

# **2006 DOE HYDROGEN PROGRAM**

## **Business Opportunities Concept Project**

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Arizona Public Service  
May 17, 2006

# OVERVIEW

## Timeline

- Started CY: 2003
- Finish CY: 2006
- Percent complete: 90%

## Budget

- Total project funding
  - DOE share: \$784,000
  - APS share: \$2,252,145
- Funding received in FY05: \$1,035,465
- Funding for FY06: \$319,341

## Barriers

- Barriers addressed
  - Cost
  - Emissions
  - Renewable Integration
  - Electricity Cost

## Partners

- BC Hydro
- Southern California Edison
- Sandia National Lab
- Idaho National Lab
- State of Arizona
- Valley of the Sun Clean Cities Coalition

# APPROACH

## Phase I. Tasks 1 & 2

### ***Create Conceptual Models***

Identify potential applications for H2 Parks

Define size and function

## Phase II. Task 3, 4, 6, 7

### ***Validate H2 Pilot Park***

Real world testing of components and function

Performance, efficiency, O& M cost

Safety, reliability, quality, public acceptance

Validate the four Power Park functions

## Phase III. Tasks 2 & 5

### ***Refine Conceptual Models***

Revise Models using actual component performance, cost, emissions and reliability

Engineer and integrate into systems, utility operations and renewable energy

Consider impacts of codes, standards and safety

## Phase IV. Task 5

### ***Identify the Value Proposition***

If possible, implement conceptual model.

# FUNCTIONS of a POWER PARK

## A. Produce Hydrogen

- Distributed electrolysis
- Advanced production methods
- Integration - systems to produce, store and manage

## B. Produce Electricity – Grid Connect and Isolated

- Fuel cells (H<sub>2</sub>)
- ICE gensets (H<sub>2</sub> and Blends of NG/H<sub>2</sub>)

## C. Fuel Motor Vehicles – Private/Public

- Fuel motor vehicles (H<sub>2</sub> and Blends of NG/H<sub>2</sub>)
- Vehicle emissions from H<sub>2</sub> and NG/H<sub>2</sub> fueled vehicles

## D. Incorporate Renewable Energy

- Arizona RPS requires renewable to electricity
- Use of APS grid to move renewable to hydrogen

# PHASE I: CONCEPTUAL MODELS

## ***Project Phase I: Define Potential Power Park Business Models***

### ***Model 1. 1 - 10 Kg/day, 5 Kw FC, Solar PV***

Small, Remote, Energy System or UPS

Applications: Telecom, Roadside Park

### ***Model 2. 20 - 100 Kg/day, 30-100 Kw, Solar PV, Grid***

Vehicle Refueling by dispenser, backup or peaking power by H2 ICE

Application: Vehicle fueling station, fleet or corporate applications

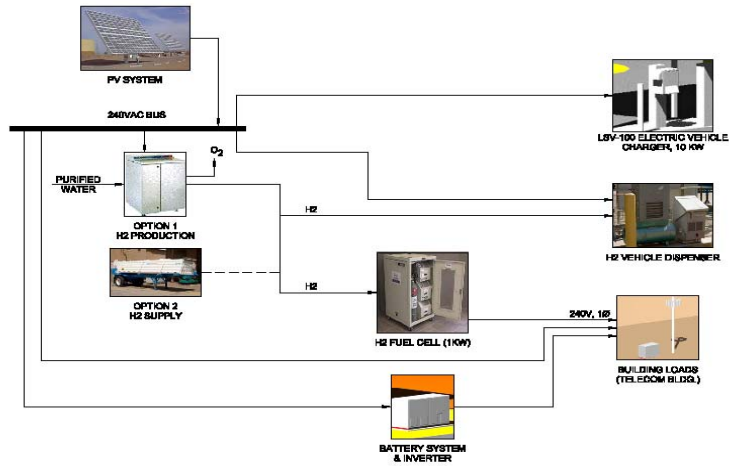
### ***Model 3. 400 - 1500 Kg/day, 400kW - 5 MW, Solar PV Grid***

Application: Utility Distributed Power

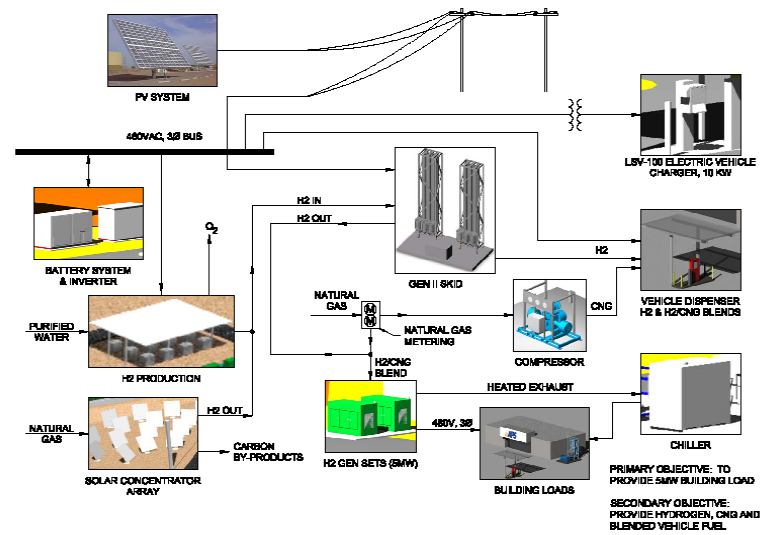
### ***Model 4. Mobile Distributed Power up to 100 kW***

Application: Utility Contingency Power, Feeder Overload

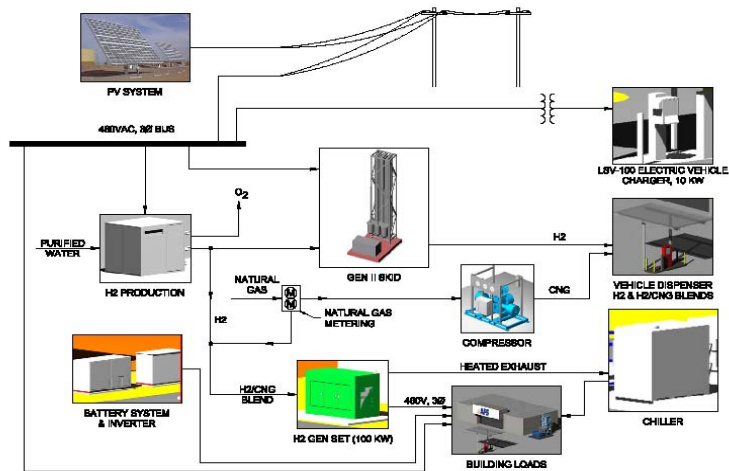
### Model 1. 1 - 10 Kg/day, 5 Kw FC, Solar PV



### Model 3. 400 - 1500 Kg/day, 400kW - 5 MW, Solar PV Grid



### Model 2. 20 - 100 Kg/day, 30-100 Kw, Solar PV, Grid



### Model 4. Up to 100 Kw Mobile



# PHASE II: PERFORMANCE TESTS COMPLETED

- Proton H2 Electrolysis Unit 318 scfh
- Proton H2 Electrolysis Unit 220 scfh
- Plug Power 5 kW Fuel Cell (4 – units)
- Hydrogen Bromine 10 kW Stack
- Onan Genset (100 kW):
  - H2 with 50% EGR NOx control
  - H2 with lean burn ignition control
  - 30/70 CHYNG blend
- Ford 5.4L V8 H2 ICE (2 supercharged variations)
- Vehicle Emissions Testing (FTP drive cycle)
  - F150 high-boost, super-charged H2 fueled
  - F150 low-boost, super-charged H2 fueled
  - Silverado Natural aspiration H2 fueled
  - F150 low-boost, super-charged 30/70 blend fueled
  - Dodge power wagon natural aspiration 15/85 blend fueled

# IN THE HISTORIC DISTRICT IN DOWNTOWN PHOENIX

*Classified as an indoor hydrogen facility in a historic building*





# PHASE II: H<sub>2</sub> PILOT PARK FUNCTION VALIDATIONS

## ➤ **Hydrogen Production**

- 8,261 Kg of H<sub>2</sub> produced by distributed electrolysis

## ➤ **Fuel Motor Vehicles**

- 438 H<sub>2</sub> fueling events
- 3,495 H<sub>2</sub> blend fueling events (15%, 20%, 30%, 50% H<sub>2</sub> with CNG)
- 9,730 total fueling events (including CNG)
- Credit card transactions to procure motor fuel.
- Taxis cabs, police vehicles, fire department vehicles, general public, fleet vehicles

## ➤ **Produce Electricity**

- 47,000 kilowatt hours of electricity

## ➤ **Renewable Energy Integrated**

- 7 kW Photovoltaic Array



**“0” ZERO – accidents, near-misses, equipment damage, a perfect Safety Record**

# PHASE II: COMPONENTS INTEGRATED AND TESTED IN PILOT PARK

<b>Qty.</b>	<b>Description</b>
3	Electrolysis Units
4	Fuel Cells
2	Hydrogen Compressors
1	Nitrogen System
3	10-Ton Chillers
1	Hydrogen Dryer
2	RO/DI Water Purification Systems
1	70 kW – H2 ICE Genset
3	ICE Vehicles Converted to H2
1	7 kW – H2 ICE Genset
1	50 kW – H2 ICE Genset
1	100 kW – H2/NG (30/70%) ICE Genset
2	ICE vehicles converted to blend of hydrogen and natural gas
9	Hydrogen Mass Flow Meters
7	Hydrogen Pressure Regulators
11	Hydrogen Pressure Transmitters
2	6,000 psi Micron Hydrogen Filters
2	Fuel Dispensers

<b>Qty.</b>	<b>Description</b>
15	Hydrogen Check Valves and Safety Valves
1	APS H2/CNG/CHyNG Fuel Dispenser
2	Credit Card Systems
3	ASME H2 Pressure Vessels
2	Hydrogen Fire Systems
1	Helium System
1	Sprinkler System
15	Carbon Composite DOT Pressure Vessels
1	10 kW HBr Cell Stack
1	7 Kw Solar Array – Flat Plat Horizon
35	10,000 psi Swagelok H2 Valves
15	6,000 psi Parker H2 Valves
2	10,000 psi Butech H2 Valves
1	Metal Hydride Canister Fueling System
2	Metal Hydride Canisters for Small Fuel Cell
Lots of H2 hoses, break-a-ways, and nozzles	
Lots of 316SS O2 cleaned tubing and fittings	
Tube trailers 120,000 scf to 300,000 scf	

# PHASE II: EFFICIENCY CALCULATIONS

<b>Electrolysis Efficiency</b>	$\frac{FM102 \text{ (scf)} / 414 \times 33.34}{\text{Electrolysis kilowatt hour usage}}$
<b>H2 Dryer Efficiency</b>	$\frac{FM103 \text{ (scf)} / 414 \times 33.4}{\text{Dryer kilowatt hour usage} + FM102/414 \times 33.4}$
<b>H2 Compressor Efficiency</b>	$\frac{FM106 \text{ (scf)} / 414 \times 33.4}{\text{Compressor kilowatt hour usage} + FM106/414 \times 33.34}$
<b>RO/DI System Efficiency</b>	$\frac{\text{RO system Flow Out (gallons)}}{\text{Water Flow Line In (gallons)}}$
<b>H2 ICE Genset Efficiency</b>	$\frac{FM115 \text{ (H2 Kg)} \times 33.4}{\text{Kilowatt-hours from Genset}}$
<b>H2 Fuel Cell Efficiency</b>	$\frac{FM 116 \text{ (H2 Kg)} \times 33.4}{\text{kilowatt hours DC out (net)}}$

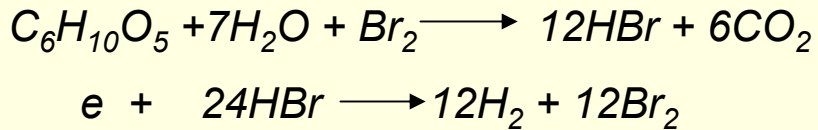
# PHASE II: H<sub>2</sub> PILOT PARK COMPONENT OPERATION RESULTS

<b>Equipment</b>	<b>Reliability (Annual hrs-Force outage hrs)</b>	<b>Quality (Mission)</b>	<b>Safety (Risk Assessment)</b>	<b>Annual Maint Hrs</b>	<b>Efficiency</b>
<i>Proton 318</i>	99+%	99.9997	100%	4	41%
<i>Proton 220</i>	95%	99.9997	100%	5	42%
<i>PDC (5 scfm)</i>	99%	100%	100%	8	92%
<i>PDC (40 scfm)</i>	99%	100%	100%	8	92%
<i>Electrodryer</i>	100%	100%	100%	2	83%
<i>Water DI/RO</i>	95%	100%	100%	12	8%
<i>ASME Vessels</i>	100%	100%	100%	0	NA
<i>H2 Safety Valves</i>	100%	100%	100%	0	NA
<i>H2 Control Valves</i>	100%	100%	100%	2	NA
<i>H2 Block Valves</i>	70%	80%	70%	16	NA
<i>H2 Combustible Gas</i>	75%	75%	75%	16	NA
<i>H2 UV/IR Scanner</i>	100%	100%	100%	4	NA
<i>N2 System</i>	90%	75%	95%	8	NA
<i>H2 Mass Flow Meter</i>	100%	100%	100%	1	NA
<i>5000 psi Carbon Tank</i>	100%	100%	100%	0	NA
<i>Plug Power #1</i>	25%	25%	100%	<i>Poor</i>	46%
<i>Plug Power #2</i>	95%	99%	100%	6	46%
<i>Plug Power #3</i>	25%	25%	100%	<i>Poor</i>	46%
<i>Plug Power #4</i>	25%	25%	100%	150	46%
<i>Onan Genset</i>	90%	75%	100%	24	28%
<i>OPW H2 Nozzle</i>	100%	95%	100%	1	NA
<i>OPW H2 Break-away</i>	100%	100%	100%	1	NA
<i>TESCOM H2 soleniod</i>	100%	100%	100%	0	NA

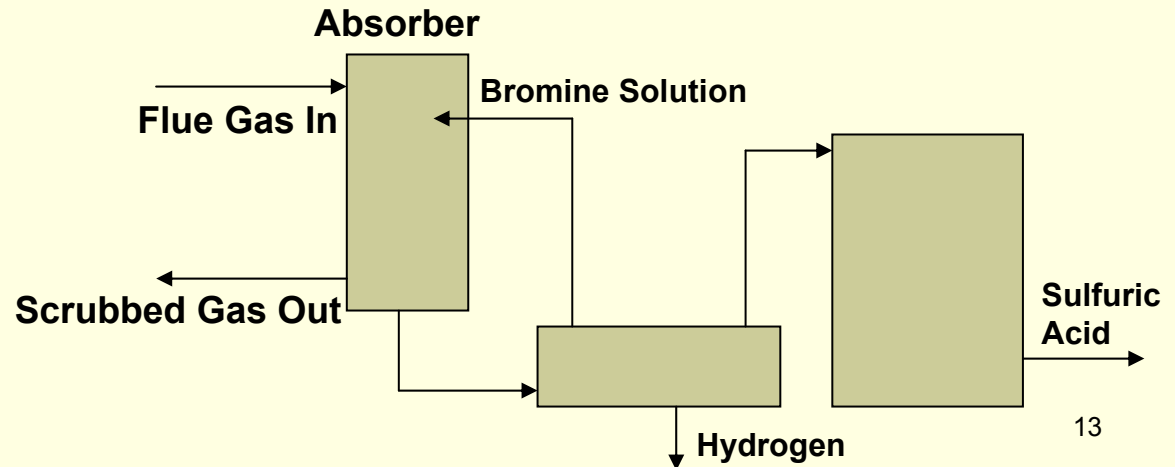
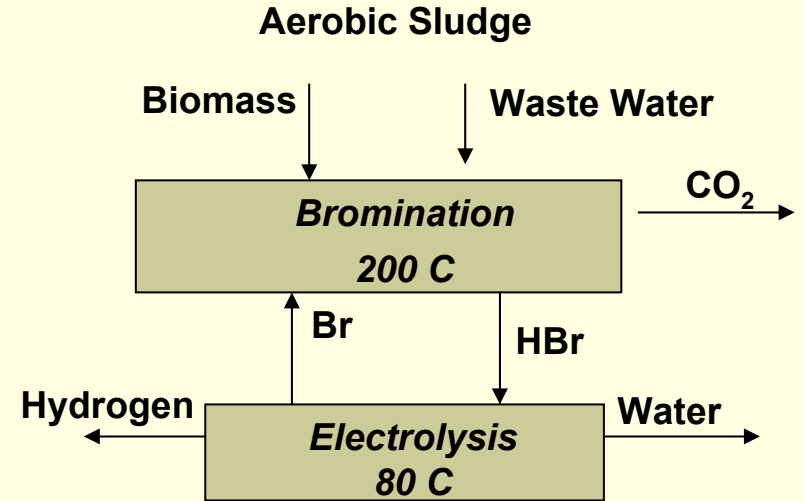
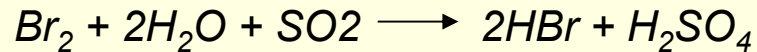
# PHASE II: HIGH EFFICIENCY HBr ELECTROLYSIS TESTING

Hydrogen produced with electricity at 18.57 whr/kg.  
Performance testing will validate manufacturer's claim.

## Waste Water Process



## SO<sub>2</sub> Emission Control



# PHASE II: 10 kw HBr ELECTROLYSIS PERFORMANCE TEST SET-UP



# PHASE IV: H2 PILOT NEW CUSTOMER CONVERTS HIS TRUCK TO BI-FUEL; H2 AND GASOLINE

## Vehicles Emissions Test Report

TEST CELL | Q-Cell  
 Test # | 4467  
 Date | 4/13/2006  
 Time | 11:08  
 Driver | KB  
 Operator | KB

VEHICLE...  
 Make | Chevrolet  
 Vehicle # | 117VJA  
 Odometer | 2528  
 Dyno Inertia | 4750

FUEL...  
 Fuel | Hydrogen

AMBIENT CONDITIONS...

Baro (inHg)	28.73		
PHASE #	1	2	3
Temp (°F)	73.1	74.1	73.9
Wet blb (°F)	54.0	54.5	54.6
Humidity	26.5%	26.0%	26.6%
Abs (gr/lb)	33.1	33.6	34.3
NOx K fac	0.836	0.837	0.839

Comments...  
 FTP  
 Hydrogen  
 Trace Violations: 112sec total duration

VARIABLES...

PHASE #	1	2	3
VMIX (ft3)	2855	4850	2831
Distance	3.484	3.845	3.514

Bag Results...

	HC ppm	CO ppm	NOX ppm	CO2 %	DF
<b>Phase 1</b>					
Sample Conc.	7.395	5.426	5.260	0.049	13.0
Ambient Conc.	7.589	1.822	0.033	0.045	
Net Conc.	0.389	3.744	5.229	0.007	
(gm)	0.018	0.352	0.676	10.761	
(gm/mile)	0.005	0.101	0.194	3.089	
<b>Phase 2</b>					
Sample Conc.	7.267	5.063	0.641	0.049	13.0
Ambient Conc.	7.423	2.893	0.116	0.047	
Net Conc.	0.415	2.392	0.534	0.005	
(gm)	0.033	0.383	0.117	12.420	
(gm/mile)	0.009	0.099	0.031	3.230	
<b>Phase 3</b>					
Sample Conc.	6.341	5.504	8.161	0.049	13.0
Ambient Conc.	6.574	3.145	0.116	0.047	
Net Conc.	0.273	2.600	8.055	0.005	
(gm)	0.013	0.243	1.037	7.509	
(gm/mile)	0.004	0.069	0.295	2.137	
Composite ...					
Grams/mile	0.007	0.092	0.136	2.904	



Customer Value Proposition

# PHASE IV: HYDRIDE CANISTER FILLING FOR SMALL FUEL CELLS INCORPORATED INTO H2 PARK



## *New Value Proposition for Hydrogen Power Park*

- Japan Steel Company developed a hydride canister filling appliance.
- Hydride canister appliance has been incorporated into the APS Pilot Hydrogen Park.
- Hydride canister appliance installation was approved by Phoenix Fire Department.
- This value added feature to the Park may support the marketing of small fuel cells.
- Hydride appliance may provide market assistance to small electrolysis equipment.
- Hydride appliance may support the marketing of consumer electronics or devices powered by fuel cells.



# PUBLIC ACCEPTANCE OF HYDROGEN PILOT

*1,751 people have toured the Pilot Park since 2003.*



*Pilot weekly tours: public groups, individuals, politicians, congressmen, international visitors, even NRC commissioners.*

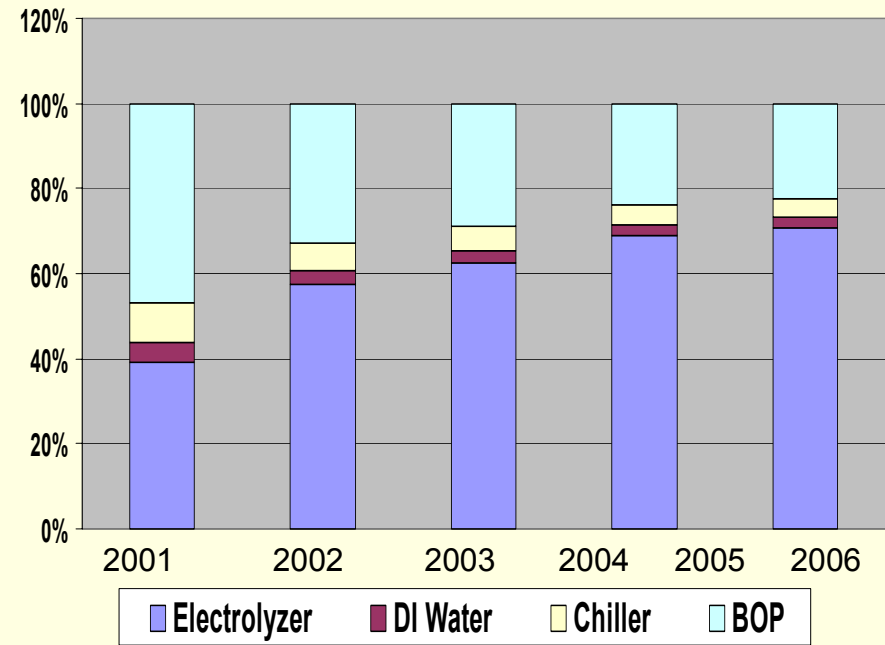
# PHASE III: REFINE CONCEPTUAL MODELS

<i>Engineering, Design, Testing, Permitting</i>	
Codes	NFPA (50A, 50B, 52, 70, 853, 496, 68, 69,54) ASME Pressure Vessel Code (B PV Section VIII, XII) Power Piping Code (B31.1, B31.3, B31.12)
Standards	CGA (S-1.3, H-1, 2, 3, 4; G-5, 5.3,5.4, 5.5, 5.6, 5.7) SAE (J2578, J2579, J2600, J2601, J2719)
Regulations and Statutes	Professional Engineering Regulations OSHA (CPL 02-02-045, 29CFR1910.119, 1910.103) ACR: Air Emissions City of Phoenix Zoning Codes City of Phoenix Fire Requirements City of Phoenix Motor Vehicle Fueling Permit City of Phoenix Compressed Gases Permit

# PHASE III: REFINE CONCEPTUAL MODELS

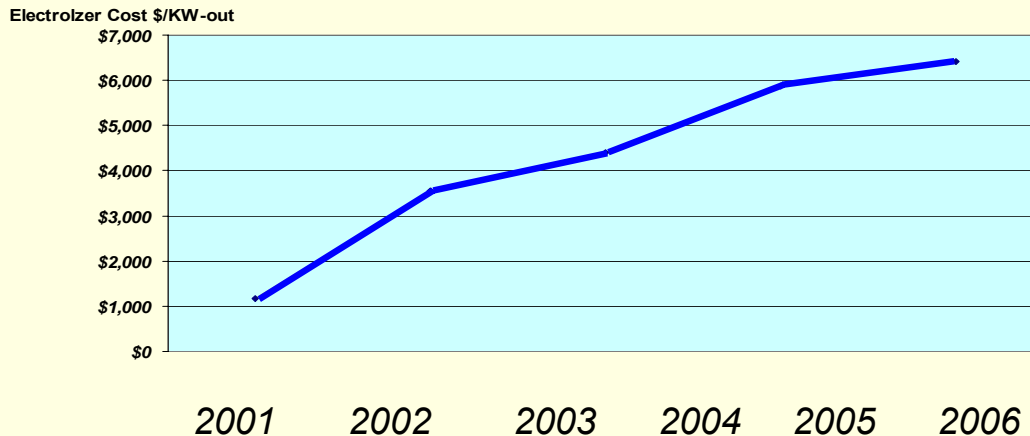
- The cost of small electrolysis equipment is increasing.
- Electrolysis unit rose from 40% of total hydrogen production system cost in 2001 to 75% of the total by 2006.
- Fixed cost (\$/Kg) of small distributed hydrogen electrolysis systems, after tax, rose from \$2.76 in 2001 to \$8.36 in 2006.

## Cost Elements for small Hydrogen Electrolysis Systems, % of total cost.

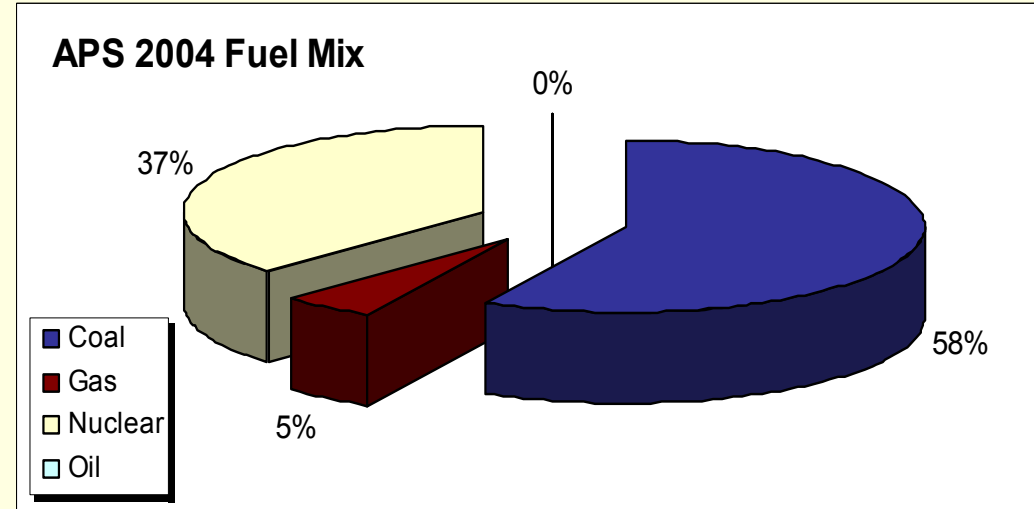
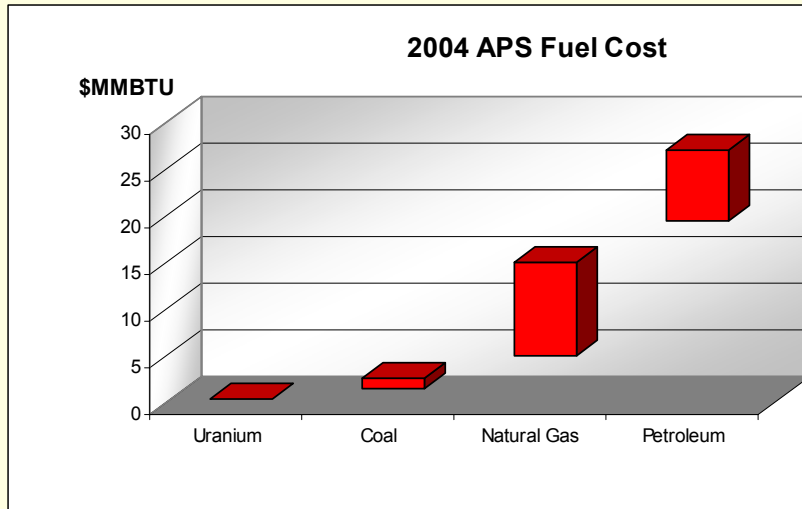


(BOP – Balance of Plant, DI – RO/DI water treatment)

## Cost of Electrolysis Units at APS (after tax - \$/kw-out)



# PHASE III: ECONOMICS REFINE CONCEPTUAL MODELS



## APS Electric Rates By Customer Class

ELECTRIC RATE CLASS	Summer: May – October		Winter: November – April		Demand	Demand
	On Peak	Off Peak	On Peak	Off Peak	Summer	Winter
	\$/kwh	\$/kwh	\$/kwh	\$/kwh	\$/kw	\$/kw
Residential	0.13310	0.04299	0.10918	0.04167		
Commercial Small	0.09610	0.04429	0.08610	0.03429		
Commercial Med	0.07938	0.04175	0.06945	0.03182	\$11.334	\$11.334
Commercial Large	0.05283	0.03797	0.04723	0.03393	\$9.390	\$8.510
Commercial X-Large	0.03529	0.02792	0.03529	0.02792	\$12.209	\$12.209

Note: Gasoline energy (LHV 114,000 BTU/gallon) is equivalent to 33.4 kWhrs. Rates effective 4-1-2005.

# PHASE III: RENEWABLE ENERGY

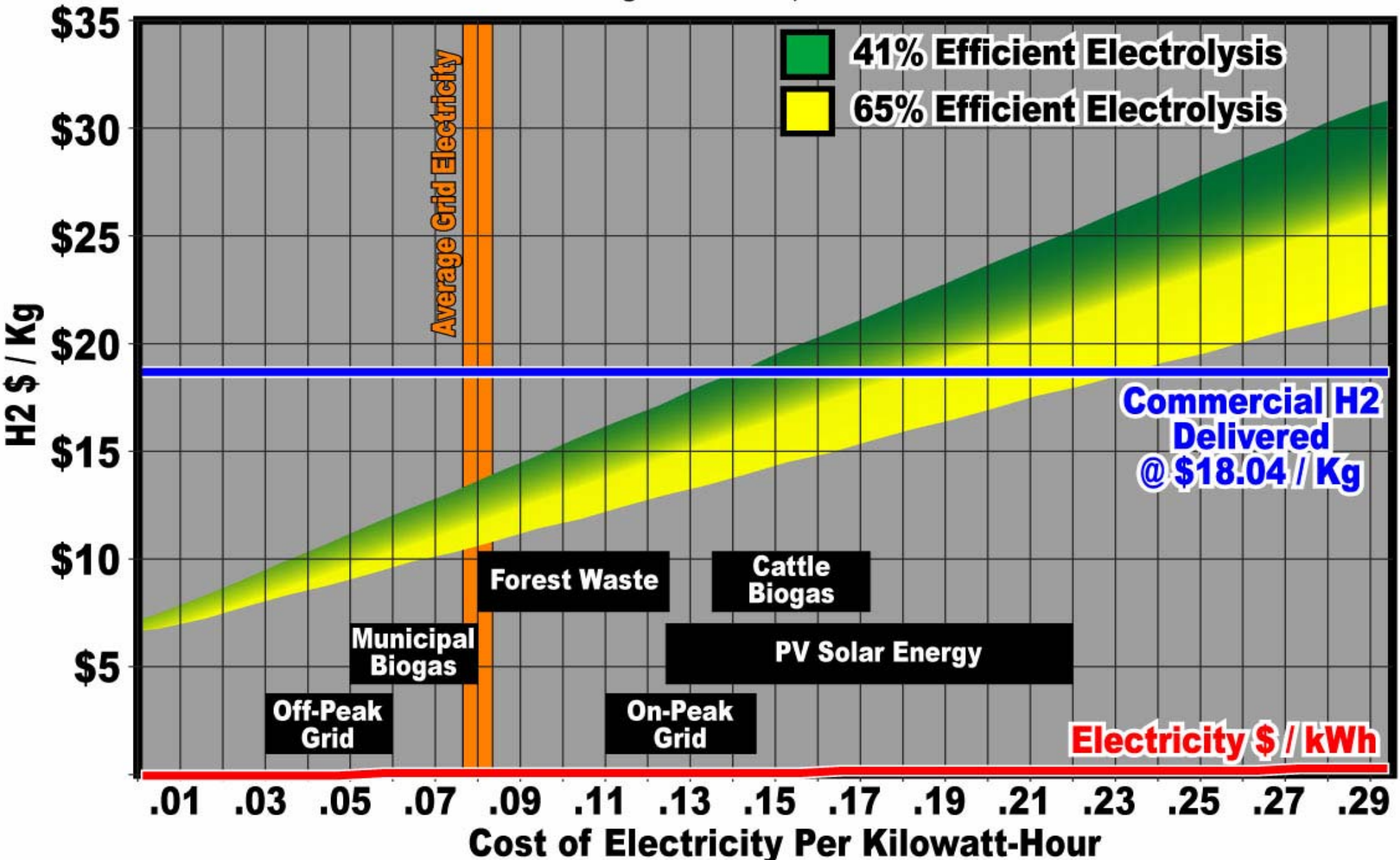


APS Solar Test and Research (STAR) Center Data					
Solar Type	Cost \$/Watt Capital	Cost \$/kWh O&M	Energy kWwh/kW-Yr	Cost Energy kWh/\$	Cost Energy \$/kWh
PV Fixed Horizontal	5.25	0.01	1,250	4.75	0.220
PV Fixed Latitude	5.25	0.01	1,630	6.20	0.171
PV Tracking Horizontal	5.50	0.01	2,350	8.55	0.127
PV Tracking Latitude	6.50	0.01	2,450	8.25	0.131
PV High-Concentration	6.00	0.01	2,030	6.75	0.158
PV High-Concentration (goal)	3.00	0.01	2,400	16.00	0.0725
Organic Rankine Cycle Trough	4.00	0.03	2,000	10.00	0.130
Dish Turbine	2.50	0.03	2,400	19.20	0.082

APS Biomass Data – Cost to Produce Electricity from APS RPS Program					
Biomass Fuel Type	Cost \$/Watt Capital	Cost \$/kWh O&M	Energy kWwh/kW-Yr	Cost Energy kWh/\$	Cost Energy \$/kWh
Forest Products	\$3000	\$0.04 - \$0.06	NA	NA	0.08 - 0.120
Biogas Municipal Waste Water Ops	\$1500 - \$2000	\$0.02 - \$0.05	NA	NA	0.05 – 0.08
Biogas Agriculture Cattle Dairy/Feed-lot			NA	NA	0.136 – 0.171

# Total Cost of Distributed Hydrogen Electrolysis

## 2005 Proton Electrolysis Unit, Fixed and Variable Cost



# PHASE III: REFINE MODELS

## ***REALITY CHECK: ENGINEERING FEASIBILITY***

### ***Model 1: Small Remote System***

Issue: Fuel cell testing in Phase II demonstrated reliability problems

Issue: Cost of electrolysis equipment

### ***Model 2: 20 to 100 kg/day, 30 – 100 kw System***

Issue: Reputable H<sub>2</sub> fueled Genset manufacturers

Issue: Cost and reliability of electrolysis units

Issue: Cost, life, reliability of fuel cells

Issue: H<sub>2</sub> purity for fuel cell cars

### ***Model 3: 500 – 1500 kg, 500 kw to 5 MW System***

Issue: Reputable H<sub>2</sub> fueled Genset manufacturers

Issue: H<sub>2</sub> purity from KOH electrolysis units (fuel cell cars)

Issue: Cost of electrolysis equipment

Issue: Reputable manufacturer of integrated systems

# PHASE IV: INSTALLED VALUE PROPOSITION

## MODEL 1 – REMOTE DISTRIBUTED HYDROGEN SYSTEM INSTALLED

### *The Value Proposition:*

#### **Economic:**

- ❑ Installed System Cost.....\$207,000  
(Proton 220, chiller, DI system, meter)
- ❑ Fixed ..... \$2.53/kg
- ❑ Variable Cost ..... \$2.28/kg
- ❑ Total Cost ..... \$4.81/kg

Cost of Delivered Hydrogen..... \$24.14/kg

Annual Savings.....\$89,981

#### **Additional Benefits:**

- ❑ Reduced Hazardous Material Storage
- ❑ Increased Reliability

(Fixed cost uses CRF 23%)





# FUTURE WORK

## ■ Phase II Performance Testing

- ❑ Complete performance testing of HBr Cell
- ❑ Continue to validate Pilot Park Functions
- ❑ Complete Assessment of Hydride Canister Refueling System
- ❑ Complete Assessment of Components for Model IV
- ❑ Complete Task Reports

## ■ Phase III Model Refinement

- ❑ Update assessment of electrolysis options
- ❑ Complete Model II refinement for substation or hospital application
- ❑ Complete Model III
- ❑ Complete Model IV
- ❑ Complete Task Reports

## ■ Phase IV

- ❑ Complete Model I & Model II Value Proposition
- ❑ Write Final Project Report

# SUMMARY

**Relevance:** Determine if Hydrogen Power Parks are feasible, safe, and provide a value proposition to potential customers.

**Approach:** Validate Hydrogen Park Models by testing components, systems, and concepts obtaining “real-world” performance and operating results.

**Functional Accomplishments:** Validated all power park functions including potential customer acceptance including; public vehicle refueling, cost of renewable energy to produce hydrogen, distributed hydrogen electrolysis, electricity production from fuel cells and H<sub>2</sub>ICE. Perfect safety record after 4 years of operation.

**Goal Accomplishment:** Identified and implemented one value proposition, resulting in “satisfied – customer”.

**Conclusion:** Hydrogen Parks are safe and feasible. Difficult to compete on cost with gasoline and diesel fuel, unless there exists a **need** for hydrogen.

**Biggest Issue:** Cost of Electrolysis Equipment.

# REVIEWER'S COMMENTS (May 2005)

## **Lack of Partnerships**

APS has “partnered” with BC Hydro and SCE, both of which have installed hydrogen operations.

APS assisted in the formation of HUG (Hydrogen Utility Group) which now has 12 utility members and meets quarterly.

## **Did not include all data analysis (didn't include capital costs of fuel cells)**

Phase III address the business case while phase II was the validation phase. The fuel cells must earn their right for incorporation into a business case by first demonstrating they will worked when called upon, then meeting the minimum economic hurdle. There were FC performance issues.

## **Include Cost reduction strategy, mainly for PV-based hydrogen production.**

The Project is part of the Technology Validation Program, and therefore it is out of our scope to create new products. APS has significant success in reducing the cost (kw & kwh) of solar PV systems. Currently our lowest cost PV complete system is \$5/watt installed. Hydrogen produced by PV electricity needs both to meet the criteria of low cost and high efficiency. Electrolysis equipment is expensive, in the case of small electrolysis units costs are greater per kw than the entire PV systems. The low operating voltages of this equipment triggers large losses in the form of heat.

# CRITICAL ASSUMPTIONS AND ISSUES

## ISSUES:

- The lack of reasonably priced electrolysis equipment.
- The lack of reputable hydrogen fueled H<sub>2</sub> ICE Gensets with performance warranties & guarantees.
- The short life of PEM fuel cells.
- The lack of reasonably priced fuel cells.
- The lack hydrogen fueled vehicles.
- The lack of public policy facilitating the market for hydrogen.