

Fuel Cells

Renewable Energy Working Group
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Fuel Cell: Definition

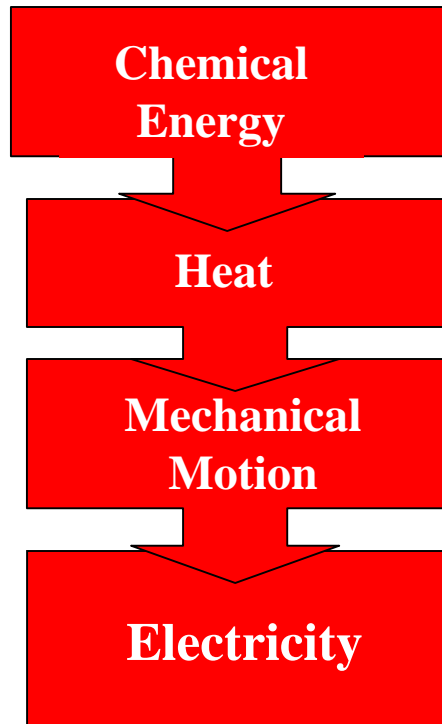
An electrochemical device that converts the **chemical energy** in a fuel directly **to electricity** without the intervening combustion used in a conventional power system

In a typical fuel cell, **hydrogen and oxygen** react electrochemically at separate electrodes, producing **electricity, heat, and water**.



H Power 5 kW
PEMFC Stack

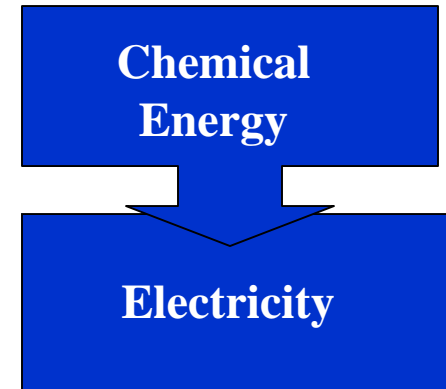
Heat Engine-Generator



Maximum engine efficiency limited by Carnot cycle

$$EFF = \frac{T_2 - T_1}{T_2}$$

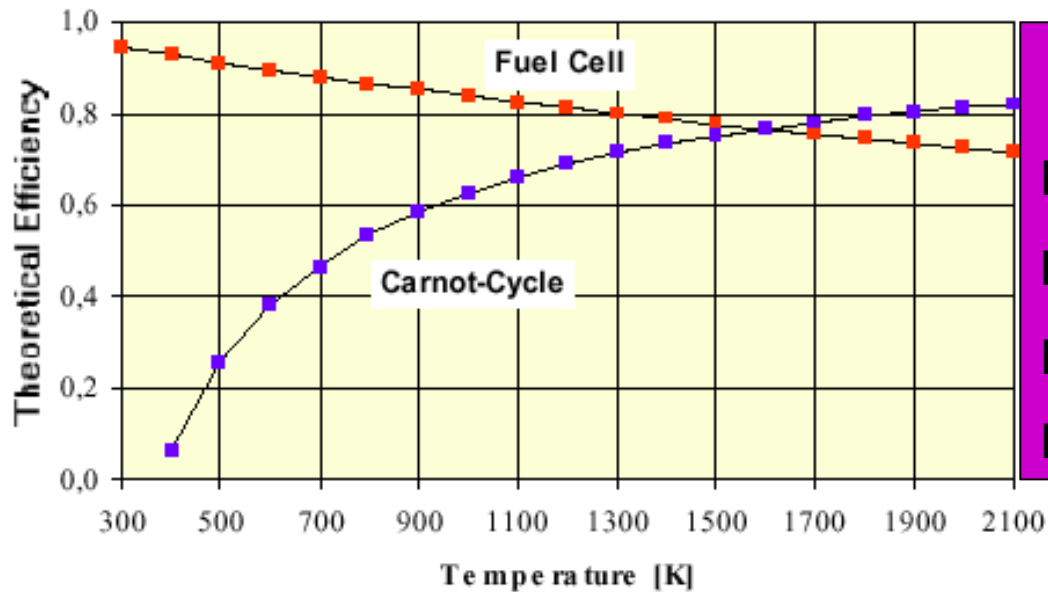
Fuel Cell



Maximum fuel cell efficiency limited by Gibb's free energy

$$EFF = \frac{\Delta G}{\Delta H} = 1 - \frac{T\Delta S}{\Delta H}$$

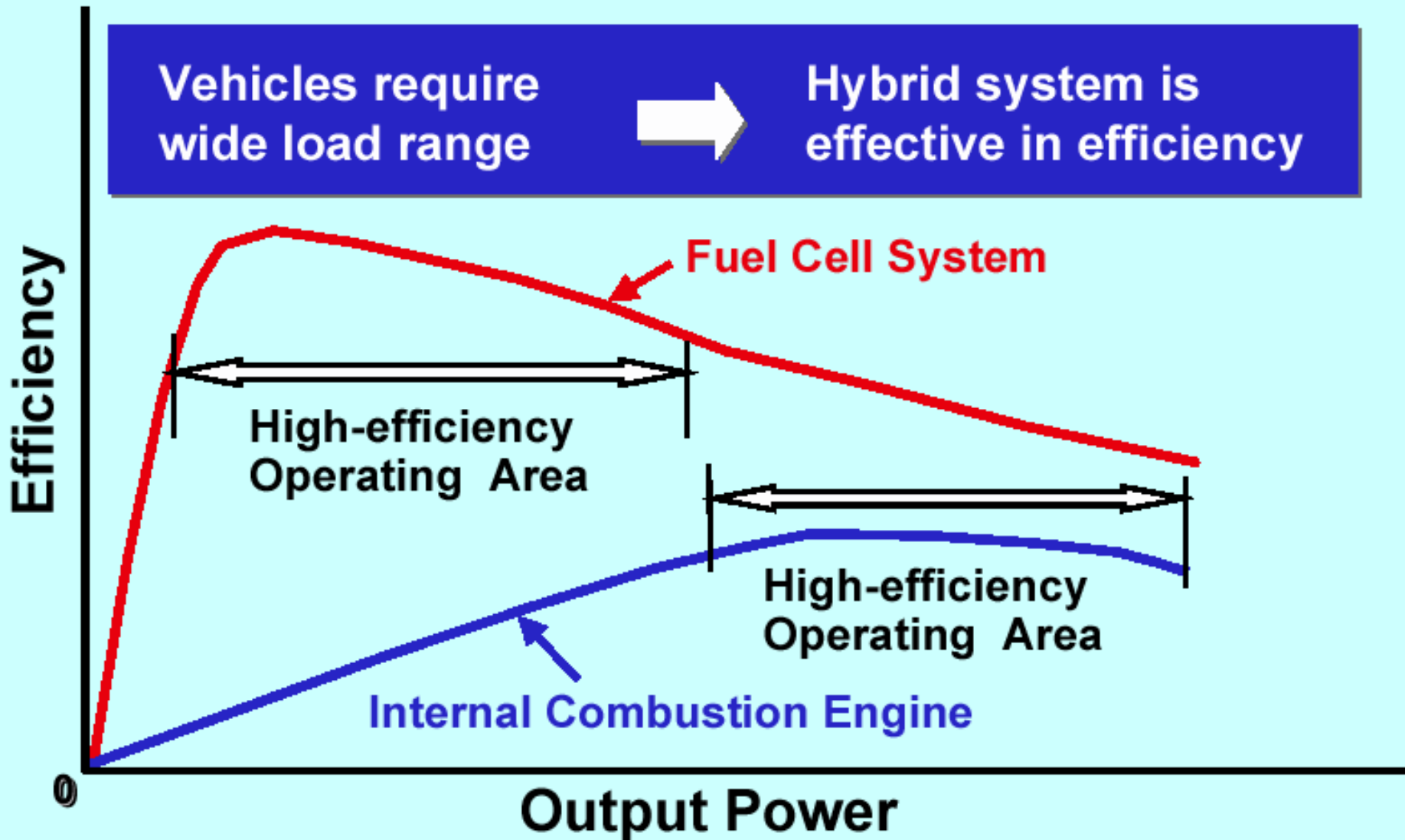
Theoretical Efficiencies



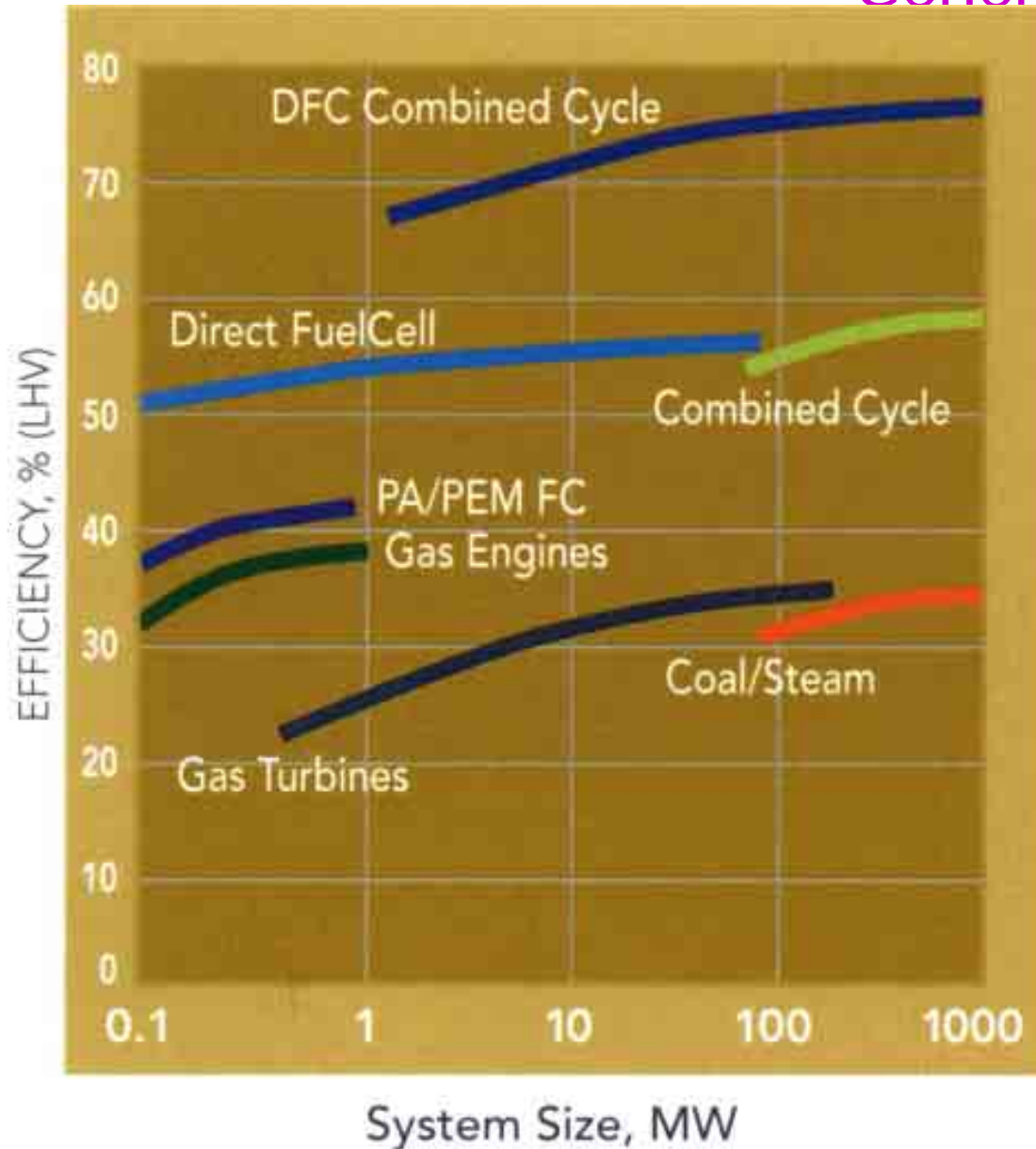
Comparative Efficiencies	
	%
PEM fuel cell - pure H ₂	> 40
Internal Combustion Engine	~20
Diesel	~30
Power plant	~ 20's

$$\text{Fuel Cell EL. Eff.} = V_{\text{eff}} + I_{\text{eff}} + \text{Fuel Utilization}$$

Efficiency Comparison



Comparative Efficiencies for Power Generation Systems



Types of Fuel Cells

Type	Operating Temp. °(C)	Electrolyte	Catalyst	System Efficiency (%)	Size	Start-up Time (hours)	Likely Applications
PEM	60-95	Ion Exchange Membranes	Pt Pt-alloy	32-40	<1 kW – 500 kW	<0.1	<ul style="list-style-type: none"> ▪ Residential ▪ Small Commercial ▪ Automotive
Alkaline	50-100	Mobilized or Immobilized Potassium Hydroxide	Pt Pt-alloy	35-45	<1 kW – 250 kW	<0.1	<ul style="list-style-type: none"> ▪ Space programs ▪ Small commercial ▪ Residential ▪ Automotive
Phosphoric Acid	200-220	Immobilized Liquid Phosphoric Acid	Pt Pt-alloy	36-45	250 kW – 5 MW	1-4	<ul style="list-style-type: none"> ▪ Large Commercial / Industrial ▪ Hospitals
Molten Carbonate	600-650	Immobilized Liquid Molten Carbonate	Nickel	43-55	500 kW – 5 MW	5-10	<ul style="list-style-type: none"> ▪ Large Commercial / Industrial ▪ Power Station
Solid Oxide	800-1000	Ceramic	Perovskites	43-55	5 kW – 3 MW	5-10	<ul style="list-style-type: none"> ▪ Large Commercial / Industrial ▪ Residential ▪ Small Commercial

Alkaline Fuel Cell (AFC)

Advantages

- **Low Temperature (~100 °C)**
- **Low cost assembly and components.**
- **Operational Experience from Space Applications**
- **Excellent O₂ kinetics – high efficiency**
- **Catalyst Flexibility- Ni, Ag, metal oxides, spinels, organometallics and noble metals.**

Disadvantages

- **Pure Hydrogen (CO₂ problem)**
- **CO₂ must be scrubbed from the air.**
- **Limited development for terrestrial uses**



Summary of Fuel Cell Types

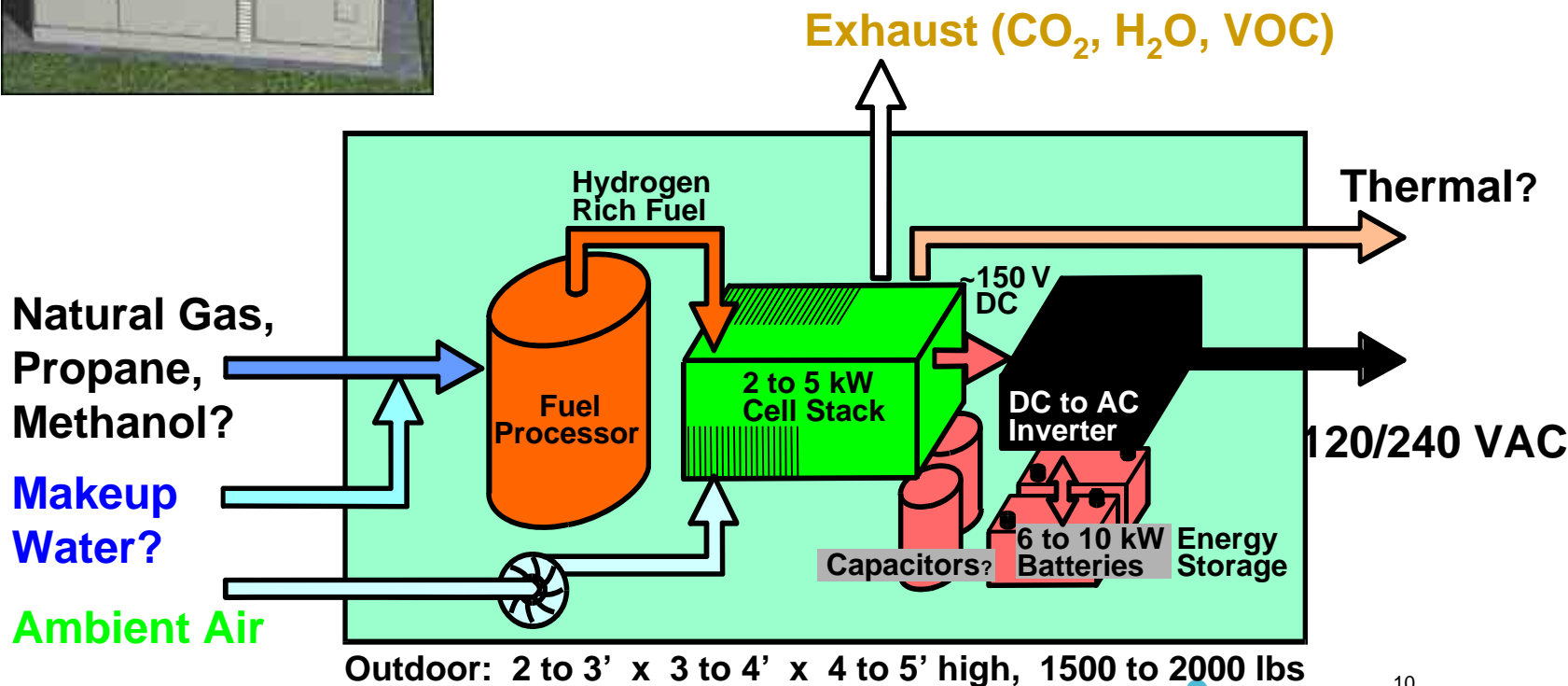
	PEFC/PEM	PAFC	MCFC	SOFC
Electrolyte	Ion Exchange Membrane	Immobilized Liquid - Phosphoric Acid	Immobilized Liquid – Molten Carbonate	Ceramic
Operating Temperature	80°C	200°C	650°C	800-1000°C (600-1000°C)
Charge Carrier	H⁺	H⁺	CO₃⁻³	O⁼
Prime Cell Components	Carbon and metal-based	Graphite-based	Stainless Steel	Ceramic
Catalyst	Platinum (Ru)	Platinum	Nickel	Perovskites
Product Water Management	Evaporative	Evaporative	Gaseous	Gaseous
Product Heat Management	Process Gas + Independent Cooling Medium	Process Gas + Independent Cooling Medium	Process Gas	Process Gas
Natural gas usage	External reformer	External Reformer	(Internal) Reforming	Internal Reforming

Home Power Unit

(PlugPower, www.plugpower.com)



- ✓ Interconnection issues – DER test Bench
- ✓ Combined heat and power - TTF



Phosphoric Acid Fuel Cell (PAFC)

Advantages

- Acid Electrolyte (CO₂ tolerant)
- Medium Temperature (~200°C)
 - CO tolerance
- Atmospheric Pressure
- Commercial Use
- Co-gen possible
 - 65% - 85% efficiency

Disadvantages

- Expensive Catalysts (Pt)
- Graphite plates
- Lifetime



Chugach EA's 1000kW Installation
at Anchorage Post Office

Fuel Cell Power Plant - Efficiency



Grid-connected or Grid-independent

**Thermal Energy
Temperature
140 degree F hot water (60
degree C)**

**Electrical Efficiency 40 %
Total Efficiency (Electric +
Heat) 80%**

**Natural Gas Consumption
1,900 cubic feet per hour**

**Pollutant Emissions
less than 6 ppmv (total)**

Molten Carbonate Fuel Cell (MCFC)

Advantages

- Higher Temperature (~650°C)
- Cheaper Catalysts
- Internal Reforming
- Use CO as Fuel
- Co-gen
- CO₂ tolerant (biogas)

Disadvantages

- Corrosive electrolyte
- CO₂ Required
- Low sulfur tolerance
- Mechanical Stability of components



Solid Oxide Fuel Cell (SOFC)

Advantages

- **Highest Temperature (800°C to 1000°C)**
- **Solid Electrolyte**
- **Ceramic Construction**
- **Fabrication possibilities**
- **Rapid Kinetics**
- **Internal Reforming**
- **Use CO as Fuel**
- **Co-gen possible (heat and electricity = >80% efficiency)**

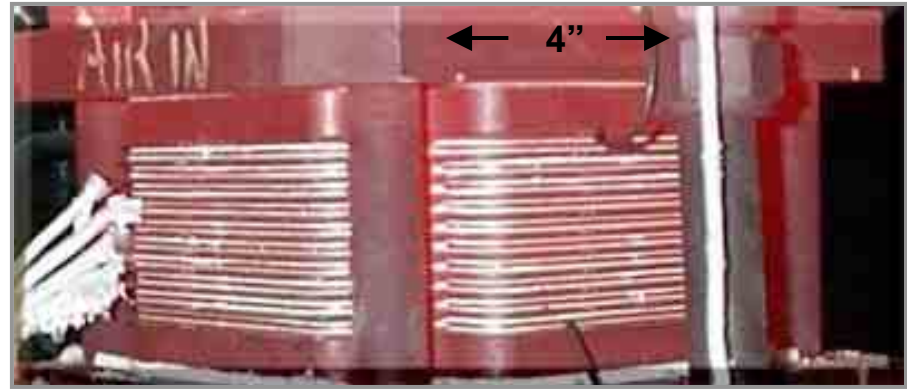
Disadvantages

- **Thermal Expansion (temperature cycling problem)**
- **Sealing**
- **Material Selection**
- **Fabrication**
- **Electrical Resistivity**



Major SOFC Designs - Ceramics

- Tubular
- Monolithic/Planar

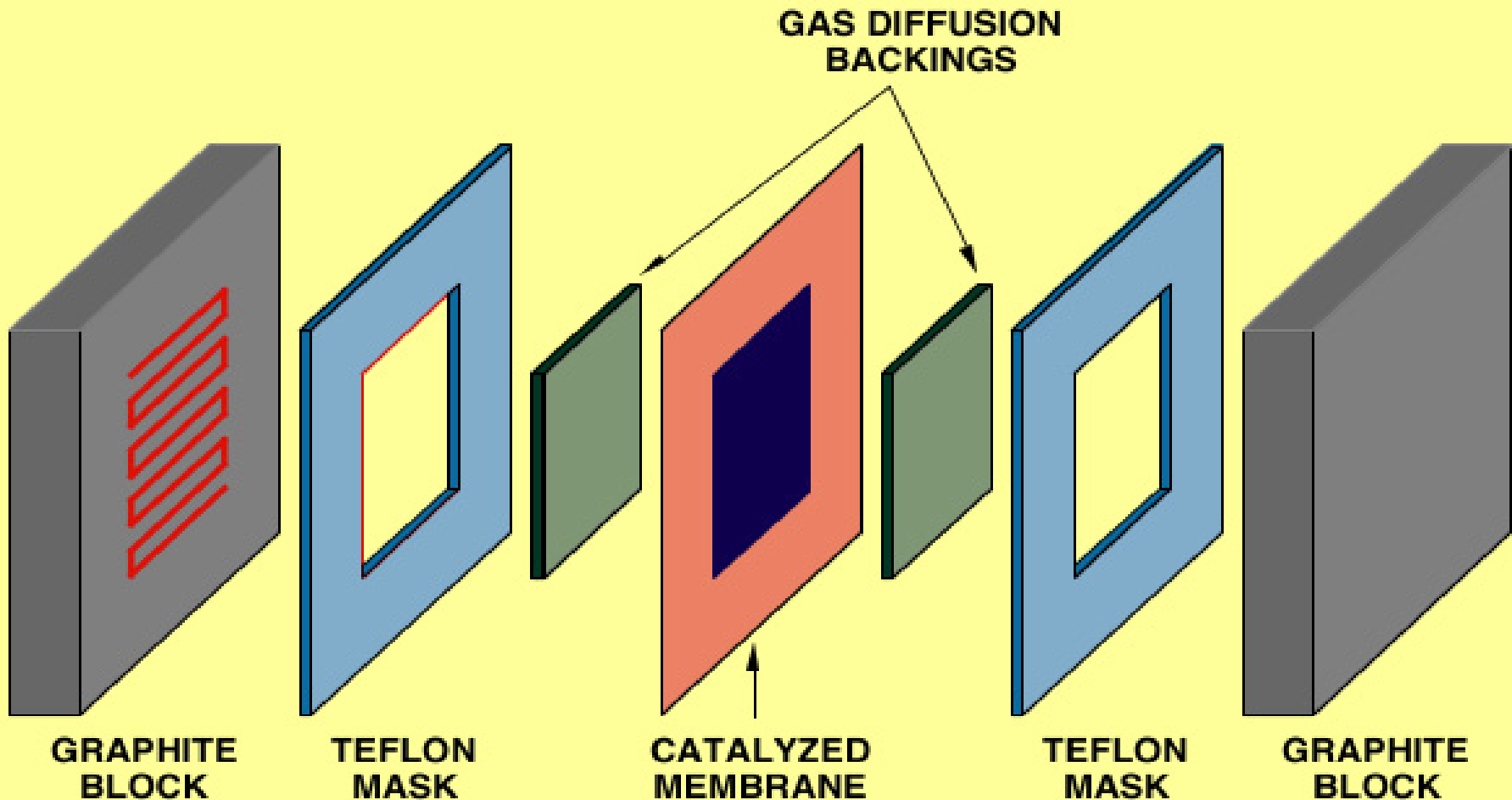


Global Thermoelectric 1 kW Planar Cell Stack running at 1400°F

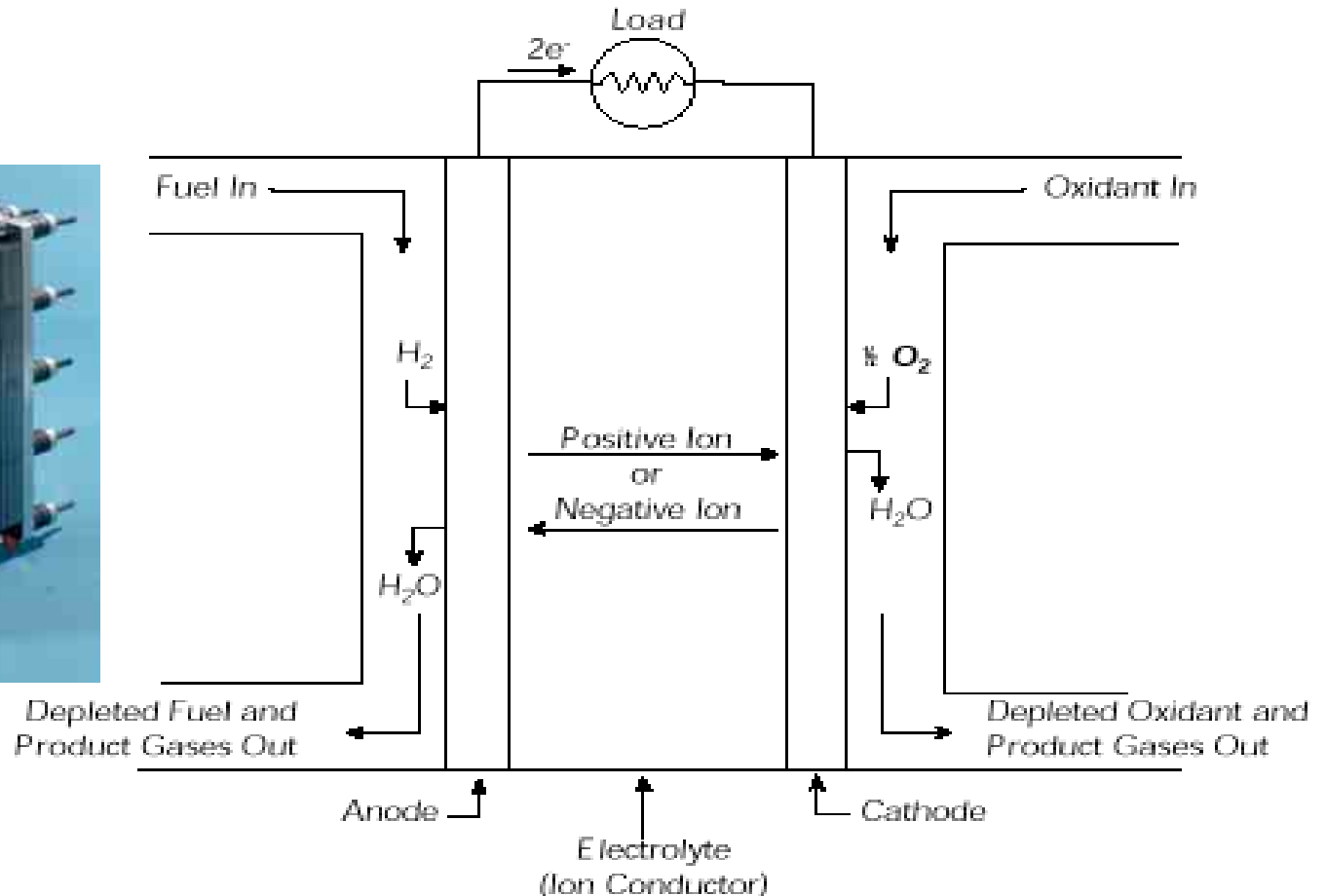
- The different designs represent compromises between cell performance and fabrication issues (true of all the fuel cell technologies).
- Tubular is more mature than the monolithic/planar.

PEM Fuel Cell - Construction

SINGLE CELL HARDWARE

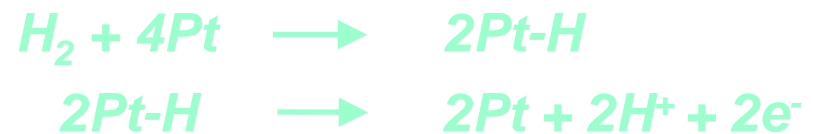
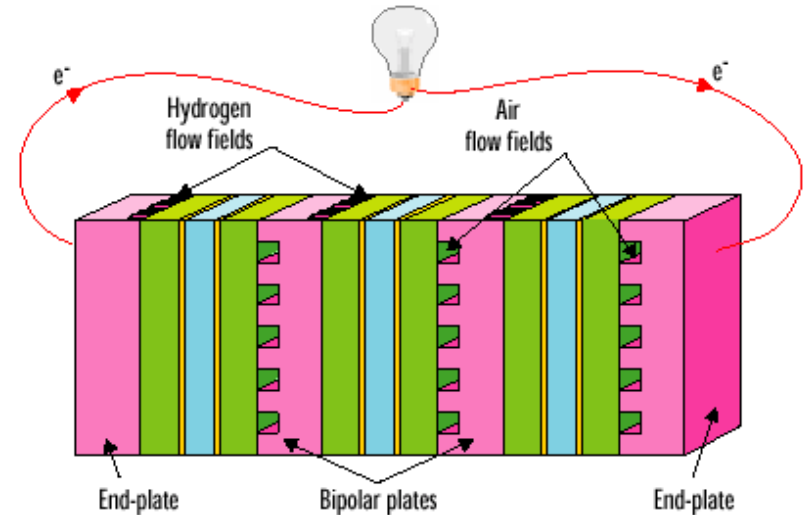


Fuel Cell Schematic



PEM Fuel Cell Attributes

- Polymer Electrolyte Membrane (PEM) Fuel Cell
 - 80°C
 - Power
 - 0.7 V average operation
 - 1 Amp/cm²
 - Stacks formed of multiple cells
 - 150-300 V
- Electrodes (anode, cathode)
 - Porous carbon with platinum (Pt) catalyst (\$)
 - Backing layers porous carbon
- Cooling required
- Water removal with air stream
 - Avoid ‘flooding’ of cathode
 - High flow rate, pressures



California Fuel Cell Partnership Vehicles

Hydrogen-fueled zero-emission vehicles



Clockwise from top left:
Hyundai, Daimler-Chrysler,
Ford, Nissan, Volkswagen,
Honda, GM(center)





Fuel Cell Powered Zero Emission Busses

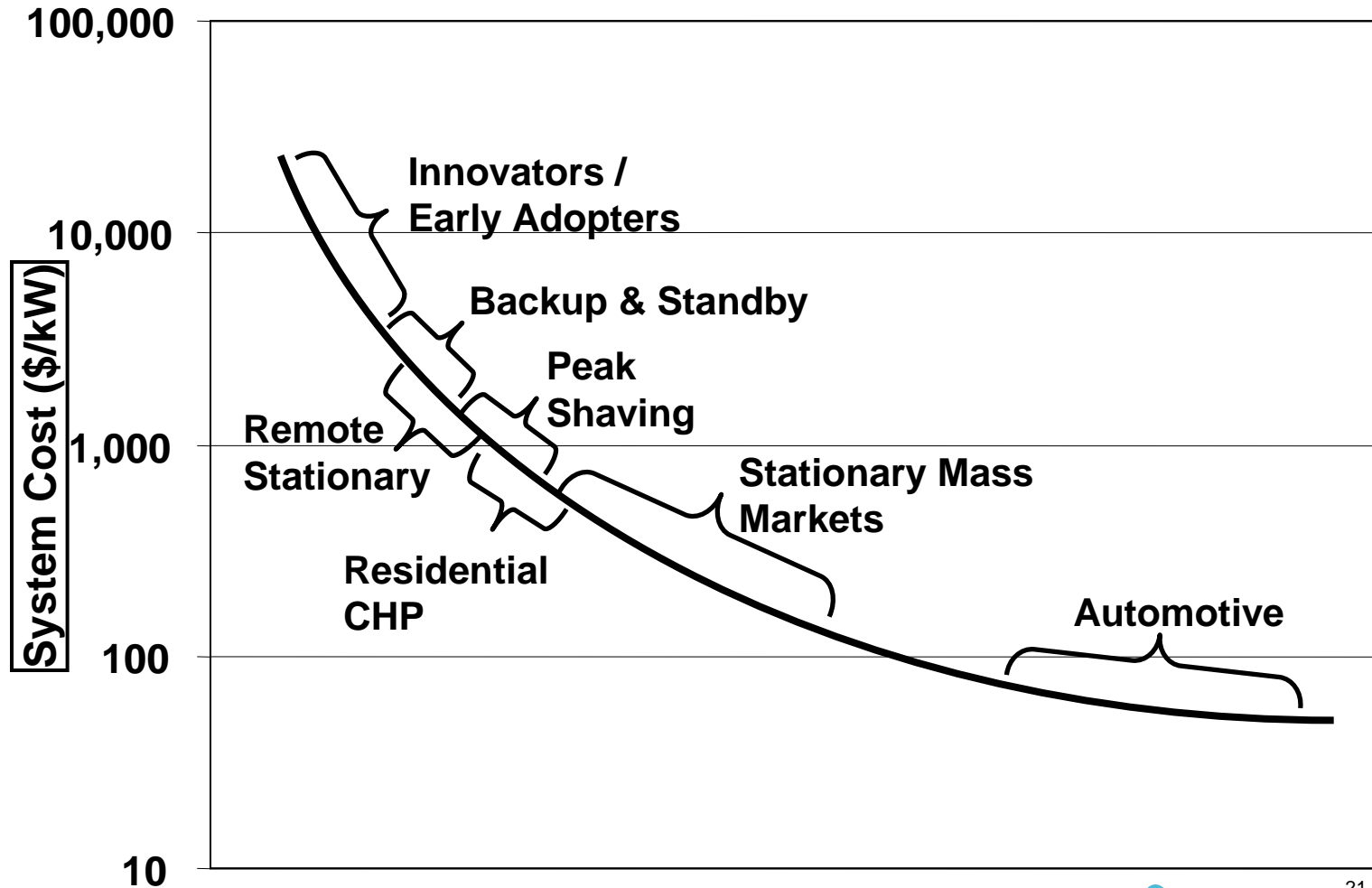


Thor UTC Bus

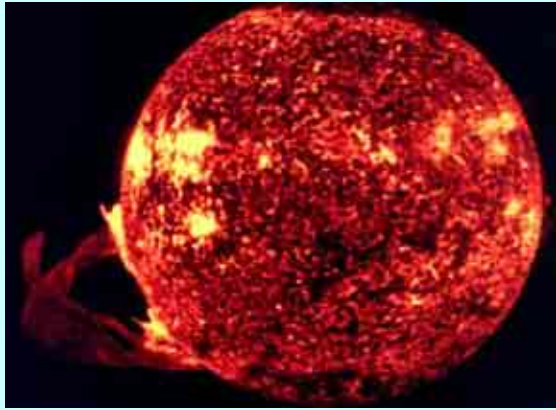


Xcellsis ZEBus

Market Timing / Industry Cost Curve for Fuel Cells

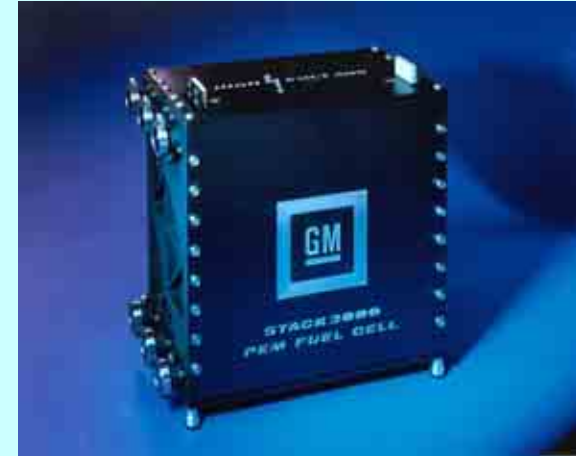
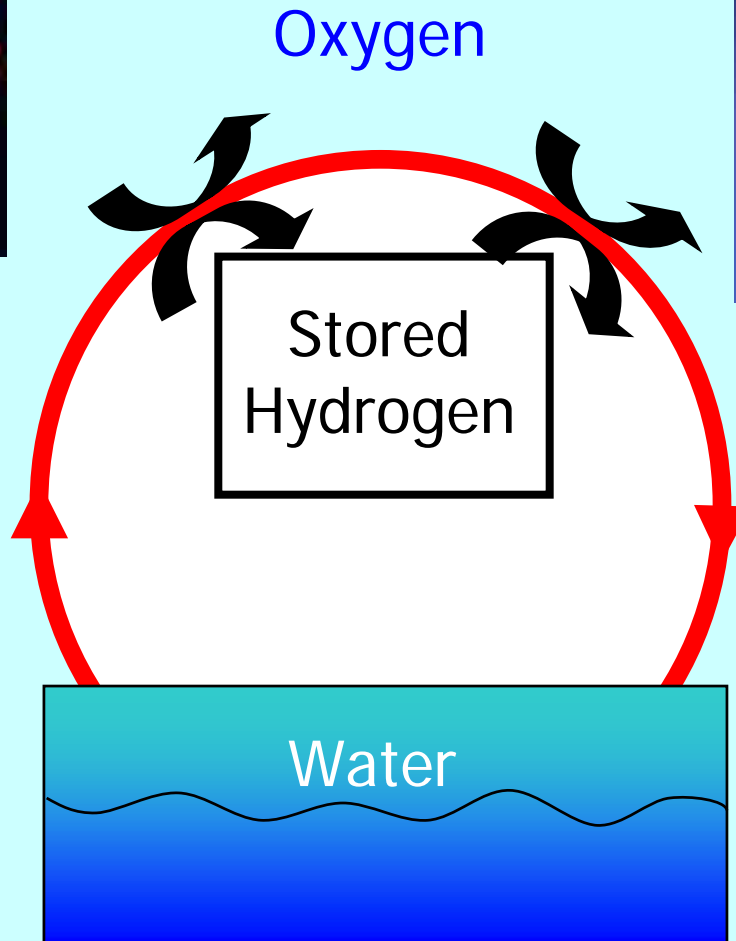


Hydrogen Economy Closed Energy Cycle



Inputs:

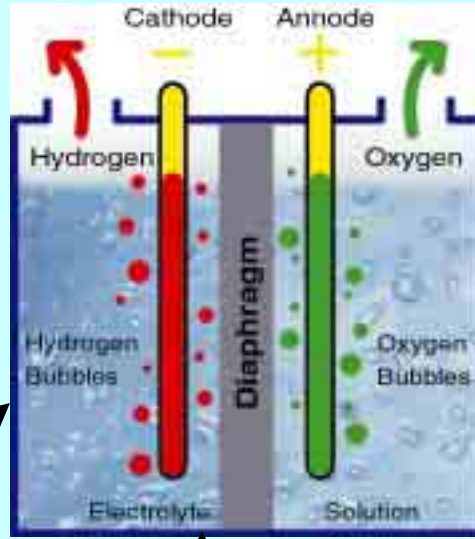
Solar Energy and
Water



Outputs:

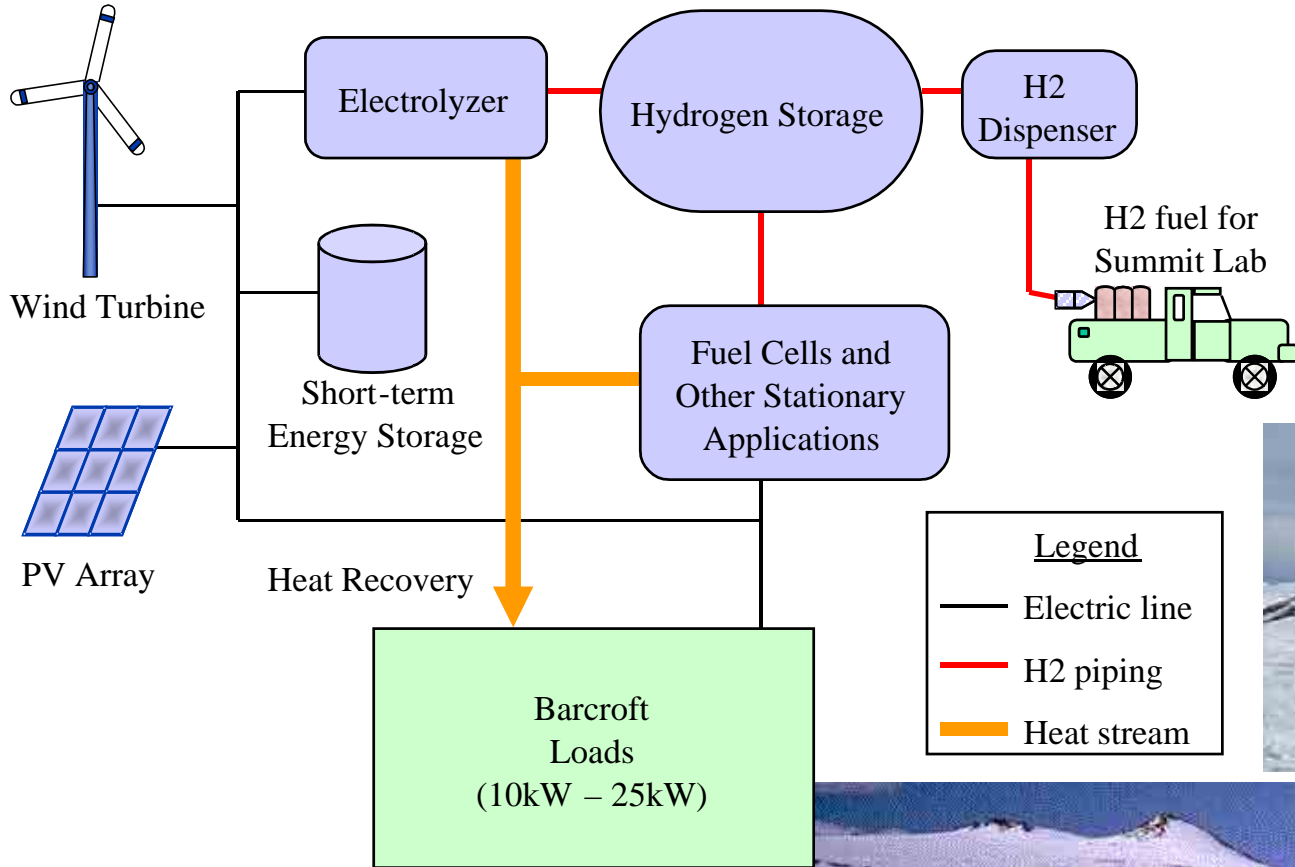
Electricity, Heat
and Water

Renewable Hydrogen Production via Electrolysis



White Mountain Research Station Renewable Hydrogen Energy System

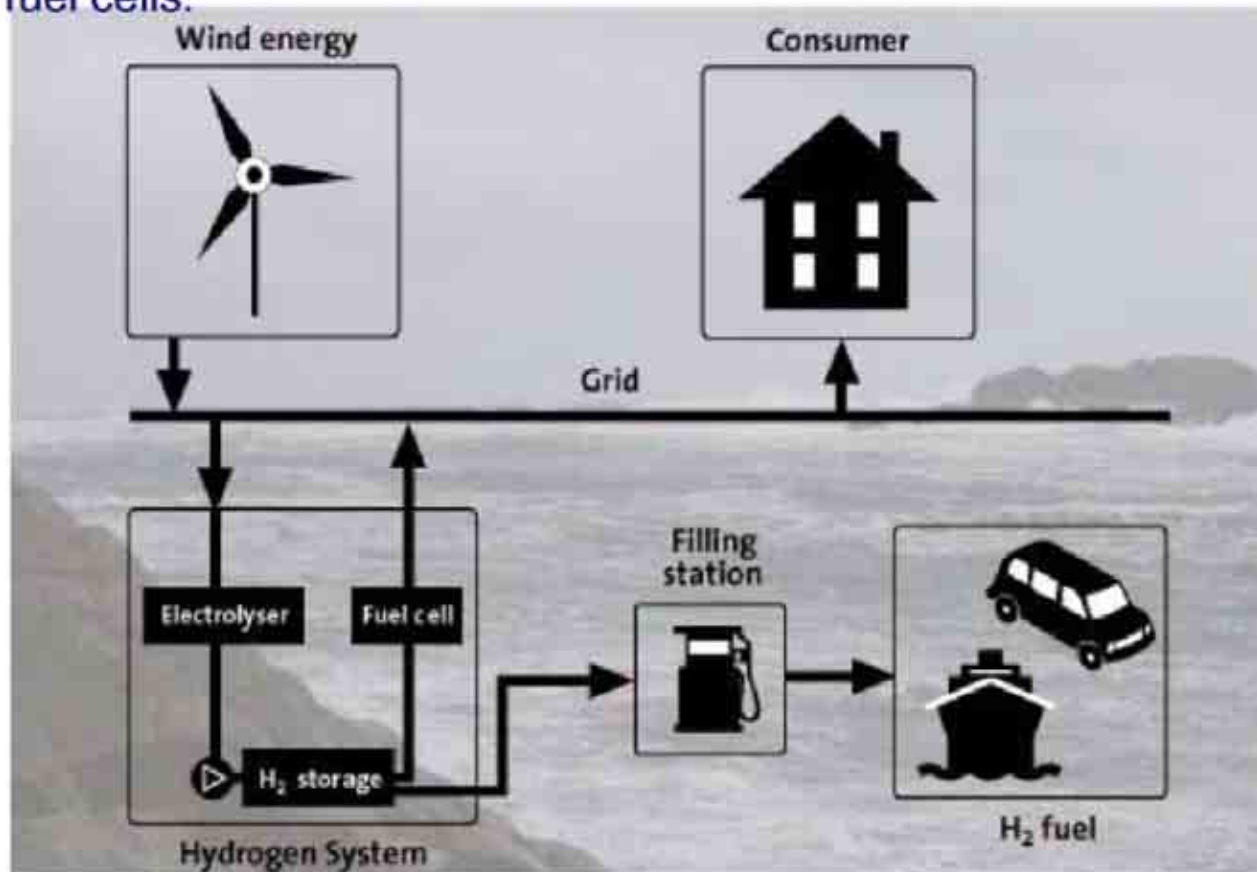
Barcroft Conceptual Design





The wind energy – hydrogen – fuel cell system planned at Utsira

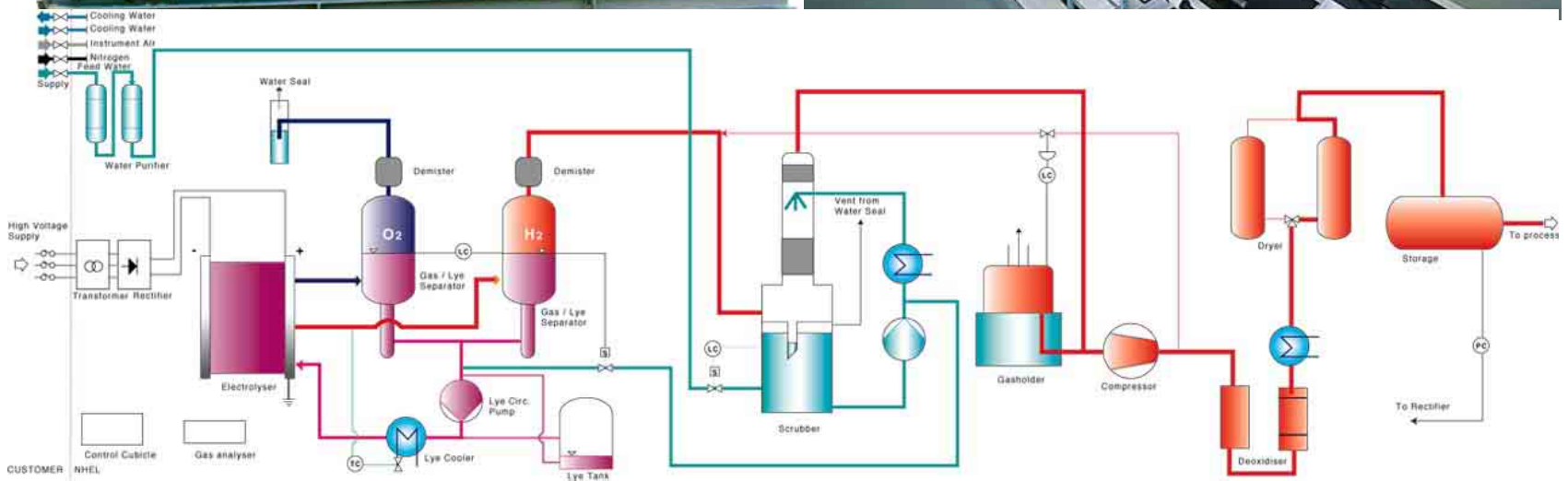
The wind mill connected to the grid will supply consumers with power, but also the hydrogen system consisting of electrolyser, hydrogen storage and fuel cells.



Norsk Hydro Electrolyzers

<http://www.electrolysers.com/> or <http://www2.hydro.com/electro/eng/>

5150 A at
400 V





Sol-Norge

Norge: 324.000 km²



Sol-el-Norge
1400 km² (0.4%)

University of Hawaii's Natural Energy Institute--Hawaii Fuel Cell Test Facility

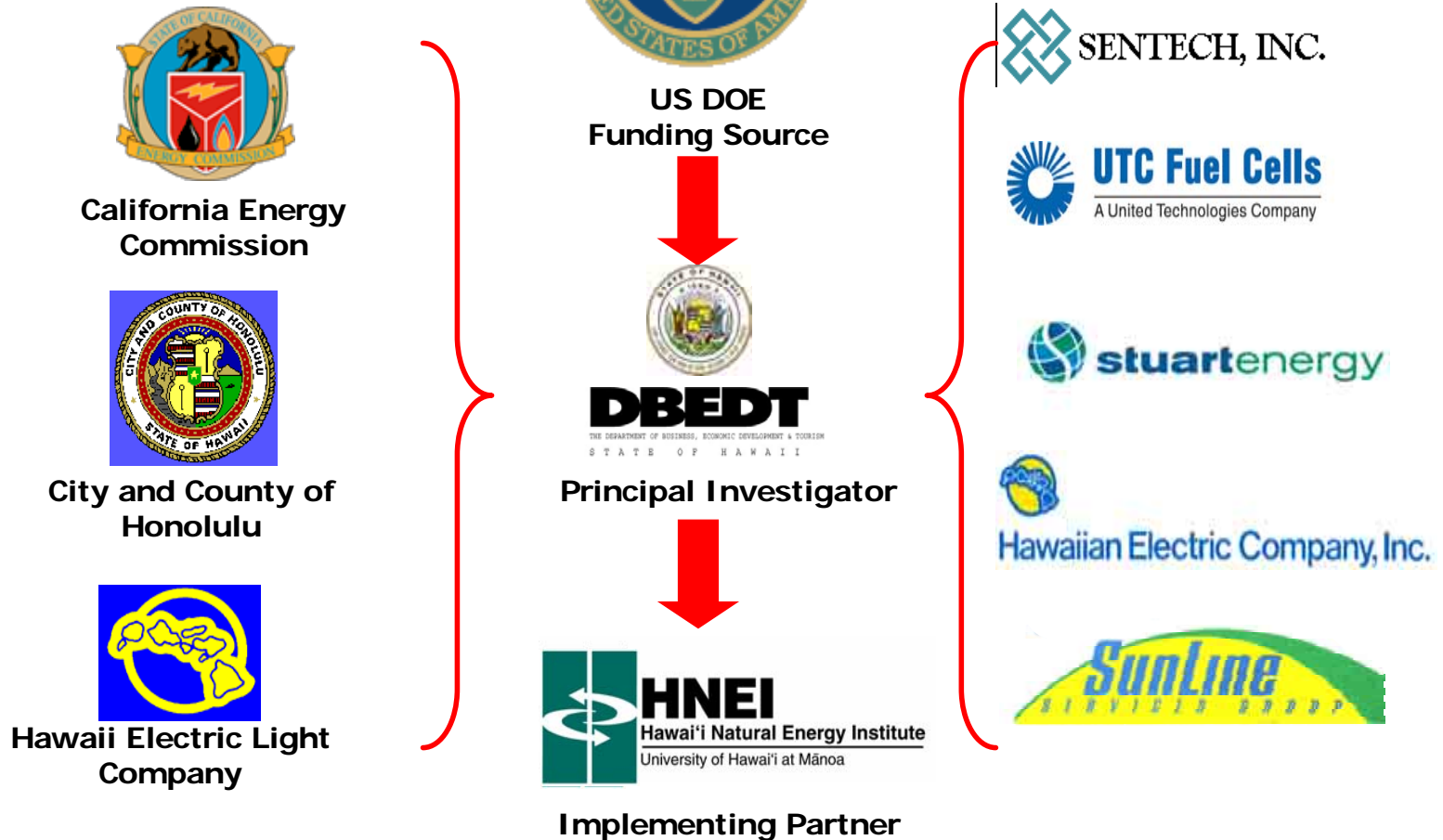


Kapolei Power Park

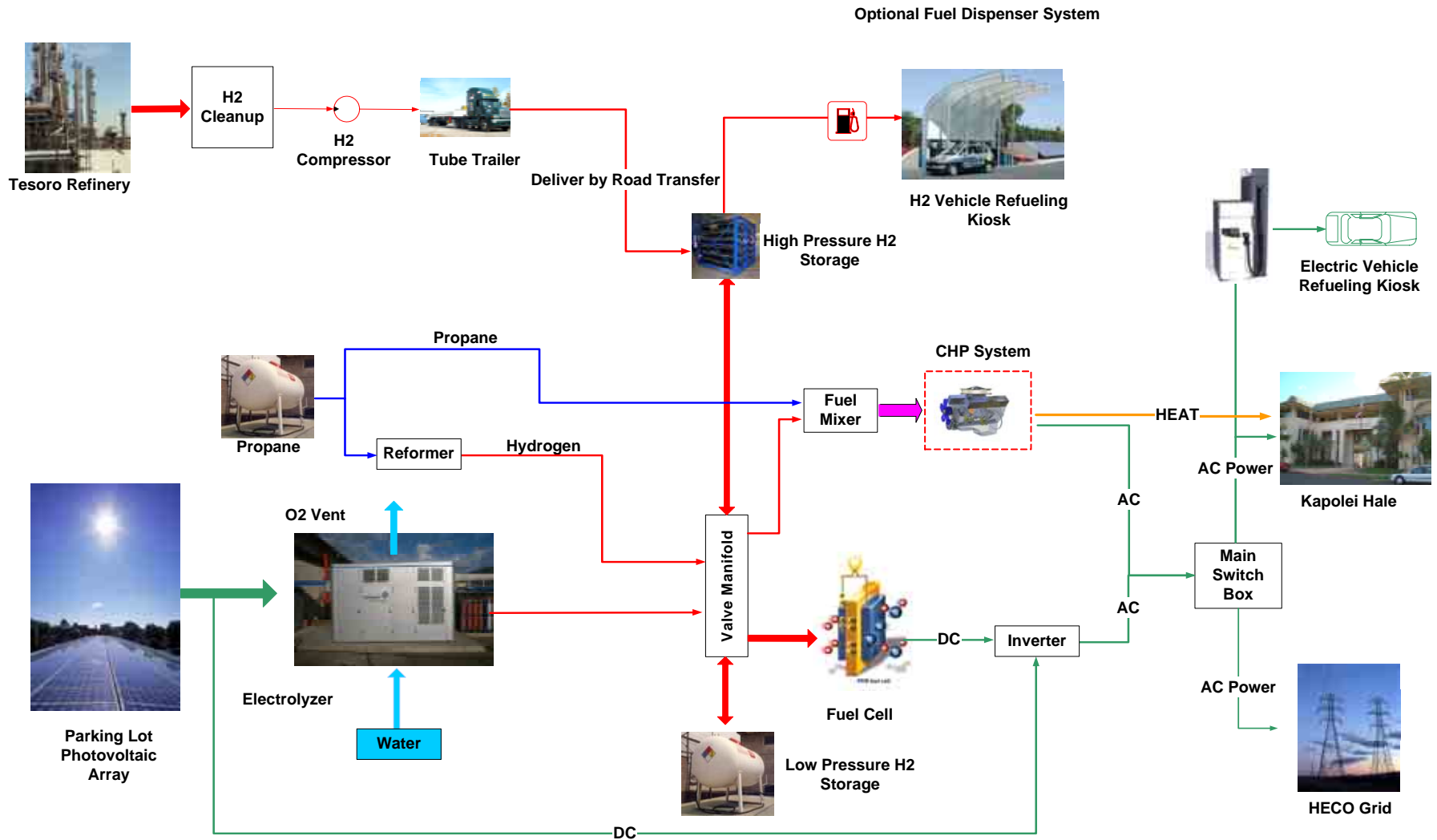


- Renewable energy from parking lot PV solar array
- **Electrolysis for hydrogen production**
- Low & high-pressure hydrogen storage systems
- **Building-connected PEM fuel cells**
- Internal combustion engine providing heat & power to building
- **Hydrogen vehicle refueling kiosk**

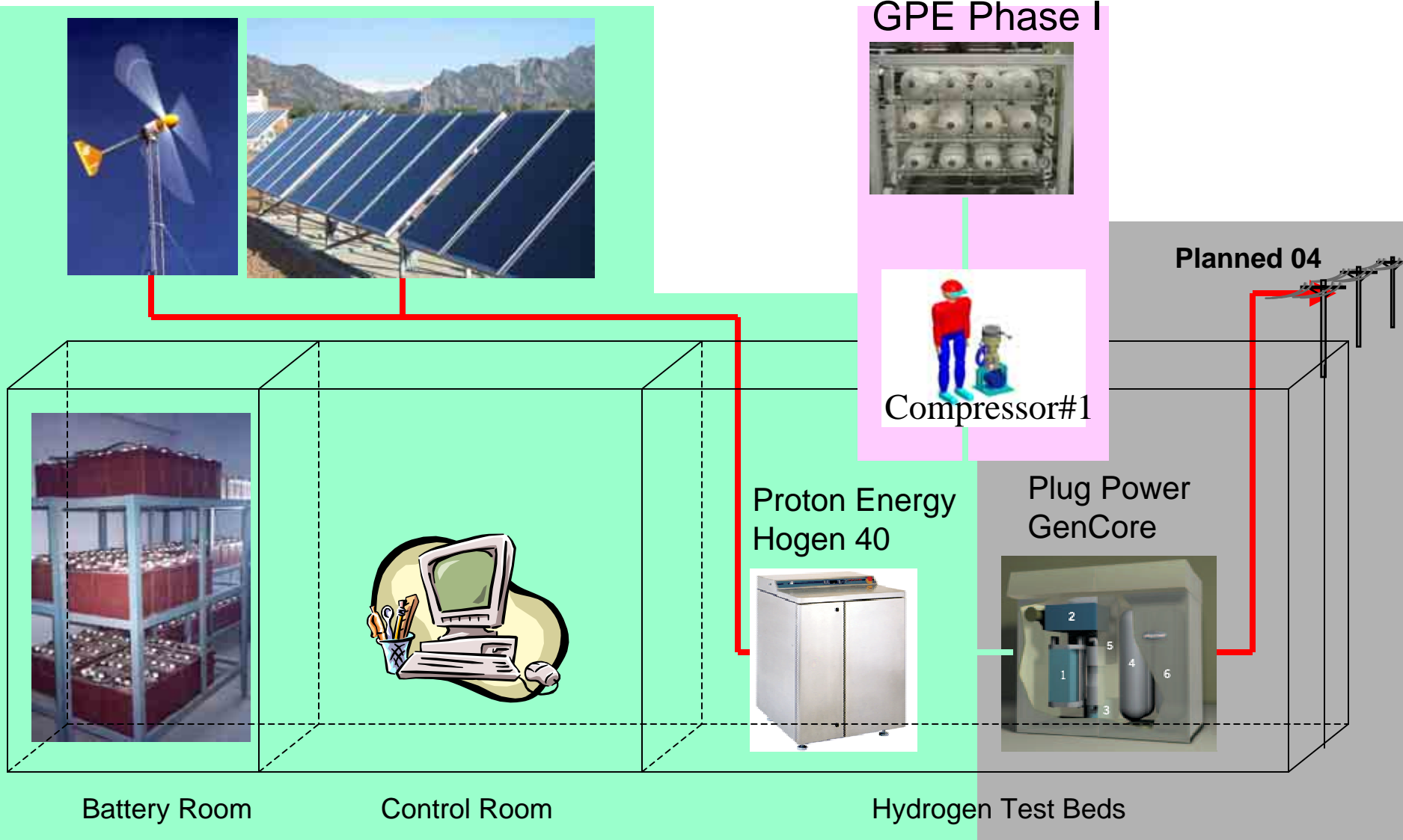
Partners in Kapolei Power Park



Kapolei Power Park Conceptual Design



NREL's Short-Term Plan to Demonstrate Renewable Hydrogen



GPE Phase I



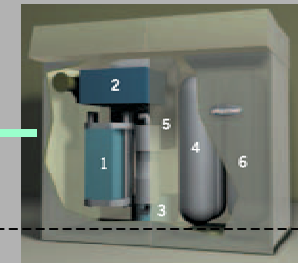
Compressor #1

Planned 04

Proton Energy
Hogen 40



Plug Power
GenCore



Battery Room

Control Room

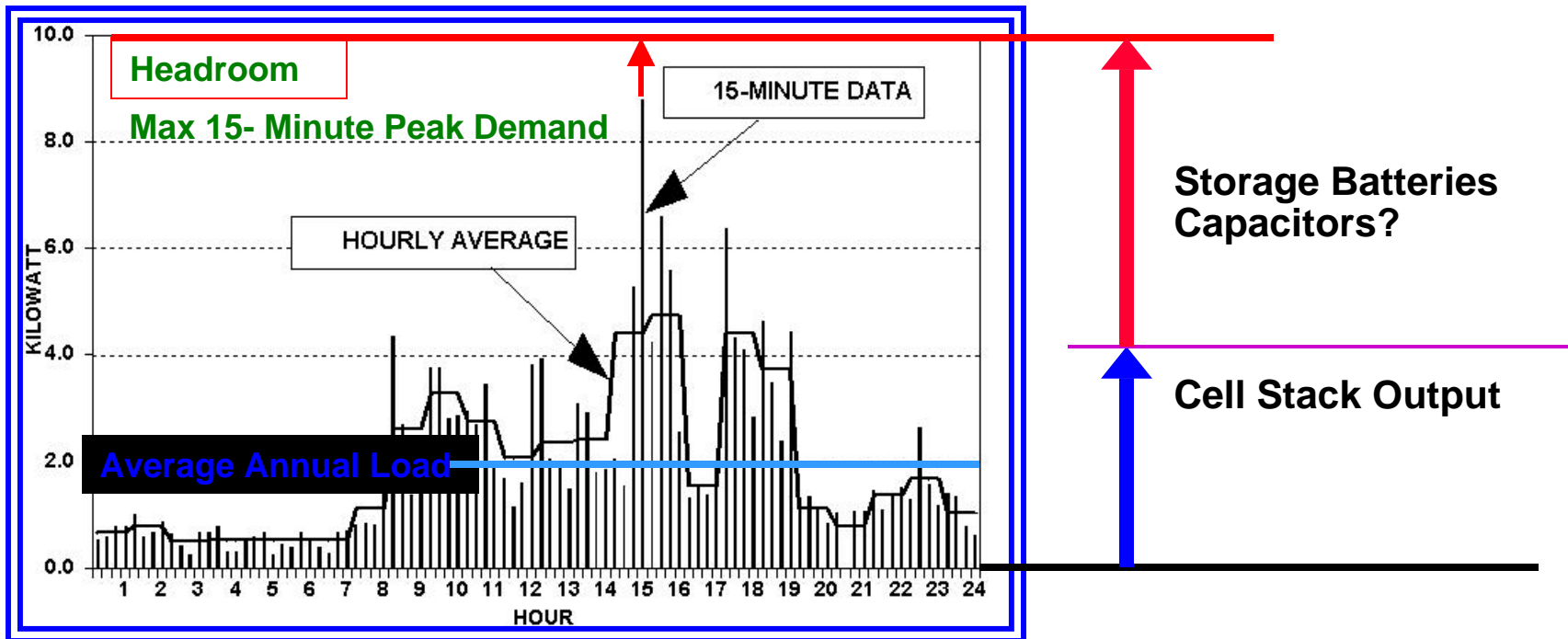
Hydrogen Test Beds

Hydrogen Test Trailer



❖ Design Philosophy:

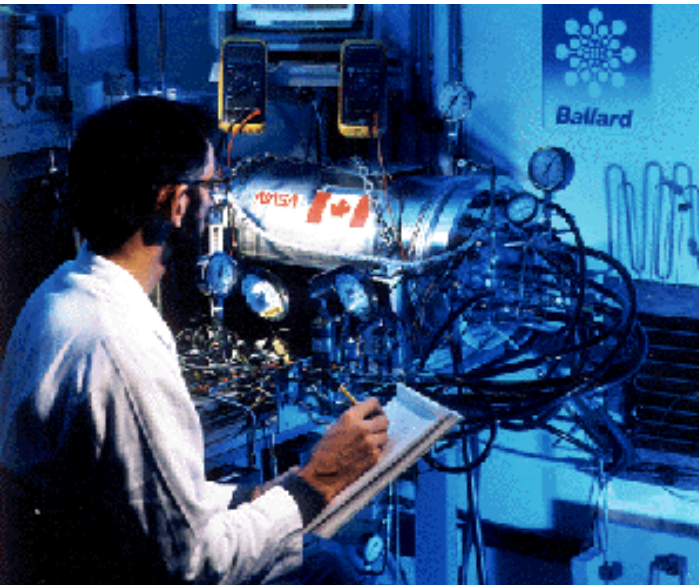
- ❖ Fuel Cell Stack is base loaded
- ❖ Batteries ... charged at night to supply daytime peaks



Cooling Peak Day --Western Utility

Source: Peter Bos, SSFCCG

Regenerative Fuel Cell System Testbed Program for Government and Commercial Applications (1995-1996?)

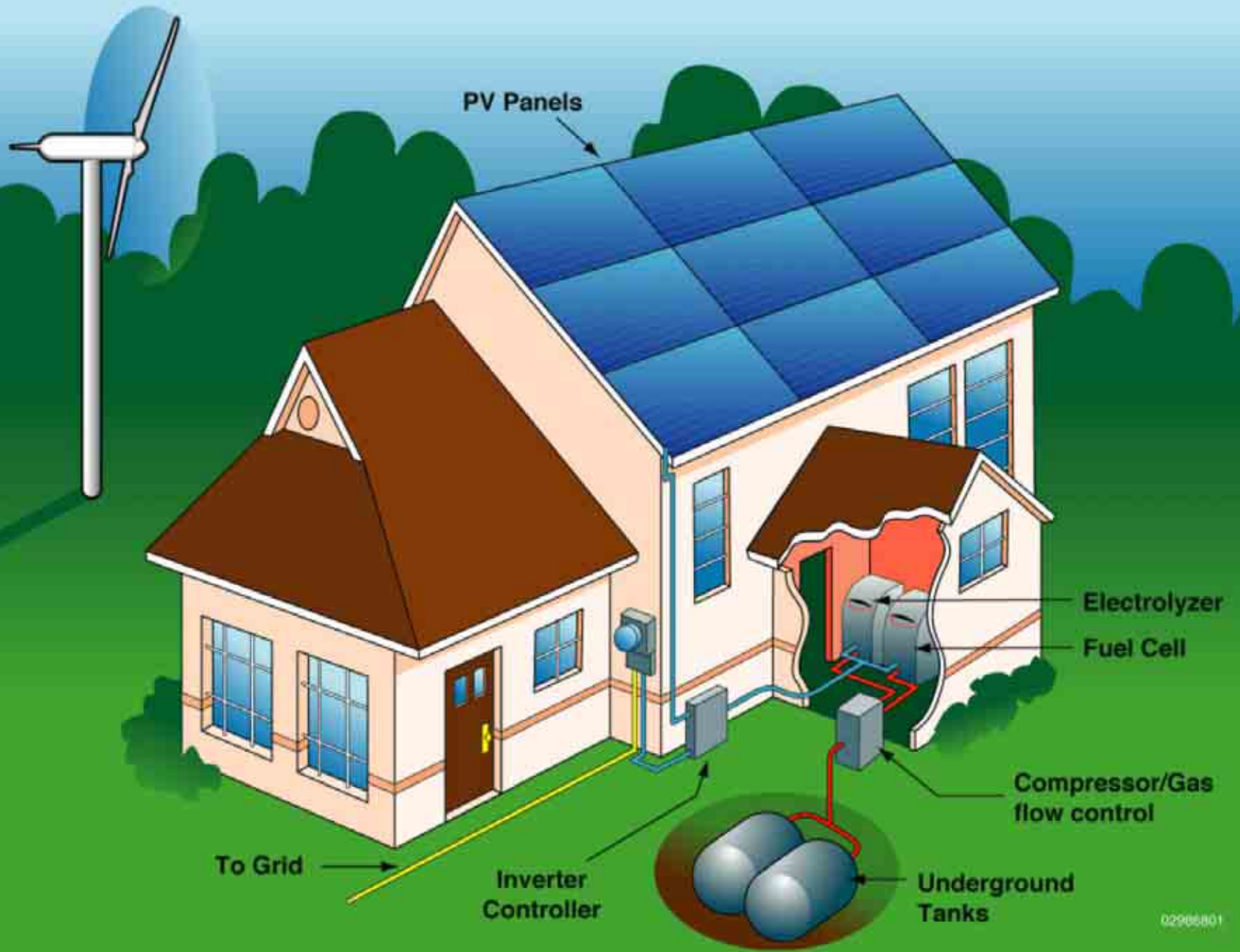


NASA Lewis ([Glenn](#)) Research Center's Electrochemical Technology Branch has led a multiagency effort to design, fabricate, and operate a regenerative fuel cell (RFC) system testbed. Key objectives of this program are to evaluate, characterize, and demonstrate fully integrated RFC's for space, military, and commercial applications. Construction of the 25-kW RFC testbed at the NASA facility at Edwards Air Force Base was completed in January 1995, and the system has been operational since that time.

RFC systems can provide efficient, environmentally benign, highly reliable, renewable energy conversion for a variety of applications. [These systems consist of the following subsystems: fuel cells, electrolyzers, photovoltaic arrays, reactant storage, thermal management, and electrical power management](#)

Fuel Cell Issues

- Cost and availability
- Lifetime and reliability
- Command and control in a dynamic system
- Knowledge of energy demand and energy availability
- Power electronics
- Safety, Codes and standards



The Hydrogen Economy

The production of hydrogen, primarily from water but also from other feedstocks, its distribution and utilization as an energy carrier.

