for improvements
- Fuel cells using hydrogen as fuel need hydrogen supply infrastructure

Future of Energy

- What will an energy system of the future look like?
- What would be a role of hydrogen in it?
- How do we get there from here?

Vision

Strategy



Hydrogen Energy and Fuel Cells
A Vision of Our Future

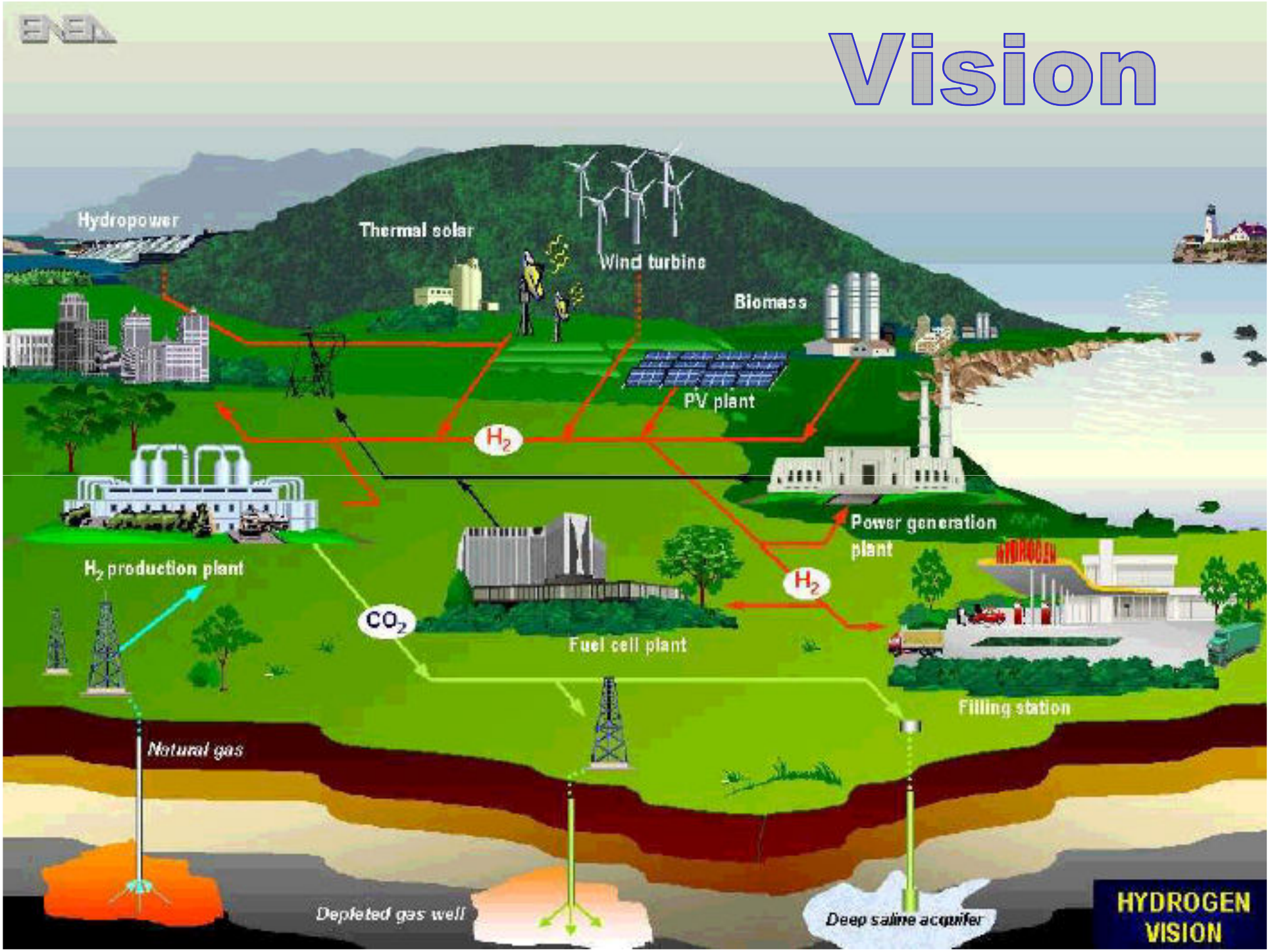
Summary

In 2050:

- Oil will likely no longer be cheap
- Europe's internal reserves will be exhausted
- Increasing proportion of primary energy production will be drawn from "CO_2-lean" resources:
  - Renewables – solar, wind, hydro and biomass
  - Nuclear
- Hydrogen will be one of the three energy vectors (besides electricity and biofuels)
  - It can be produced from variety of primary energy sources
  - It can be used in a variety of applications
  - It can be stored more effectively than electricity
- Fuel cells will be mature technology and cost competitive (other technologies will include turbines and ICE)
- Fuel cells will be used in transport, stationary and portable applications
- Fuel cells are likely to predominantly consume hydrogen, but should be fuel flexible

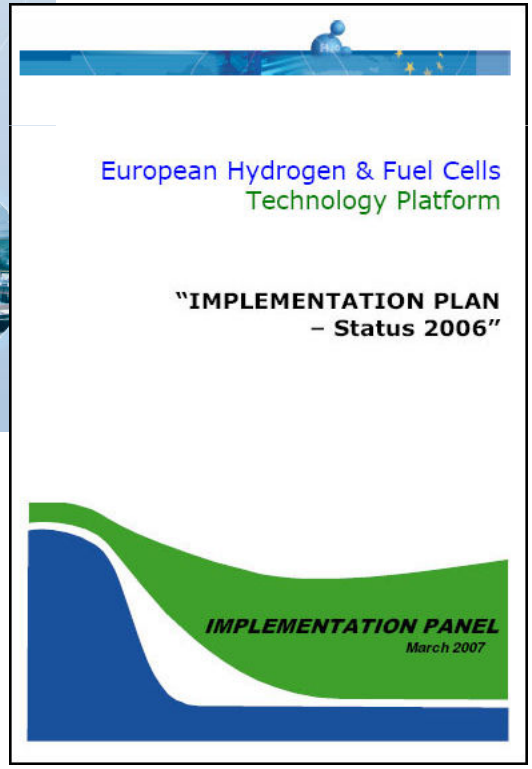
Quote:
By 2050, competitively priced hydrogen is expected to be widely available in industrial nations.
It will not only serve as a major transport fuel but complement electrical power from renewable energy sources in order to match stochastic energy generation and demand.

Vision


Hydropower
Thermal solar
Wind turbine
Biomass
PV plant
H_2
Power generation plant
H_2 production plant
CO_2
Fuel cell plant
H_2
Filling station
Natural gas
Depleted gas well
Deep saline acquifer
HYDROGEN VISION

Strategy

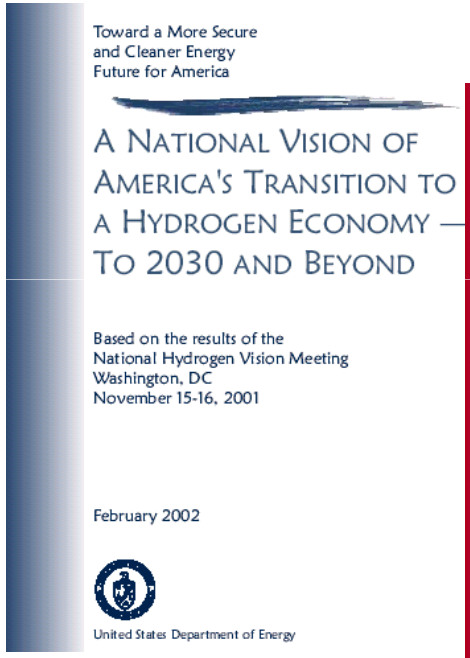
Achieving
the 2050 vision

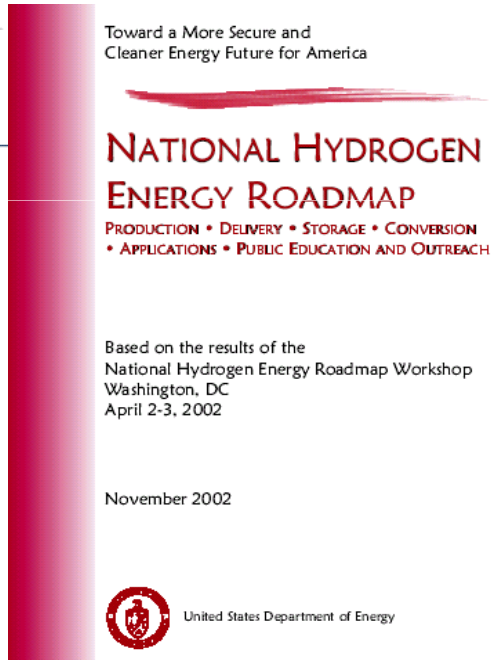


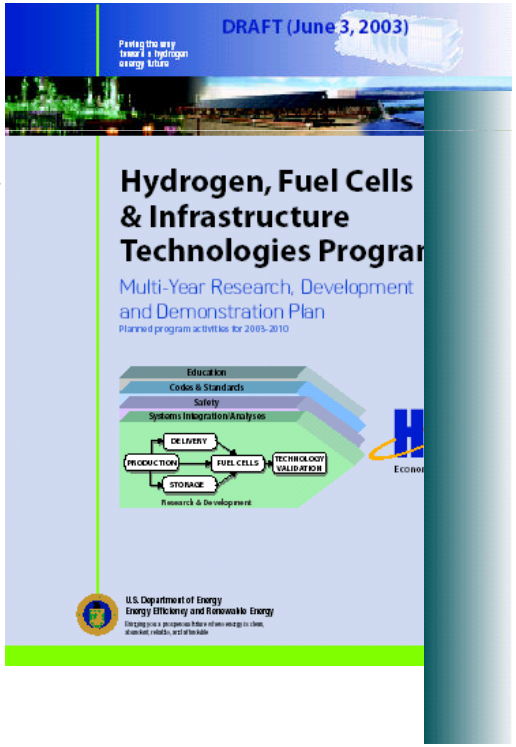
U.S. DOE Hydrogen Activities
Hydrogen, Fuel Cells and Infrastructure Technologies Program

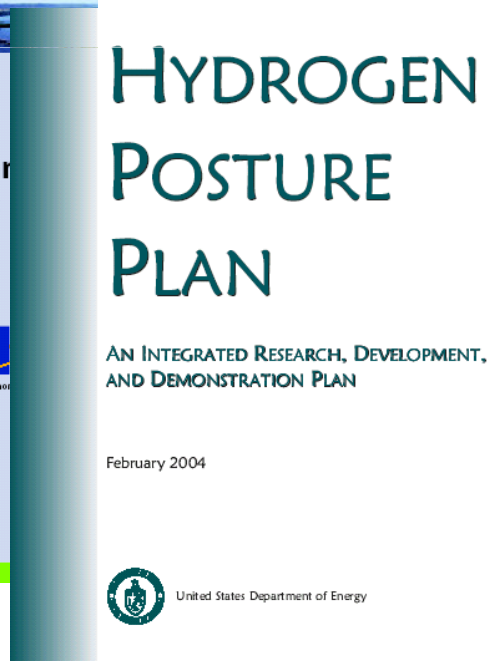
Vision

Strategy









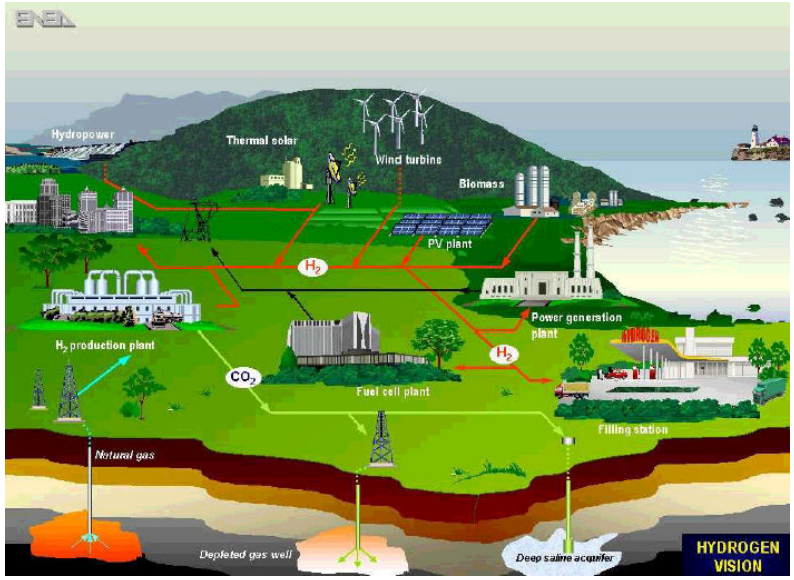
United States
Department of Energy
Science, Technology and Energy for our Future

Countries that have adopted hydrogen strategy or a roadmap:

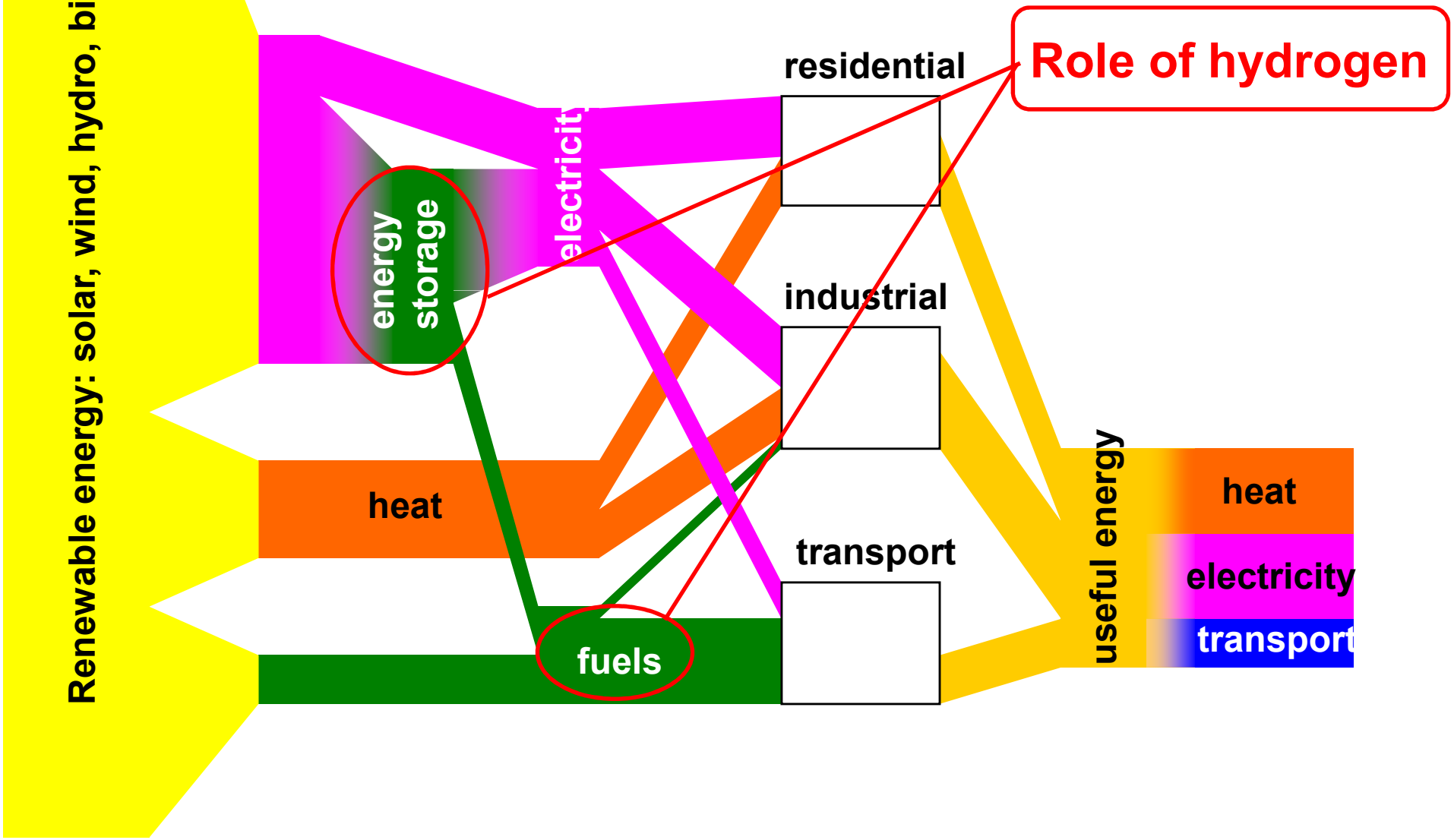
- United States
- European Union
- Canada
- Japan
- China
- India
- Malaysia
- South Africa
- Australia
- Argentina

In which context is there a future for hydrogen?

- There should be an imminent shift in global energy supply from an unsustainable system based on fossil fuels to a new sustainable system
- Renewable energy sources may result in a sustainable energy system
- Renewable energy sources need energy carriers:
  - electricity and hydrogen
- In such a system hydrogen will have a role:
  - solving the problem of variable intensity
  - as fuel for transportation sector
  - as fuel where electricity cannot be used

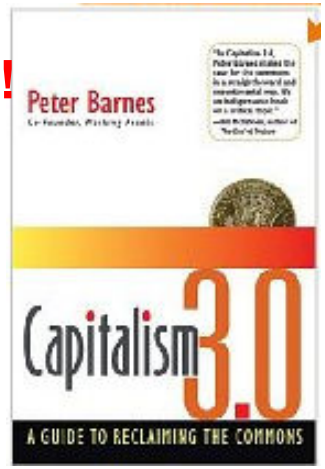


Hypothetical Future Energy System Based on Renewable Energy



How to change an entire energy system?

- There should be no competition – there should be transition
- Transition requires vision and commitment
- Transition may cause economic hardship
- It is not simply a replacement – transition will require a major shift in our mind sets, priorities, culture and life style
  - shift from the goals of continuous growth to the goals of sustainable development !
  - promote energy and resources conservation !
  - give priorities to the protection of the environment !
  - new operating system – Capitalism 3.0 !



Future of Hydrogen

- Future of hydrogen is tightly related to the pace of global energy shift/transition to sustainable (renewable) energy
- Difficulties in transition:
  - renewables do not need hydrogen for initial penetration in the energy market
- Outside the context of global energy shift/transition individual hydrogen technologies may be applied only:
  - where they are economically competitive,
  - where they bring advantage which is more important than immediate financial effect, or
  - as curiosity in various demonstrations.

Evolution of modern civilization