Technoeconomic Boundary Analysis of Photobiological Hydrogen Producing Systems

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Overview

Timeline

- Start Date: April 2008
- End Date: May 2009
- Percent Complete: 95%

Barriers

- AK. Diurnal Operation Limitations
- AJ. Systems Engineering
- AS. Waste Acid Accumulation

Budget

- Total project: $206,149
- FY08: $206,149
- FY09: none
- No Contractor Share

Partners

- DOE/NREL Bio H_2 Working Group
- Gerald C. Dismukes - Princeton University

Objectives

- **Conceptual System Designs**
  - Photobiological H_2 production systems
  - Dark fermentation H_2 production systems
  - Microbial Electrolysis H_2 production systems
  - Integrated H_2 production systems

- **Hydrogen Cost Calculations**
  - Calculate Capital costs, Operating costs, Feedstock costs for conceptual systems
  - Compute levelized hydrogen costs for conceptual systems
  - Determine key factors affecting cost estimates

Approach

Photobiological Systems

- **5 Organisms:** Characterize H_2 production
- **4 Reactor Concepts:** Define operation process
- **5 Plant Designs:** Design a reactor and plant for each organism

Fermentation & Microbial Electrolysis Systems

- Fermentation using waste organisms from photobiological systems
- Fermentation using lignocellulose feed
- MEC (Microbial Electrolysis Cell) systems using acetate feedstocks

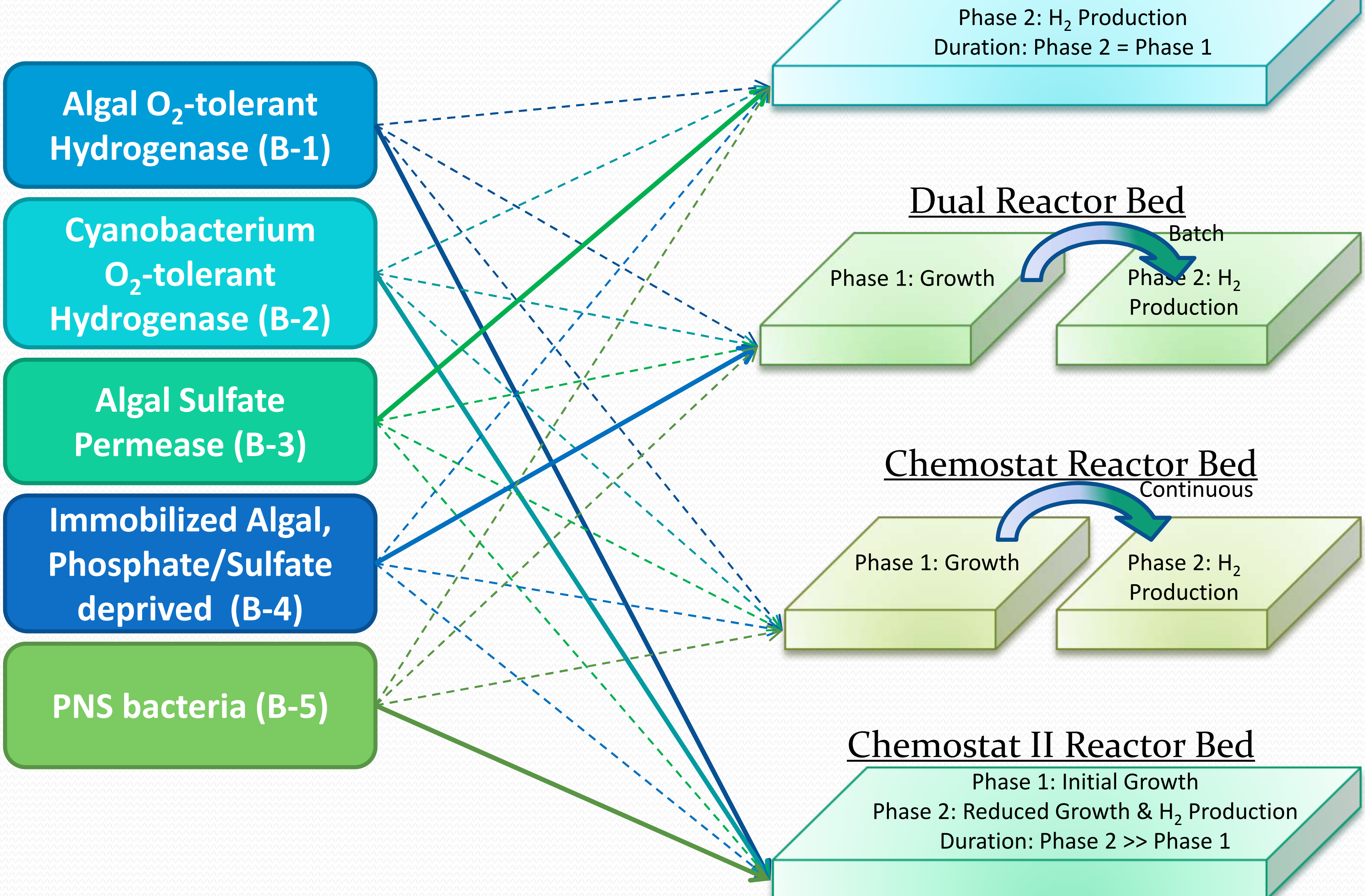
Integrated Systems

- Combined photobiological systems
- Combined photobiological and fermentation systems
- Combined fermentation and MEC systems

Photobiological Approach

1. Define growth and hydrogen production characteristics of the photobiological organisms
2. Preliminary Evaluation of various reactor systems
3. Downselect reactor bed design: cost criteria, production efficiency, land efficiency
4. Design auxiliary systems and conceptual plant (modular approach)
5. Develop bill of materials and capital costs
6. Calculate levelized H_2 cost by performing H2A analysis
7. Repeat with each organism

Organisms & Reactor Beds

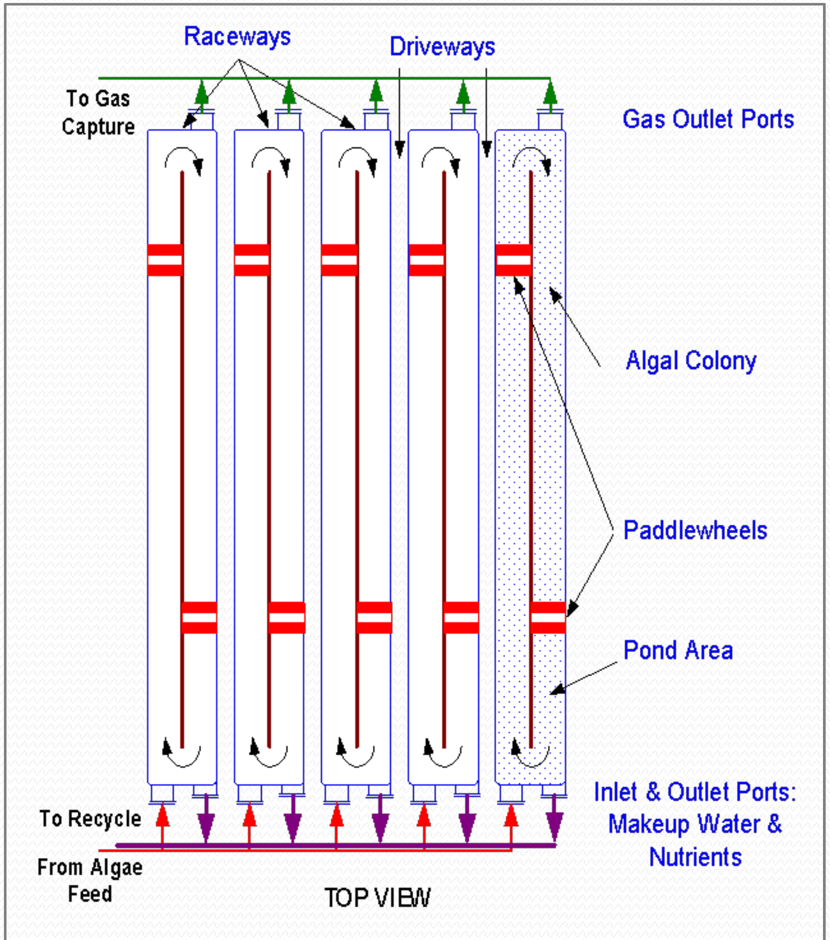


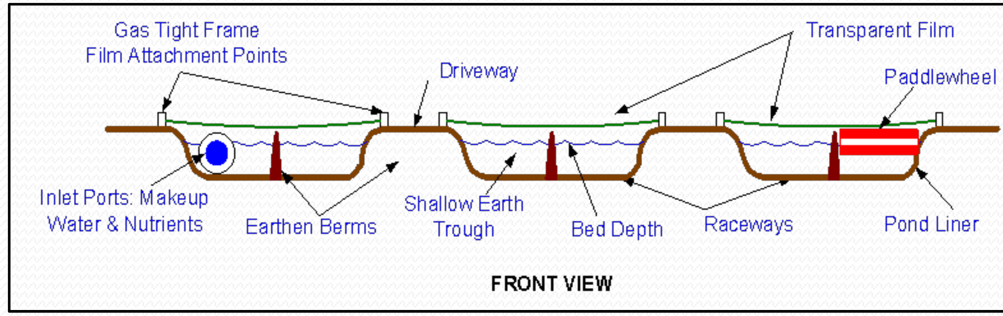
Organism Characterization/Assumptions: 1 TPD Module

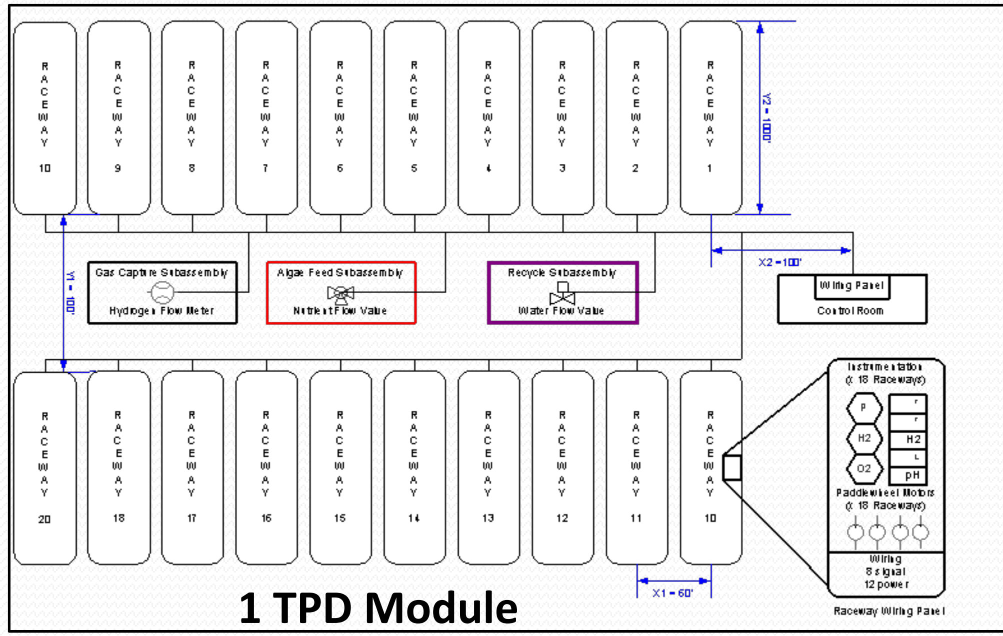
	Algal O2-tolerant Hydrogenase	Cyanobacteria O2-tolerant Hydrogenase	Algal Sulfate Permease Mutant	Immobilized Algal, Phosphate& Sulfate deprived	Purple Non-sulfur (PNS) Bacteria
Subsystem Path ID	B-1	B-2	B-3	B-4	B-5
Reactor Bed Type	Chemostat II	Chemostat II	Single-Bed	Dual-Bed	Chemostat II
H_2 Production Rate	1111 kgH_2/day	1111 kgH_2/day	1111 kgH_2/day	1111 kgH_2/day	1111 kgH_2/day
Number of Raceways	20	20	36	64 Production 4 Growth	38
Dimensions of Raceways (ft) (LxWxD)	1090'x40'x0.33' (10 cm)	1090'x40'x0.33'	1090'x40'x0.33'	1060'x40'x0.33'	1060'x40'x 0.33'
Reactor Bed Area (acres)	20	20	35	65	37
Cell line	C. reinhardtii cc124	Synechocystis H2ase mutant	C. reinhardtii cc124	C. reinhardtii cc124	Rhodobacter sphaeroides RV
Antennae Type	LHC (Light Harvesting Complex) deletion Mutant	Phycobilin deletion Mutant	LHC deletion Mutant	LHC deletion Mutant	LHC - II deletion Mutant
Types of Macro- and Micro-Nutrients	Fertilizer containing K, N, and P, CO2	Fertilizer containing K, N, and P, CO2	Fertilizer containing K, N, and P	Fertilizer containing K, N, and P	Fertilizer containing K, N, and P, Organic acids
Cell Concentration (g/L – Dry Wgt)	0.2	0.2	0.2	26	0.2
Deprivations from media (During H_2 Production)	CO_2 deprived	CO_2 deprived	none	Phosphate and Sulfate deprived	Nitrogen deprived
Duration of Production Cycle (days)	Inf. continuous	Inf. continuous	3 days production 4 days growth	25 (300 hrs)	Inf. continuous
Product Gases Produced	H_2, O_2	H_2, O_2	H_2, CO_2	H_2, CO_2	H_2, CO_2
Theoretical Product Gas Ratio	2 mol H_2 1 mol O_2	2 mol H_2 1 mol O_2	2 mol H_2 1 mol CO_2	2 mol H_2 1 mol CO_2	2 mol H_2 1 mol CO_2
STH Energy Efficiency: *upper bound*	9.2%*	9.2%*	5.2% *	3%	5%
STH Energy Efficiency: *current level*	-	-	-	0.8%	2.5%

* level based on 100% utilization of PAR photons for growth and H2 production and with no light saturation limit

Reactor Bed Design & Plant Layout





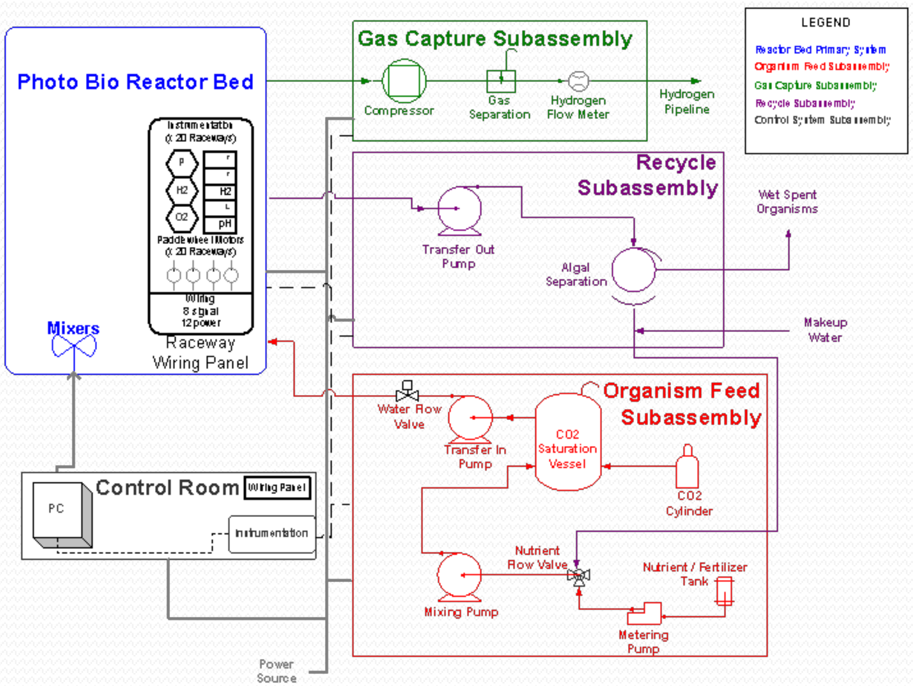


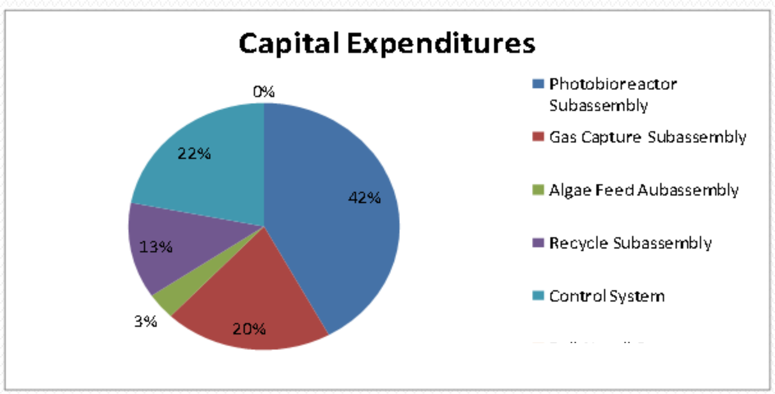
10 TPD Plant Capacity = 1 TPD Module x 10
1 TPD Module(at 9.2% STH efficiency) = 20 reactor beds (raceways) over 26 acres
1 Raceway = 1090 ft x 40 ft x 0.33ft

Plant Design

Algal O_2-tolerant Hydrogenase (B-1)

Process Diagram





Bill of Materials: 1 TPD Module

Description	Size Req'd	Units	Unit Size	Units	Unit cost	Qty Req'd	Total Cost
Photo Bio Reactor Bed Subassembly							
Transparent Film	87080	m2	1	m2	$ 0.54	87,080	$ 46,871
Pond Lining	93998	m2	1	m2	$ 0.47	93,998	$ 44,412
Pond Edging	13982	m	1	m	$ 7.00	13,982	$ 97,876
Installation of Ponds			1	raceway	$ 26,083.00	20	$ 521,660
Paddlewheel Mixers			1	each	$ 5,000.00	40	$ 200,000
Inlet Water Valve	0.5	in	1	each	$ 43.46	20	$ 869
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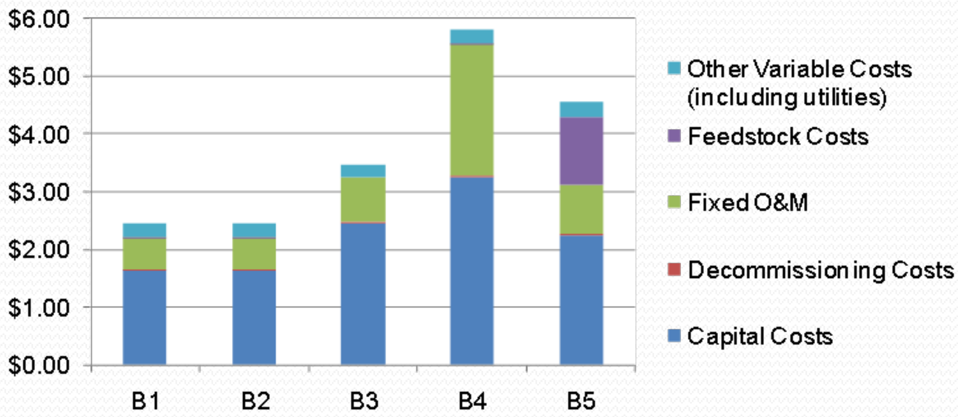
Outlet Gas Valve	1.0	in	1	each	$ 67.23	20	$ 1,345
Flanges	0.5	in	1	each	$ 8.00	60	$ 480
Gas Capture Subassembly							
Compressor	37	kgmol/hr	37	kgmol/hr	$ 9,233.00	1	$ 338,347
PSA					$ 89,215.16	1	$ 89,215
Piping - 4"	1180	ft	1	ft	$ 6.18	1180	$ 7,292
Piping - 1"	40	ft	1	ft	$ 1.00	40	$ 40
Organism Feed Subassembly							
Transfer In Pump	150	gpm	150	gpm	$ 10,252	1	$ 10,252
Nutrient Metering Pumps			1468	Gal/Hr.	$ 2,594	7	$ 18,158
Mixing Pump	150	gpm	150	gpm	$ 10,252	1	$ 10,252
CO2 Cylinder	50	lb	50	lb	$ 360	1	$ 360
CO2 Saturation Vessel	15000	gal	15000	gal	$ 30,000	1	$ 30,000
Nutrient Tank	8	gal	10	gal	$ 30.00	1	$ 30
Initial Medium	3.80	lb/Acre/yr	1	Acre	$ 0.76	20	$ 15.21
CO2 Gas	156	lb CO2	50	lb CO2	$ 35.00	3	$ 112
Water	2142022	gal	1	gal	$ 0.001665	2,142,022	$ 3,566
Piping - 1/2"	40	ft	1	ft	$ 0.52	40	$ 21
Piping - 1.5"	1180	ft	1	ft	$ 1.57	1180	$ 1,853
Piping - 2"	180	ft	1	ft	$ 2.12	180	$ 382
Recycle Subassembly							
Rotary Drum filter	9639	gph	3750	gph	$ 87,000.00	3	$ 261,000
Transfer Out Pump	150	gpm	150	gpm	$ 10,252	1	$ 10,252
Piping - 1/2"	40	ft	1	ft	$ 0.52	40	$ 21
Piping - 1.5"	1180	ft	1	ft	$ 1.57	1180	$ 1,853
Control System							
Control Room	160	ft2	1	ft2	$ 50.00	160	$ 8,000
Control Room Wiring Panel			1		$ 3,000.00	1	$ 3,000.00
Raceway wiring Panel			1		$ 146.00	20	$ 2,920
Computer and Monitor			1		$ 1,500.00	1	$ 1,500.00
Labview Software			1		$ 4,299.00	1	$ 4,299.00
Level Indicators			1		$ 3,000.00	20	$ 60,000.00
Pressure Sensors			1		$ 4,700.00	20	$ 94,000.00
Hydrogen Area Sensors			1		$ 5,500.00	20	$ 110,000.00
Air Temperature Indicator			1		$ 1,800.00	20	$ 36,000.00
Water Temperature Indicator			1		$ -	20	$ -
pH level Indicator			1		$ 1,200.00	20	$ 24,000.00
Oxygen Area Sensors			1		$ 5,500.00	20	$ 110,000.00
Nutrient Flow Valve			1		$ 5,500.00	1	$ 5,500.00
Water Flow Valve			1		$ 5,500.00	1	$ 5,500.00
Hydrogen Flow Meter			1		$ 5,500.00	1	$ 5,500.00
Instrument Wiring	69270	ft	1	ft	$ 0.02	69270	$ 1,343.84
Power Wiring	102150	ft	1	ft	$ 0.02	102150	$ 1,981.71
Conduit	4810	ft	1	ft	$ 0.58	4810	$ 2,788.84
						System Initial Cost	**$ 2,173,735**

Study Results - Photobio

	B-1	B-2	B-3	B-4	B-5
Bed Type	Chemostat II	Chemostat II	Single Bed	Dual Bed	Chemostat II
Total Bed Area (m^2)	809,680	809,680	1,433,230	2,493,830	1,496,300
Solar to H_2 Efficiency (%)	9.2%*	9.2%*	5.2%*	3.0%	5.0%
Production (kg H_2/day)	10,000	10,000	10,000	10,000	10,000
Capital Cost ($M)	21.73	21.73	32.84	43.43	33.92
Cost ($/kg$H_2$)	**2.41**	**2.41**	**3.47**	**5.67**	**4.41**
Product Mix	2 mol H_2 + 1 mol O_2 (Potential Combustion Issues)		2 mol H_2 : 1 mol CO_2		

* level based on 100% utilization of PAR photons for growth and H2 production and with no light saturation limit



Plant Capital Costs minimized by accumulating product H_2 in pond headspace and sizing gas processing for 24 hr/day operation.

Dark Fermentation & MEC Systems

- **Fermentation of Algae or Bacteria**
  - Evaluate H_2 production capability from photobiological system waste
  - Feedstock of 2.3 TPD, Generates 7 kg/day H_2
- **Fermentation of Corn Stover**
  - Developed from NREL report on ethanol production from corn stover[1]
  - Use bacteria developed by NREL for H_2 production with acetate byproduct
  - Size based on feedstock of 2,000 TPD corn stover, Generates 41 TPD H_2
- **Microbial Electrolysis Cell (MEC)**
  - Uses byproduct acetate from fermentor, or purchased acetate
  - Process design based on experimental work done at Penn State[2]
  - System Generates 104 TPD H_2
- **All Systems**
  - Design plant, develop bill of materials, compute capital cost, operating cost, feedstock cost
  - Perform levelized hydrogen cost computations

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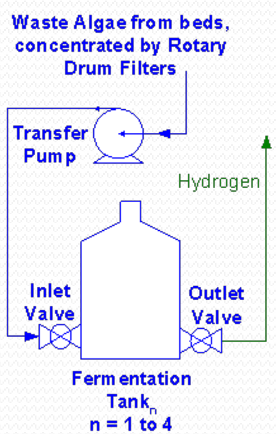
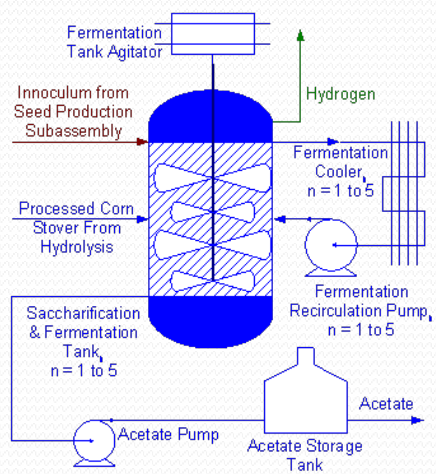
[1] A. Aden, et al., "Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover", NREL/TP-510-32438, June 2002.
[2] D. Call, et al "High Surface Area Stainless Steel Brushes as Cathodes in Microbial Electrolysis Cells", Environ. Sci. Technol, 2009.

System Designs

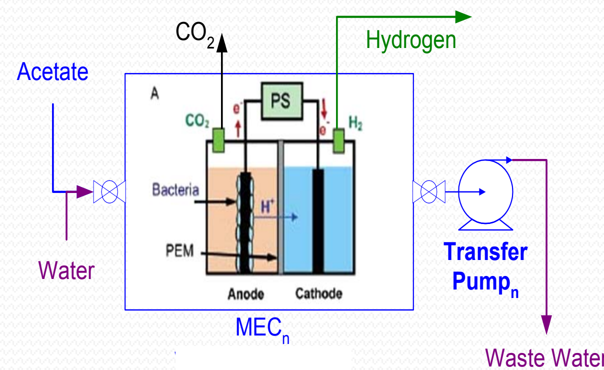
Parameters	Algal Fermentor	Lignocellulosic Fermentor	MEC
Design Basis	NREL Research	NREL / TP-510-32438 (ethanol) NREL H_2 Bacteria Research	Penn State Research, NREL Research
Feedstock	Waste Algae/ Bacteria from Photobio	Corn Stover	Acetic Acid
Feedstock Usage (kg/day)	2,312– 4,272	2,000,000	852,530
Reactor Parameters	55 ^oC Fermentation	150 ^oC Hydrolysis 55 ^oC Saccharification & Fermentation	40 ^oC 0.9 Volt Potential
Electricity Usage (kWhr/day)	43-58	163,356	3,340,862
Residence Time (hours)	72	36	24
# of primary reaction Vessels	4 (2500 – 4500 gallons)	5 (1 million gallons each)	113 (1 million gallons each)
H_2 Production Rate (kg/day)	~7-13	41,315	104,410
Mass Conversion rate (kg H2/kg feedstock	0.4%	2.5%	12%



Algal Fermentor
(4 units used)

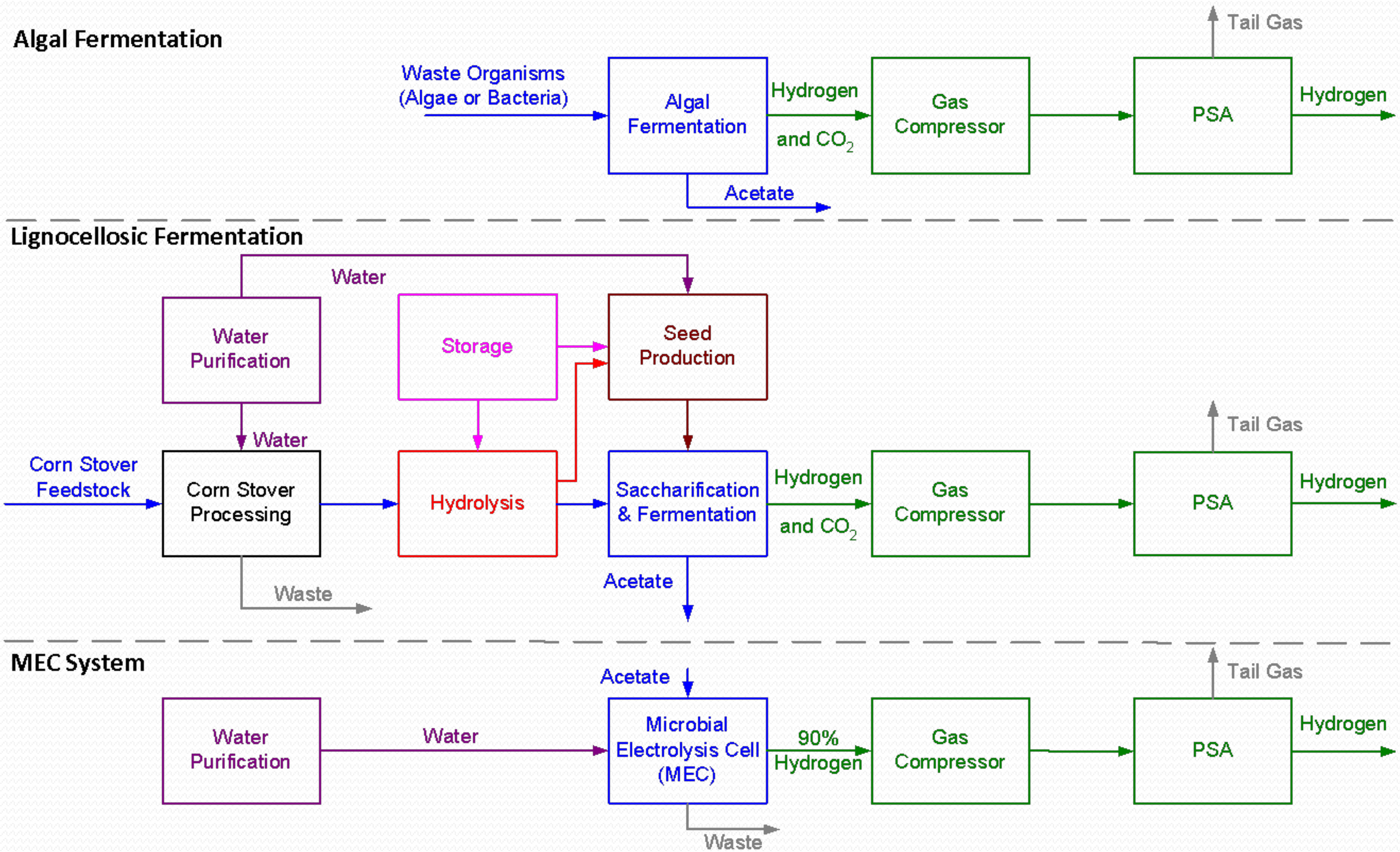


Lignocellulosic Fermentor
(5 units used)



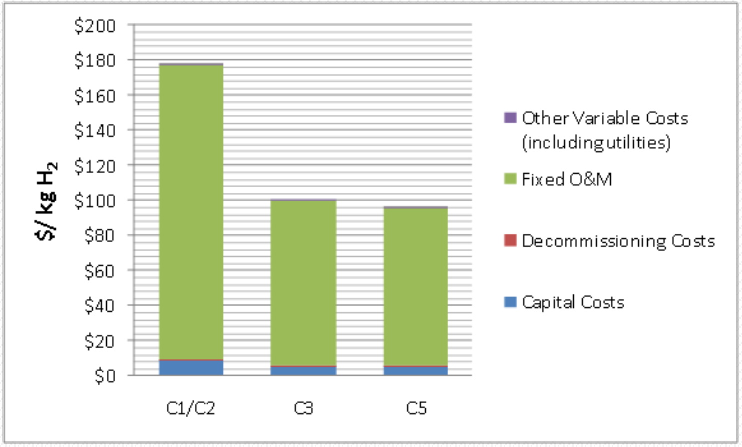
MEC
(113 units used)

Fermentation Plant Process Diagrams



Algal Fermentation Results

System Criteria	C-1	C-3	C-5
Organism Input Basis	B-1 or B-2	B-3	B-5
Feedstock	Algal or Cyanobacterium O_2-tolerant Hydrogenase	Algal Sulfate Permease	PNS Bacteria
Feedstock Usage (kg/day)	2,312	4,092	4,272
Production (kg H_2/day)	7	12	13
Capital Cost ($)	$52,198	$80,351	$86,211
Cost ($/kg H_2)	**$178.40**	**$103.45**	**$98.99**
Mass Conversion (kg H2/kg feedstock)	0.4%	0.4%	0.4%



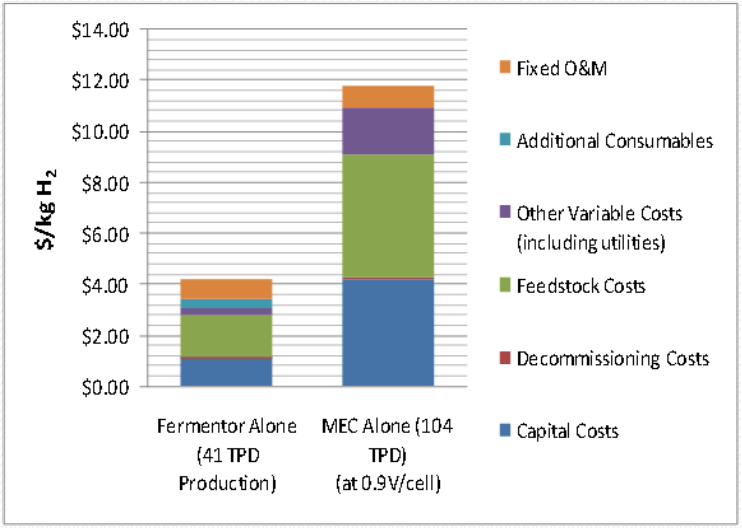
- Feedstock is spent waste from single 10TPD Photobio System
- Stand-alone system costs assume no cost algae feedstock
- Current low conversion rate yields high Capital Cost / per kg H_2
- Systems are too small: labor (in fixed O&M) is very high % of cost

  (with zero labor cost , hydrogen cost would be $6.54-$7.47/kg H_2)

System requires algal waste of very large photobiological systems to achieve suitable throughput volume. Also, organism waste transportation will add additional expenses.

Lignocelloulose Fermentor and MEC Results

	Lignocellulosic Fermentor	MEC
Feedstock	Corn Stover ($30/ton dry)	Acetate + Electricity (at $0.60/kg acetate)
Area (acres)	11 (+ 500 acres for long term corn stover storage)	10
Production (Tonnes H_2/day)	41	104
Mass Conversion (kg H_2/kg Feedstock)	2.6%	12.9%
Capital Cost ($M)	$47.5M	$563.9M
H_2 Cost ($/kg H_2) - No acetate sale - $0.20/kg acetate sales	 $4.18/kg H_2 $0.65/kg H_2	 $11.79/kg H_2 NA

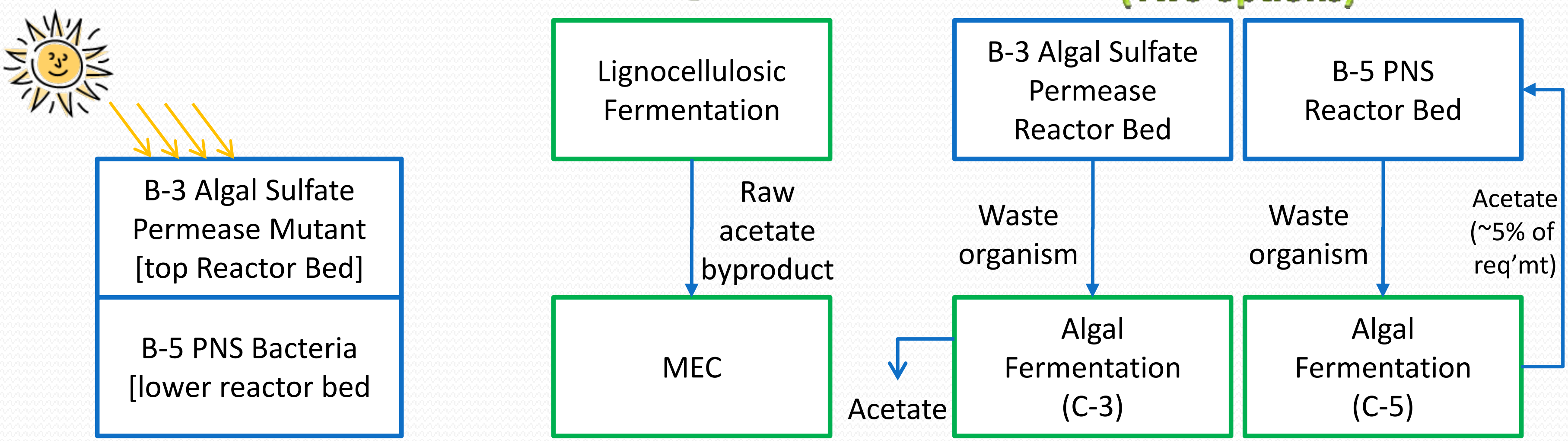


- MEC sized for potential integration with fermentor as acetate byproduct processor
- High Fermentor/MEC integration potential: raw fermentor byproduct readily used as MEC feedstock
- Sale of fermentor byproduct acetate drives down fermentor H_2 cost: acetate purification cost needs to be quantified
- Fermentor design based on production ethanol plant and thus has higher cost confidence than MEC design
- MEC H_2 cost is dominated by high cathode cost and high acetate dilution % (high system volume): and further developments to reduce these would greatly improve system cost effectiveness

Lignocellulose fermentor offers pathway to ~$1/kg H_2 due to byproduct acetate sales

Integrated Systems

Photobiological Stacked Beds | **Fermentor/MEC Integration** | **Photobio-Fermentor Integration (Two options)**



Photobiological Stacked Beds

- Lower bed organism captures photons outside of photosynthesis band of top bed organism
- Shared excavation and labor costs
- Resized BOP subassemblies

Fermentor/MEC Integration

- Ligno byproduct stream = MEC feedstock
- Shared water purification system
- Separate gas processing systems

Photobio-Fermentor Integration (Two options)

- C-3 and C-5 are sized to accept B-3 and B-5 waste respectively.
- Integration reduces labor and gas processing costs associated with Algal Fermentation
- IB-5/C-5 Integration slightly reduces acetate costs for PNS

These combinations were selected from several possible combinations and others can be explored based on the synergies of their flowstreams.

Integrated Systems Results

Photobiological Stacked Beds	
System	$/kg H_2
Stand alone B-3 (10 TPD)	$3.47
Stand alone B-5 (10 TPD)	$4.41
Integrated (12 TPD)	$4.33

Photobio & Organism Fermentor		
System	$/kg H_2	$/kg H_2
Stand alone Photobio 10 TPD	$3.47 (B-3)	$4.41 (B-5)
Stand alone Algae Fermentation (~0.02 TPD)	$103.45 (C-3)	$98.99 (C-5)
Integrated (~10.02 TPD)	$3.62	$4.96

Lignocellulose Fermentator & MEC	
System	$/kg H_2
Fermentor alone 41 TPD	$4.18 (~$1.00 with acetate sale)
MEC alone 104 TPD (not optimized for lowest cost)	$11.79
Integrated 144 TPD (unoptimized)	$4.18 from fermentor $6.48 from MEC $5.83 combined

- Algal Fermentation & MEC a possibility for future integration
- MEC based on PSU research data, not optimized for lowest capital cost
- Integration of more than 2 systems possible, but can be logistically difficult

Integrated systems make best use of land and waste products.
Further developments can yield more cost effective systems.

Collaborations

Collaborator	Organization	Role/Expertise
Bio-Hydrogen Working Group	DOE	System and Organism Guidance
- Tasio Melis	UC - Berkeley	Photobiological systems
- Maria Ghirardi	NREL	Photobio organisms & Fermentation processes
- PinChing Maness	NREL	PNS organisms & Fermentation processes
- Mike Seibert	NREL	Immobilized Algal systems, Sulfur deprived (B-4)
Gerald C. Dismukes	Princeton Univ.	Consultant, Photobio
Bruce Logan	Penn State Univ.	MEC system data

Summary

- Technoeconomic Boundary Analysis Conducted
  - Defined and Evaluated 4 different H_2 Production approaches
    - Photosynthesis with algae and bacteria, waste algae fermentation, lignocellulose fermentation, and microbial electrolysis
    - Approaches included multiple system embodiments and system integrations
  - Estimated concepts' feasibility, performance, and cost and resultant \$/kg H_2
  - Provided systems contexts and issues to researchers
- Plant performance based on component performance projections
  - Photosynthesis systems
    - Postulated advanced truncated antenna mutants without light saturation limit yield 5-9% STH efficiency (best case result)
    - Such mutants are in development, however, current STH efficiency is much lower <1%
    - Large shallow reactor beds with thin film cover are most economic approach
    - Results point to future H_2 costs with mutants ~\$2.40-6.00/kg H_2
  - Algal Fermentation
    - Based on experimental results, Utilizes waste organisms from photobio systems
    - Resulting high cost due to effects of labor cost and low H_2 Production ~\$100/kg H_2

Summary (continued)

- Lignocellulose Fermentation
  - Complicated process, but well defined from ethanol production examples
  - Assumed Hydrolysis process and fermentation bacteria are technical advances
  - Predicted H_2 price of $4.18/kg could be lowered to ~$1.00/kg with byproduct sales (exact byproduct composition and treatment not yet defined)
- Microbial Electrolysis Cell
  - Promising experimental results used as basis for analysis
  - Significant scale-up issues for production not yet resolved
  - Current immature production concept suggests H_2 price of $11/kg using purchased acetate or $5.80/kg using no-cost acetate from fermentor
  - Extensive cost reduction potential from system component development
- Integrated systems
  - 4 integrated systems examined
  - Significant symbiotic effect with Fermentor/MEC combination but not with others
  - Examination of additional concepts may lead to additional improvement
- Extensive collaboration/coordination with DOE Bio-Hydrogen Working Group

Proposed Future Work

- Integrated Systems
  - Validate costs and scaling benefits and alternative pathways
- Photobio Systems
  - Sensitivity analysis including effects of algae photon utilization rate saturation (e.g., electron transport rate saturation of truncated antenna mutants)
  - Alternative reactor bed concepts
  - More mature design study addressing mixing and pH control, thermal control, CO_2 absorption
- Algae Fermentation Systems
  - Pre-treatment of algae (e.g., hydrolysis) to increase conversion rate
  - Large-scale production using high glucose algae grown specifically for fermentation
- Lignocellulose Fermentation System
  - More detailed analysis/verification of subsystems
  - Analysis of byproduct utilization and consequent reduction in effective $/kg$H_2$.
- MEC System
  - Optimized production process and components for low capital cost system
    - Increased solution density, Increased pressure operation
    - Low cost cathodes and anodes
    - Cathode and anode optimization for large reactors
  - Determination of ion transport loss increases in large scale reactors