Technoeconomic Boundary Analysis of Photoelectrochemical (PEC) Hydrogen Producing Systems

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Project ID #
PD_23_James

Overview

Timeline

- Start: May 2008
- End: June 2009
- Percent Complete: 90%

Barriers

- AD. Systems Design and Evaluation
- AE. Diurnal Operation Limitations

Budget

- Total project: $190,718.57
- FY08: $190,718.57
- FY09: N/A
- No Contractor Share

Partners

- DOE PEC Working Group
  (DOE plus 12 organizations)

Relevance

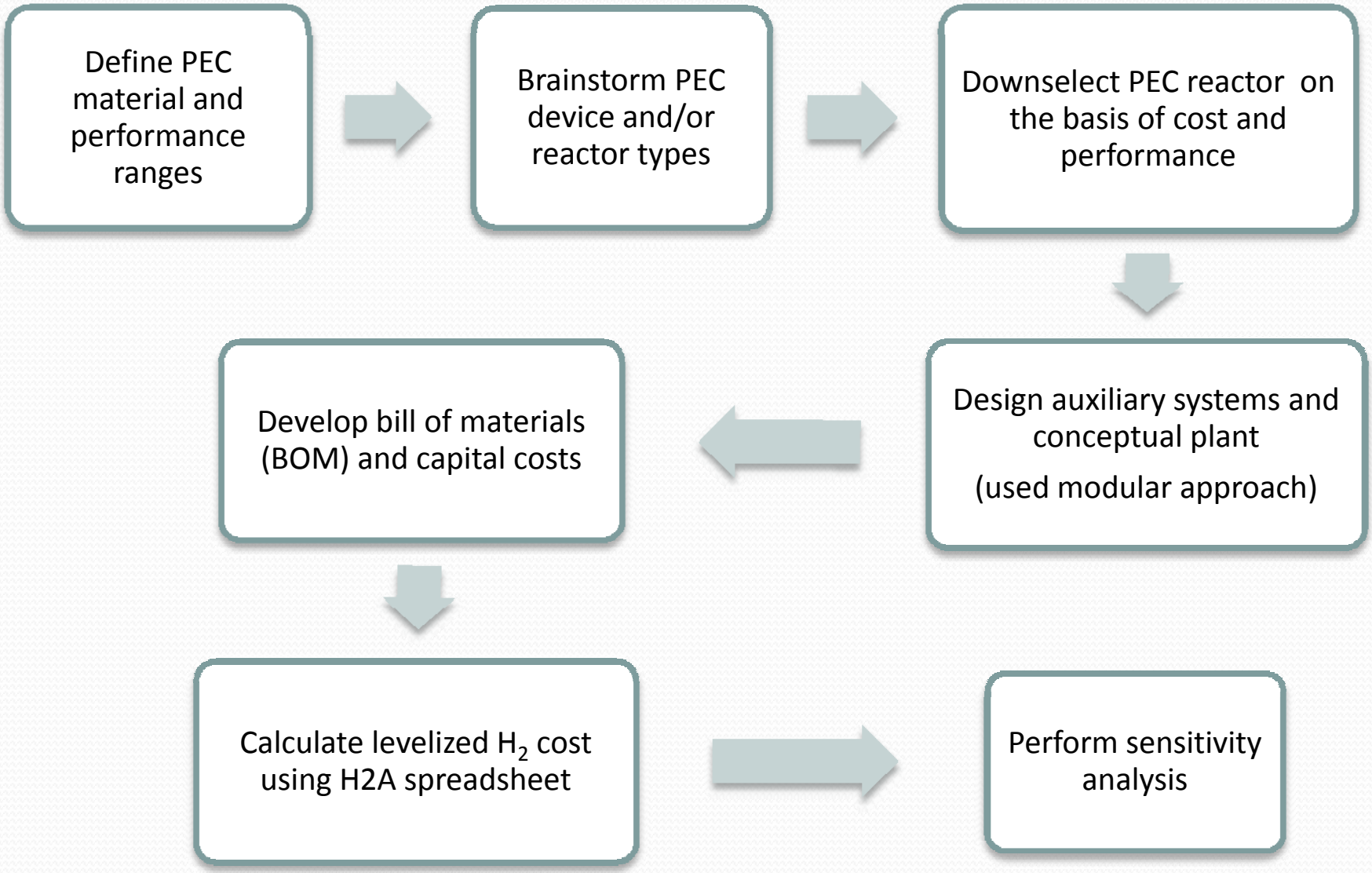
Project Objectives

- Perform Economic & Technical Analysis of H_2 producing systems
  - Create photoelectrochemical (PEC) H_2 production conceptual system designs
    - Colloidal Suspension
    - Photoelectrode
  - Hydrogen Cost Calculations
    - System capital costs
    - Levelized H_2 costs
- Identify key factors affecting cost estimates

Design Features

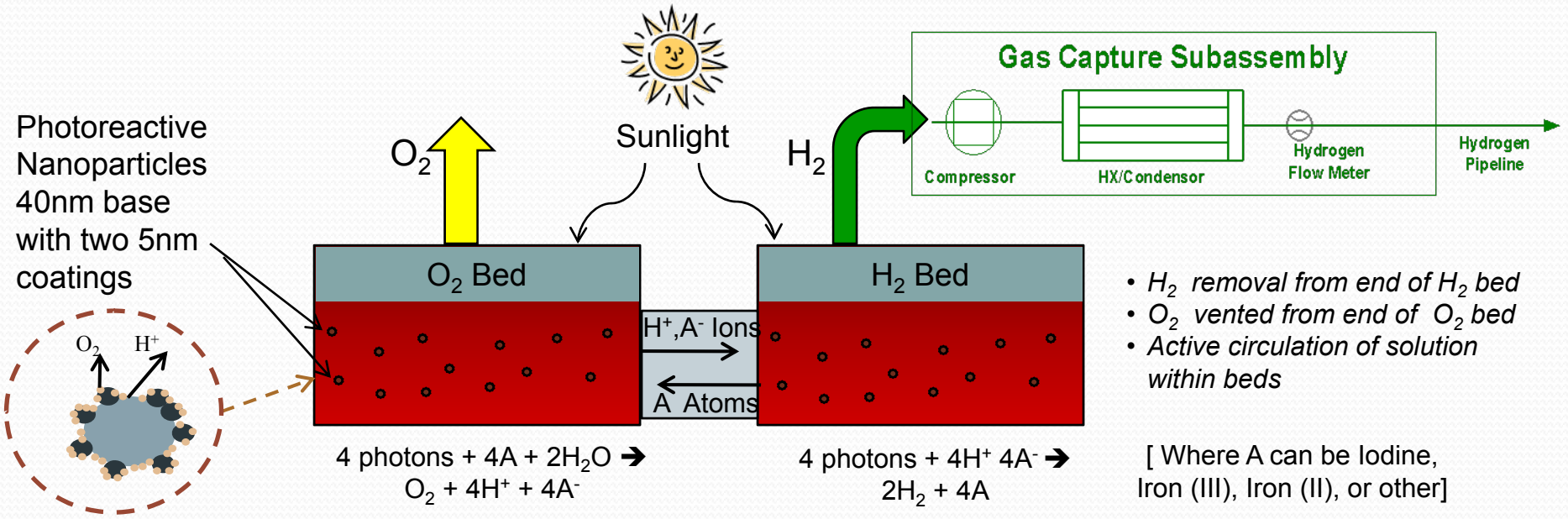
- Advancing implementation of new technology by designing physical systems tailored to PEC materials
- Design of gas collection system for continuous operation
- Design of solar collection for maximum sunlight conversion

Approach



Colloidal Suspension Reactor Concept

Plant Capacity = 1 TPD Module x 10

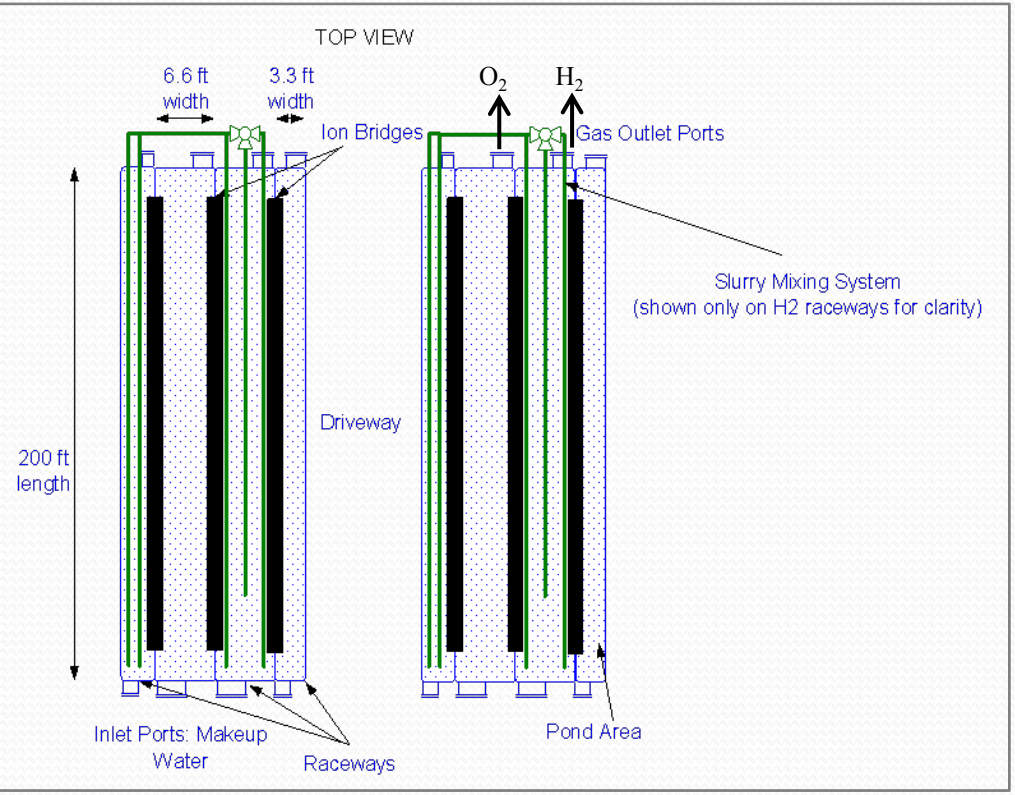


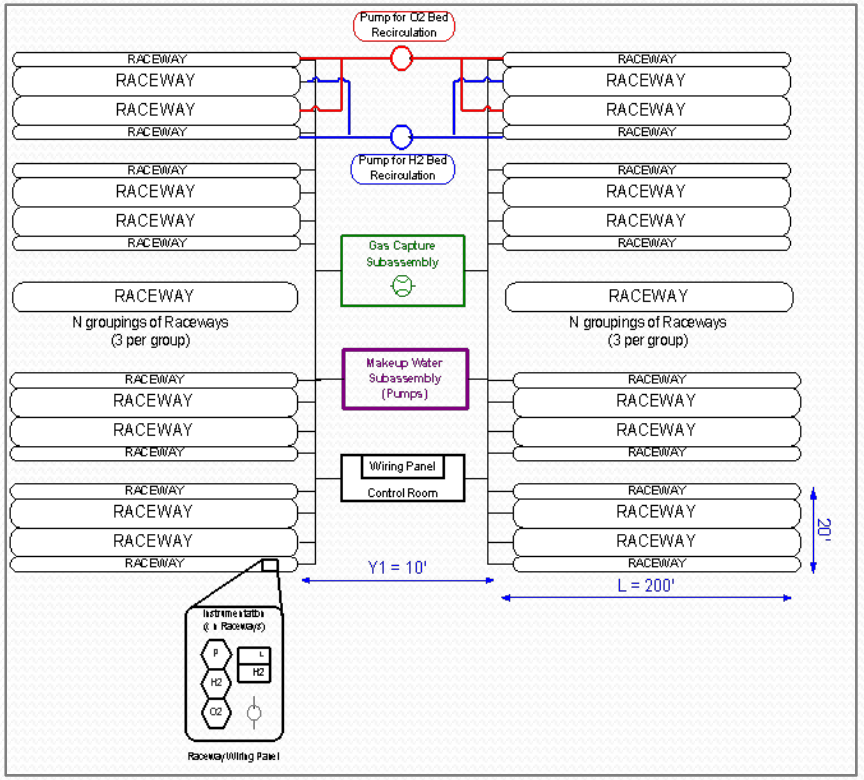
- *H_2 removal from end of H_2 bed*
- *O_2 vented from end of O_2 bed*
- *Active circulation of solution within beds*

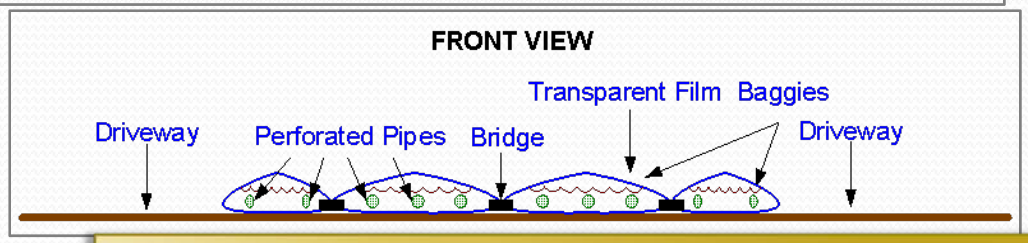
[Where A can be Iodine, Iron (III), Iron (II), or other]

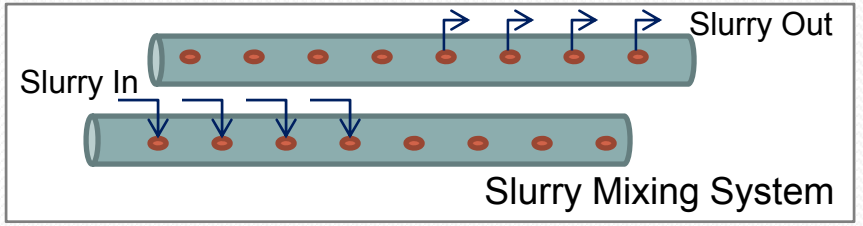
Pure Water Splitting	10% Solar-to-Hydrogen Efficiency (baseline)	Reactant contained in Shallow Bags
Coated Nanoparticles in 0.1M KOH Electrolyte Solution	Product Gas after condensor: 99% H_2 1% H_2O	LDPE fibrous mat is liquid permeable "window" between beds
	O_2 not collected, released to atmosphere	10 TPD H_2 output from ten linked 1 TPD H_2 modules

Colloidal Suspension Reactor Design









1 Baggie System = 2 full baggies (200 ft x 6.6 ft x 1.5 ft) + 2 half baggies (200 ft x 3.3 ft x 1.5 ft)
1 TPD Module (at 10% efficiency) = 368 Baggie Systems over 43 acres
10 TPD Plant Capacity = Ten x 1 TPD modules

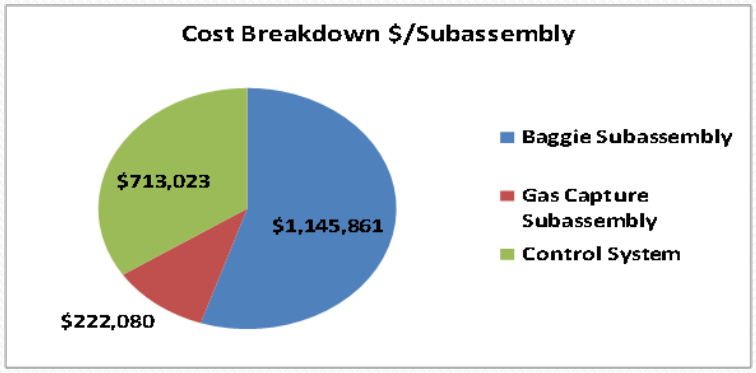
Plant Design: 1 TPD Module

Effective Reactor Cost: $9/m²

Nanoparticle Colloidal Suspension Concept

Parameter	Value
Base Material	Fe_2O_3
Base Particle Size	40 nm
Coating	TiO_2
Coating thickness	5 nm x 2 layers
Solar Efficiency	10%
Suspension Beds	134,667 m²
Lifetime	5 yrs
Cost (nanoparticles)	$304/kg

Capital Expenditures



Bill of Materials

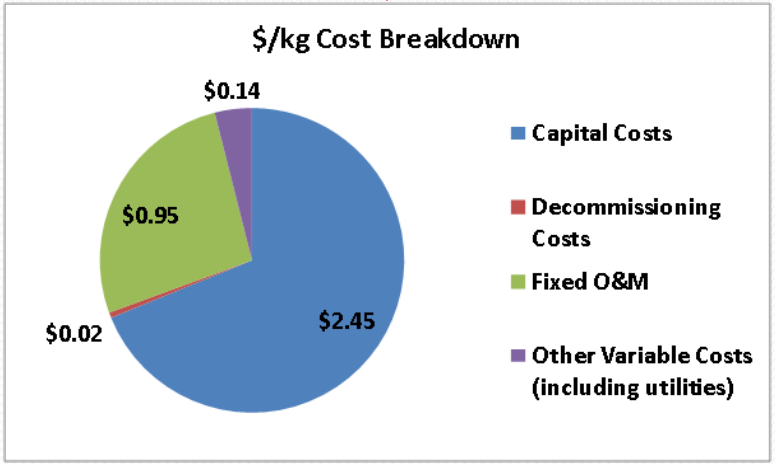
Description	Unit Size	Units	Unit cost	Qty Req'd	Total Cost
Baggie Subassembly					
Baggie Cost	1	Module	$ 839,400	1	$839,400
Levelling of Area	1	Acre	$ 3,896.00	36	$140,256
Forklift	1	Forklift	$ 18,571.00	1	$18,571
Coated PEC Microparticles	1	kg	$ 304.00	142	$43,271
Miscellaneous Piping					$104,150
Make-up Water Pump	1	pump	$ 212.50	1	$213
Gas Capture Subassembly					
Compressor	23	kgH2/hr	$ 9,233.00	23	$ 208,783
PSA					$ -
Piping - 4"	1	ft	$6.18	2140	$13,225
Piping - 1"	1	ft	$1.00	72	$72
Control System					
PLC	1		$ 2,000.00	1	$2,000
Control Room	1	ft2	$ 50.00	160	$8,000
Control Room Wiring Panel	1		$ 3,000.00	1	$3,000
Raceway wiring Panel	1		$ 146.00	36	$5,256
Computer and Monitor	1		$ 1,500.00	1	$1,500
Labview Software	1		$ 4,299.00	1	$4,299
Level Indicators	1		$ 3,000.00	36	$108,000
Pressure Sensors	1		$ 4,700.00	36	$169,200
Hydrogen Area Sensors	1		$ 5,500.00	36	$198,000
Oxygen Area Sensors	1		$ 5,500.00	36	$198,000
Hydrogen Flow Meter	1		$ 5,500.00	1	$5,500
Instrument Wiring	1	ft	$ 0.02	193,350	$3,751
Power Wiring	1	ft	$ 0.02	192,150	$3,723
Conduit	1	ft	$ 0.58	4,810	$2,789
				System Initial Cost	**$ 2,080,963**

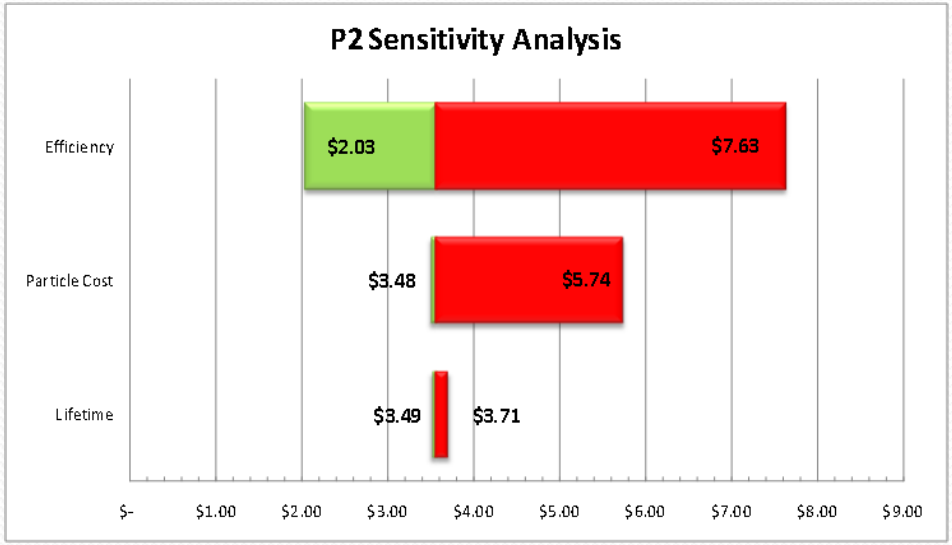
Effective System Cost: $15/m²

Colloidal Suspension Results: 10 TPD Plant

Sensitivity Analysis Parameters		
Efficiency	Particle Cost	Particle Lifetime
5%	0.5x	1 Year
10%	1x	5 Year
20%	30x	10 Year

Baseline Conditions

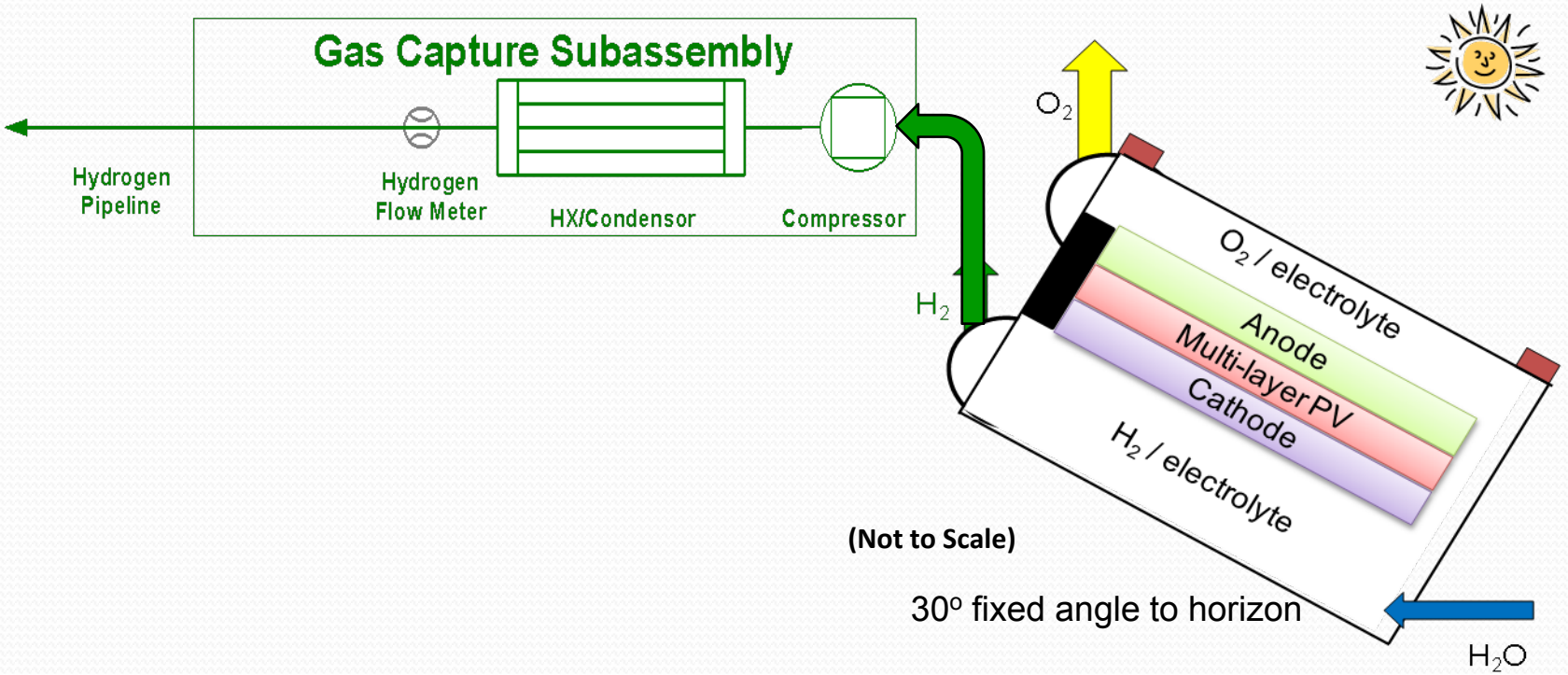




Baseline Cost = $3.56/kg H_2

H2 cost estimated at ~$3.50/kg but cost is highly dependant on nanoparticle material system which is currently undefined

Photoelectrode Concept: Fixed Flat Plate



1.1x factor on horizontal insolation to reflect 30° fixed angle to horizon	10% Solar-to-Hydrogen Efficiency (Baseline)	H_2 compression to 300psi (external compressor)
0.1M KOH Electrolyte Solution	100% H_2 recovery; Inherent separation of H_2 and O_2	Plexiglass window, 95% photon transmittance
	O_2 not collected, released to atmosphere	10 TPD H_2 from linked 1 TPD (net) H_2/day modules

Multi-layer PEC Electrode Cost Analysis:

Based on DFMA analysis and analogy to PV cell cost

FASST™, Heliovolt

- Proprietary printing process
- Heliovolt patented processes claim to cut PV coating times down by a factor of 100 to 6 minutes per cell
- Reported PV cell efficiencies of 12.2%, using CIGS (copper indium gallium selenide) thin-film technology

Roll Printing, Nanosolar

- Solar cell printing rate of 30 m/min
- Goal PV cell efficiency of ~ 14% using CIGS
- Nanosolar PV price projection: (at 14% effic.)
  - Panels at \$0.99/Watt cells => \$139/m^2
  - "Manufac. Cost" at \$0.30/Watt => \$42/m^2

Magnetron Sputtering

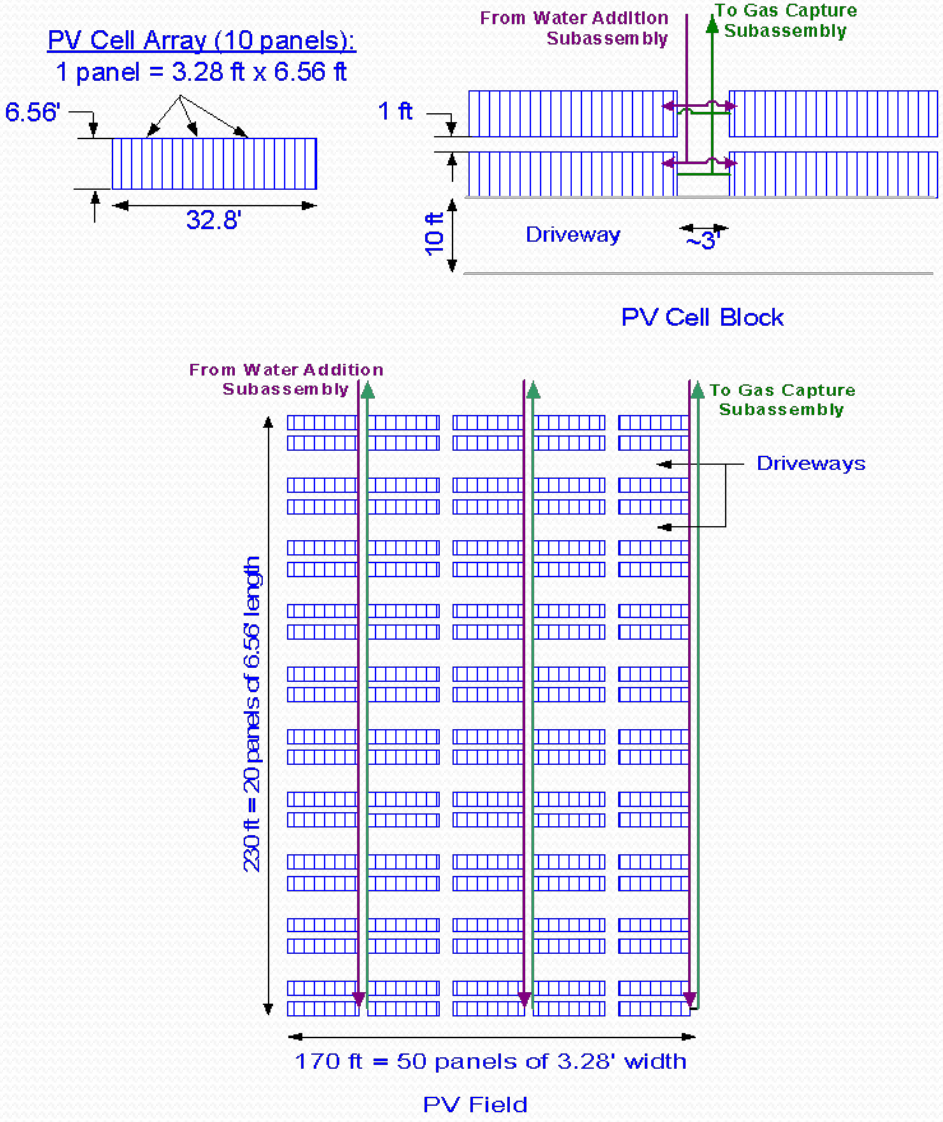
- Thin Film:
  - three 2μm layers at \$300/kg (70% yield)
  - three 2μm layers at \$100/kg (70% yield)
  - 2 mil 310 SS substrate at \$4/m^2
- Deposition Machine:
  - \$1.5M Magnetron Sputtering machine
  - 2.5 nm/s deposition rate
  - 1m x 2.13 m target size
- Cost: (DFMA Analysis) \$246.96/m^2

Ink Deposition

- Thin Film:
  - three 2μm layers at \$188/kg (90% yield)
  - three 2μm layers at \$278/kg (90% yield)
  - 2 mil 310 SS substrate at \$4/m^2
- Deposition Machine:
  - \$870K Verti-Coater System
  - 10 m/min line speed
  - 1m web width
- Cost: (DFMA Analysis) \$25.73/m^2

Selected Thin Film PEC element baseline cost of \$100/m^2 with a \$30-\$150/m^2 spread for parametric analysis.

Photoelectrode System Parameters



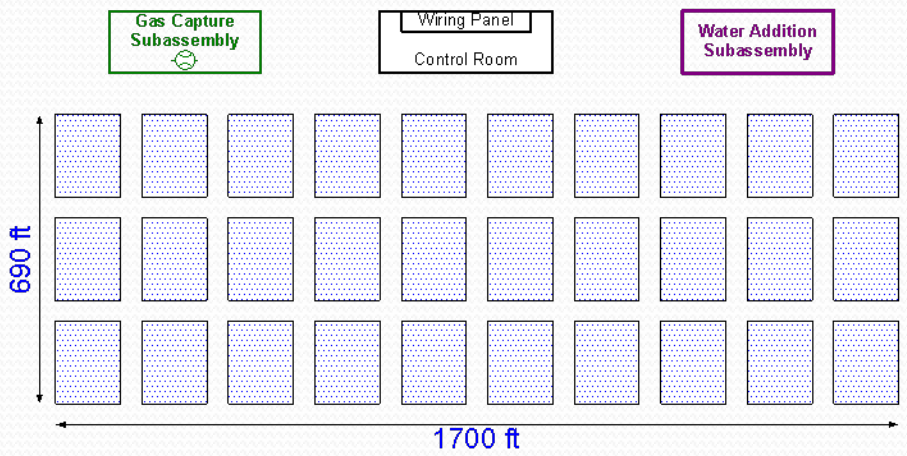
Photoelectrode Cell Concepts

Parameter	Value
Transparent Anode	
Multi-Layer Thin film PV Cell:	
- High Bandgap	1.5 – 2.0 eV
- Low Bandgap	1.0 – 1.5 eV
Stainless Steel Cathode Substrate	2 mil thickness
Pressure	1 atm
Solar-to-H_2 Efficiency	10%
Lifetime	10 yrs
Cost (baseline)	$100/m^2

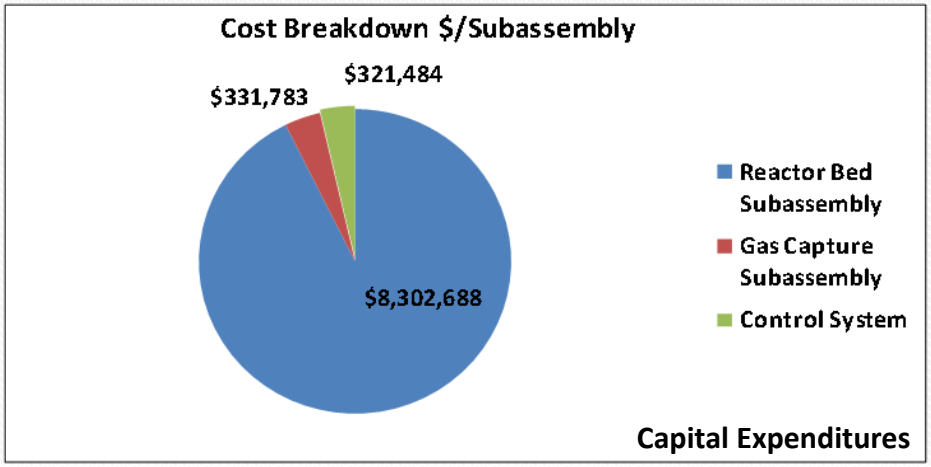
Fixed Panel Plant Design

Effective Reactor Cost: $143/m²

1 TPD Module



10 TPD Plant = 10 x 1 TPD Modules
1 TPD Module = 27 acres (14 acres of cells)
14 acres = 300 PV Fields = 28,995 cells



Bill of Materials for 1 TPD Module

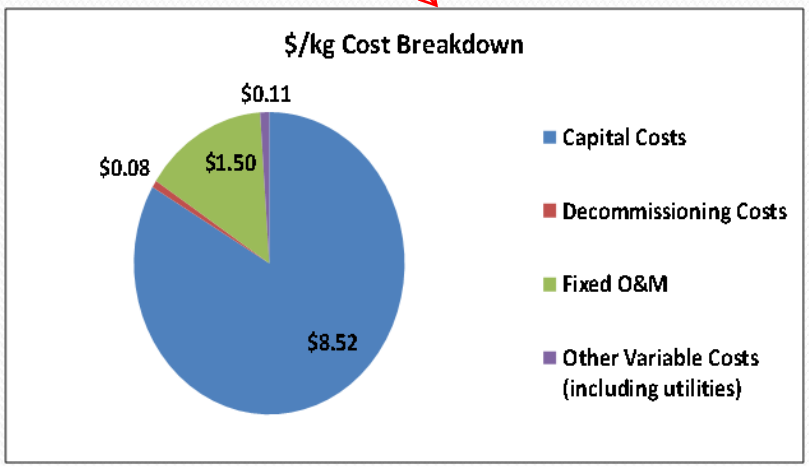
Description	Unit Size	Units	Unit cost	Qty Req'd	Total Cost
Reactor Bed Subassembly					
Thin Film PV Cell	1	m^2	$ 100.00	57,990	$ 5,799,043
Plexiglass Window	1	m^2	$ 15.00	63,789	$ 956,842
Frame	1	m^2	$ 20.00	57,990	$ 1,159,809
Frame Assembly	1	m^2	$ 5.00	57,990	$ 289,952
Manifold Piping	0.5	in	$ 0.52	186619	$ 97,042
Collection Piping	0.5	in	$ 0.52	33350	$ 17,342
Column Collection Piping	2	in	$ 2.12	3400	$ 7,208
Final Collection Piping	3	in	$ 4.31	200	$ 862
Gas Capture Subassembly					
Compressor	23	kgH2/hr	$ 9,233.00	23	$ 208,783
Condensor/HX #1	1		$ 123,000.00	1	$ 123,000
Condensor/HX #2	1		$ 65,300.00	1	$ 65,300
Control System					
PLC	1		$ 3,000.00	1	$ 3,000
Control Room	1	ft2	$ 2.00	8,763	$ 17,527
Control Room Wiring Panel	1		$ 3,000.00	1	$ 3,000
Raceway wiring Panel	1		$ 146.00	15	$ 2,190
Computer and Monitor	1		$ 1,500.00	1	$ 1,500
Labview Software	1		$ 4,299.00	1	$ 4,299
Level Indicators	1		$ 3,000.00	15	$ 45,000
Pressure Sensors	1		$ 4,700.00	15	$ 70,500
Hydrogen Area Sensors	1		$ 5,500.00	15	$ 82,500
Oxygen Area Sensors	1		$ 5,500.00	15	$ 82,500
Hydrogen Flow Meter	1		$ 5,500.00	1	$ 5,500
Instrument Wiring	1	ft	$ 0.02	43,295	$ 836
Power Wiring	1	ft	$ 0.02	42,525	$ 825
Conduit	1	ft	$ 0.58	3,980	$ 2,308
				System Initial Cost	**$ 9,046,667**

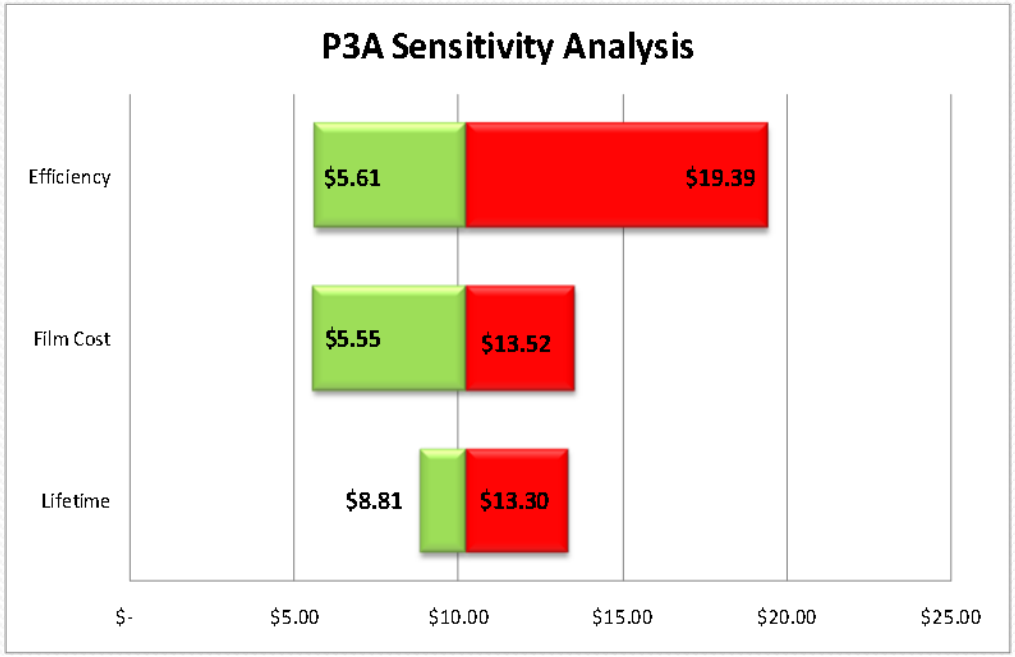
Effective System Cost: $156/m²

Photoelectrode Results

Sensetivity Analysis Parameters		
Efficiency	Film Cost	Thin Film Lifetime
5%	$30/m^2	5 year
10%	$100/m^2	10 year
20%	$150/m^2	20 year

Baseline Conditions



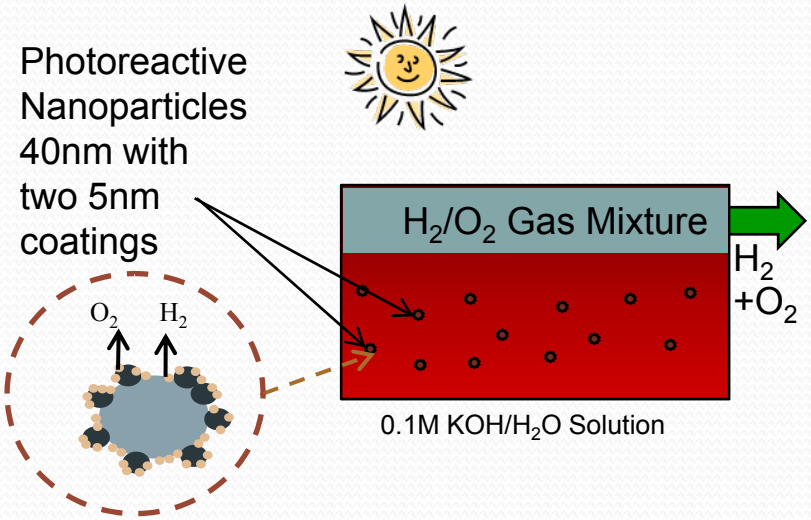


Baseline Cost = $10.20/kg

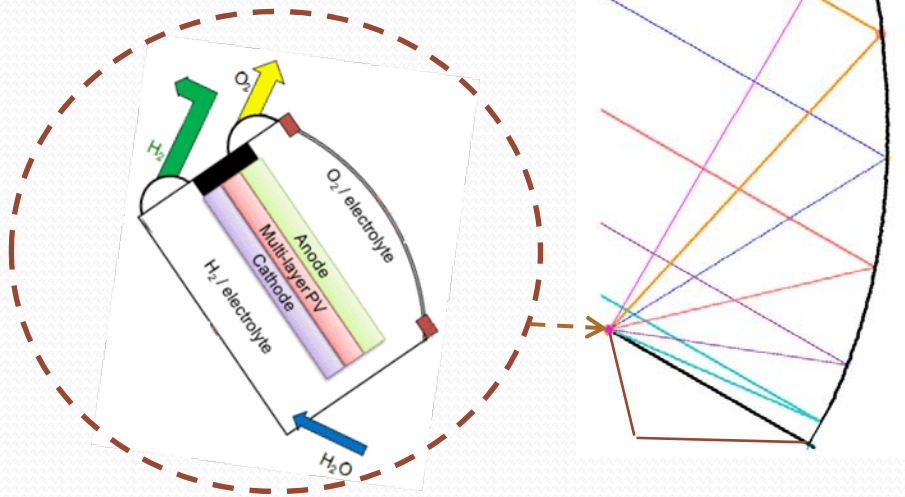
Hydrogen Cost ~$10/kg but PEC system benefits directly from PV cell cost reductions. Cost Reduction to ~$5.50/kg H_2 is quite possible.

Other PEC Variants

- **Colloidal Suspension, Single Bed**
  - Same Nanoparticle Material System
  - Fewer beds, Lower Capital Cost
  - Mixed H_2/O_2 Output Gas (potential combustion issue)



- **Photoelectrode, Tracking Concentrator**
  - Higher efficiency (15% baseline, 25% max)
  - Reduced Active PV area
  - 300 psi (or higher) operation, No Compressor
  - Lower Capital Cost, More complex (solar tracking)



Costs	Single Bed	Concentrator
Capital ($) (1 TPD Module)	$1.0M to $2.7M	$5.94M
H2A H_2 Cost	$1.63 to $3.18 Per kg	$3.98 Per kg

Collaborations

Collaborator	Organization	Role	Expertise
Photoelectrochemical Working Group	DOE + DOE Funded Organizations	Material Systems, Directional support	All PECs
Eric Miller	University of Hawaii	System Concept Exploration	PEC electrode systems, Comprehensive PEC R&D awareness
Eric McFarland	UC-Santa Barbara	System Concept Exploration	Colloidal Suspensions
Tom Jaramillo	Stanford	System Concept Exploration	Colloidal Suspensions

Proposed Future Work

Current Contract

- Prepare Final Report

Future Work

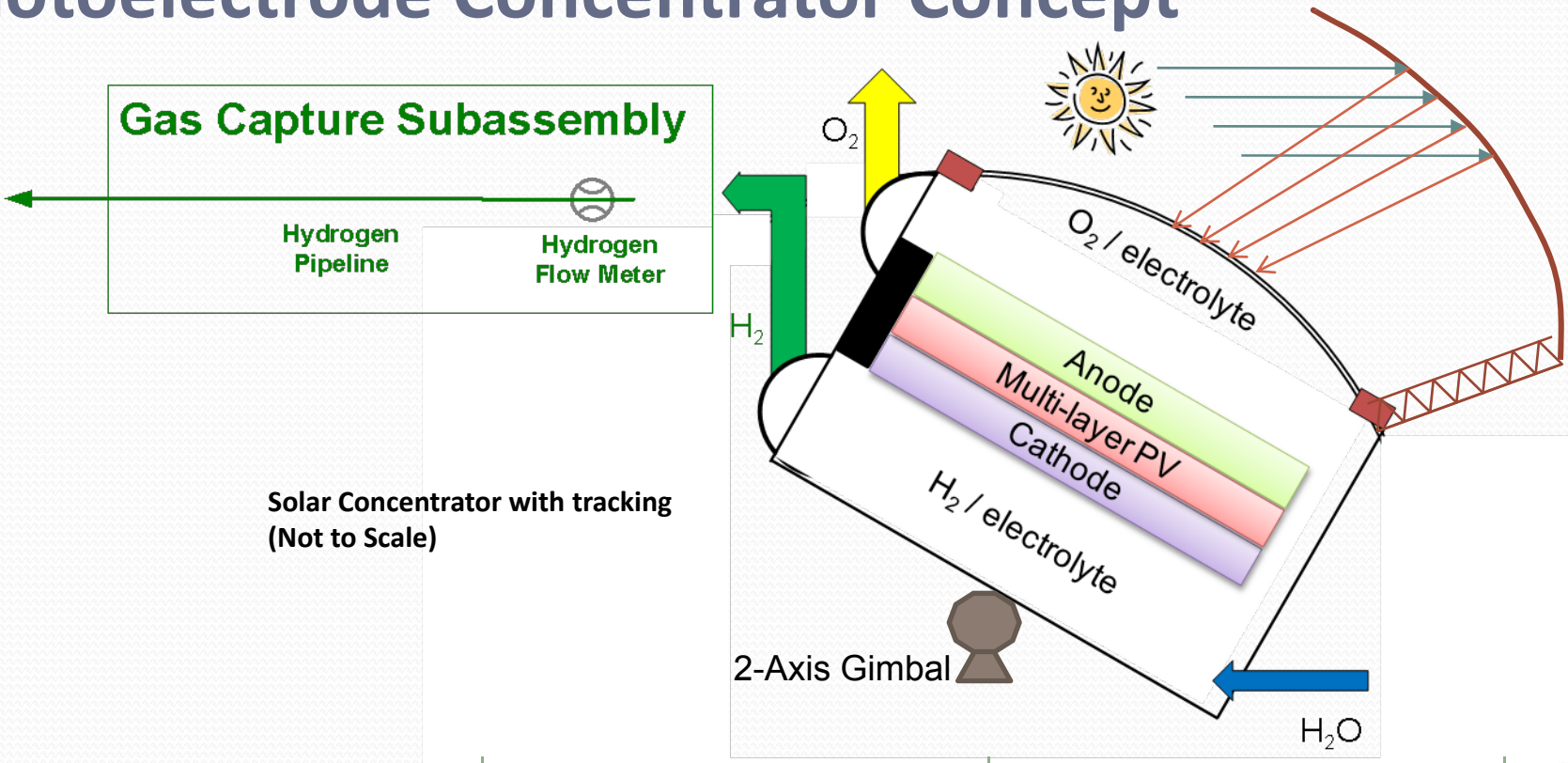
- Refine cost projection for new material systems & fabrication methods
- Explore new system concepts
  - Have only looked at simplest most straightforward applications
  - Investigate other concepts which may have merit:
    - HBr/Br_2 systems
    - Waste-water as feedstock
    - Electrolyzer mode (PEC with electrical bias)
    - Detailed system definition of Low Cost Concentrator PEC

Summary

- **Photoelectrochemical (PEC) H_2 Production**
  - 12.2% solar-to-H_2 efficiency previously demo'd in lab but with short lifetime
  - Research is focused on identifying & fabricating appropriate long-lasting material systems
- **Technoeconomic Boundary Analysis conducted**
  - Evaluate system concepts
  - Estimate $/kg of resulting PEC H_2
  - Provide system context to researchers
  - Better understand cost drivers & sensitivities
- **Two Primary Concepts explored**
  - Colloidal Suspension Systems
    - Separate beds for H_2 and O_2 production
    - 10% STH appears feasible
    - "Baggie" concept feasible but inter-bed diffusion needs further study
    - Expected price: $3.56/$kg_{H_2}$ (Potential range: $2.03-$7.63/kg)
  - Photoelectrode Systems
    - Analogous to PV panels but suspended in water/KOH electrolyte
    - Benefits from PV panel cost reduction in Solar Cell Industry
    - 10% STH feasible (possibly 25%)
    - Expected price: $10.20/$kg_{H_2}$ (Potential range: $5.61-$19.39/kg)
    - Concentrating Photoelectrode systems offer lower price $3.98/$kg_{H_2}$ but with increased complexity
- **Alternate PEC concepts worth exploring**
- **Extensive collaboration/coordination with DOE PEC Working Group**

Backups

Photoelectrode Concentrator Concept



Solar Concentrator with tracking (Not to Scale)

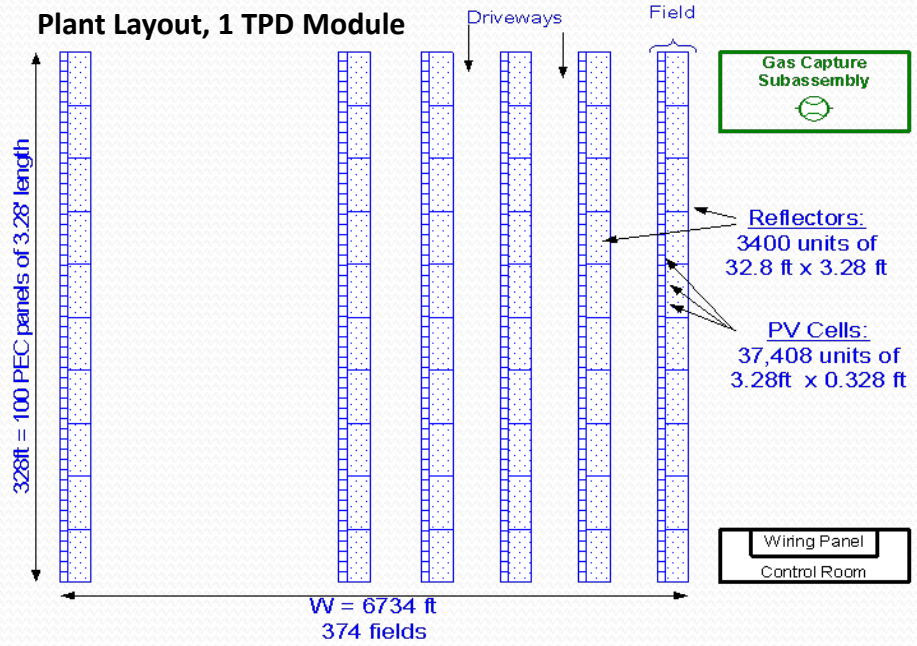
- Solar Concentration:
  - 10:1 baseline
  - 20:1 achievable
- 0.1M KOH Electrolyte Solution
- Can easily add PEM membrane if needed for ion separation
- 1.32x factor on horizontal insolation to include combined effects of tracking gain and diffuse sunlight loss

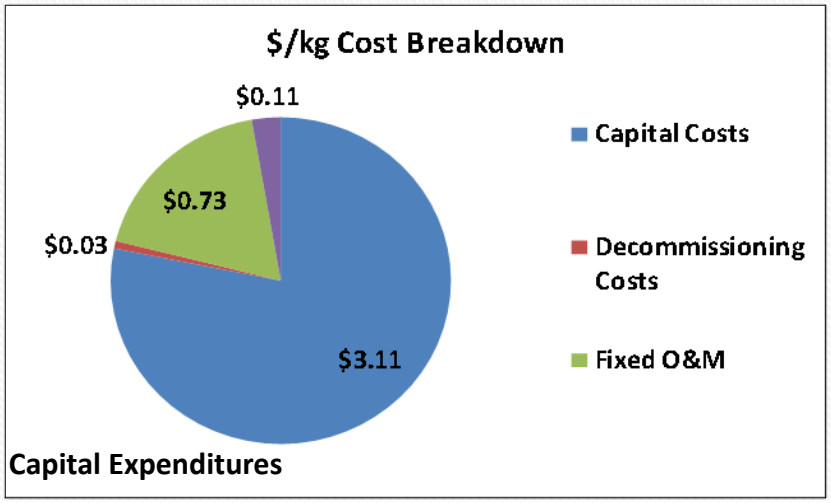
- Solar-to-Hydrogen Efficiency
  - 15% baseline
  - 25% max
- 100% H_2 recovery; Inherent separation of H_2 and O_2
- O_2 not collected, released to atmosphere

- 10 TPD H_2 from linked 1 TPD H_2/day modules
- Plexiglass window:
  - 90% photon transmittance
  - circular section to reduce stress
- Reduced size PEC cell allows operation at 300psi and higher → no compressor required

Concentrator Plant Design

Plant Layout, 1 TPD Module





Bill of Materials for 1 TPD Module

Sized for 1000kgH2/day Module.

Tracking & Concentrating	34,007	m2	1	m2	$	89.00	34,007	$	3,026,599.33
PEC Subassembly 3B -10: 1 & 300 psi									
Area ratio	10	:1							
Pressure	300	psi							
PEC element	3,401	m2	1	m2	$	150.00	3,401	$	510,101.01
Plexiglass Window	3,401	m2	1	m2	$	37.00	3,401	$	125,824.92
Frame	3,401	m2			$	20.00	3,401		
Assembly	3,401	m2			$	5.00	3,401		
Manifold Piping	0.5	in	1	1	ft		131324.5	$	68,288.73
Collection Piping	0.5	in	1	ft		0.52	24150	$	12,558.00
Column Collection Piping	2	in	1	ft		2.12	3400	$	7,208.00
Final Collection Piping	3	in	1	ft		4.31	200	$	862.00
Gas Capture Subassembly									
Compressor								$	-
Drying System								$	-
Controls									
PLC					$	3,000.00	1	$	3,000.00
Control Room	8,763	m	1	m	$	2.00	8,763	$	17,526.78
Control Room Wiring Panel					$	3,000.00	1	$	3,000.00
Raceway wiring Panel					$	146.00	1	$	146.00
Computer and Monitor					$	1,500.00	1	$	1,500.00
Labview Software					$	4,299.00	1	$	4,299.00
Level Indicators					$	3,000.00	1	$	3,000.00
Pressure Sensors					$	4,700.00	1	$	4,700.00
Hydrogen Area Sensors					$	5,500.00	1	$	5,500.00
Oxygen Area Sensors					$	5,500.00	1	$	5,500.00
Hydrogen Flow Meter					$	5,500.00	1	$	5,500.00
Instrument Wiring					$	0.02	1,725	$	33.47
Power Wiring					$	0.02	1,575	$	30.56
Conduit					$	0.58	400	$	231.92
Overall Cost								$	3,805,409.70