II.H.2 Technoeconomic Boundary Analysis of Photoelectrochemical (PEC) Hydrogen Producing Systems

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Objectives

- Develop conceptual designs of four system configurations to produce hydrogen (H_2) using photoelectrochemical (PEC) processes.
- Calculate capital costs, operating costs and feedstock costs for conceptual designs.
- Perform boundary level economic and technical analysis using the current state of technology and future predictions.
- Compute levelized hydrogen costs for conceptual design.
- Determine key factors affecting cost estimates and quantify necessary improvements in the technology and system performance.

Technical Barriers

This project addresses the following technical barriers from Section 3.1 - Hydrogen Production of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(AD) System Design and Evaluation

(AE) Diurnal Operation Limitations

Technical Targets

This project is conducting systems engineering analysis for PEC H_2 production. These studies and their results support the accomplishment of Hydrogen Production section milestones from the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan, namely;

- **Milestone 30:** Update technoeconomic analysis on the projected technology.
- **Milestone 31:** Identify materials/systems with a 2.3-eV useable semiconductor bandgap, 8% plant solar-to-hydrogen efficiency, and projected durability of 1,000 hours.

Accomplishments

- Designed single bed 'baggie' reactor for colloidal suspension system producing H_2 and O_2 mixed at an expected price of \$1.89/kg H_2.
- Designed dual-bed 'baggie' reactor for colloidal suspension system capable of producing separated H_2 at an expected price of \$3.56/kg H_2.
- Designed PEC cell panel concept for system capable of producing H_2 at an expected price of \$10.20/kg H_2.
- Designed a concentrator PEC system concept for a system capable of producing H_2 at an expected price of \$3.98/kg H_2.
- Concluded that primary factors affecting hydrogen costs from these systems are photoelectrode efficiency, material costs, and lifetimes.

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Introduction

Renewable resources such as solar, wind and biomass are ideal hydrogen feedstocks because of their sustainability and clean nature. This study focuses on PEC hydrogen production from sunlight using both colloidal photoparticle suspension and photoelectrode cell technologies. The project goal is to design reactor systems which capitalize on the hydrogen producing capabilities of these technologies and predict costs of H_2 plants, including gas compression and separation, for continuous gas production. Baseline analyses of four PEC systems were performed with a sensitivity analysis showing sensitivities to performance assumptions for equipment, materials, and design. Economic potential of each system was postulated and compared to DOE metrics.

This effort will inform the DOE of predicted costs of H_2 as produced by various PEC methods. In turn, DOE will better understand the potential of this technology for H_2 production and be better able to allocate future resources to the most promising H_2 production alternatives.

Approach

For each of the four PEC systems, this analysis defined hydrogen production characteristics, individual reactor designs, and balance-of-plant equipment. This information was used to compute capital costs and levelized hydrogen costs. The analysis leveraged concepts, reactor parameters, and material assumptions generated by the PEC Working Group. The analysis was based on developing a large plant size from several smaller modules. Each module was sized for 1 tonne/day (TPD) H_2 production with large quantities of similar components within a single module. Additional capital cost reductions as a result of increased purchase quantities are not likely thus, capital costs of larger plants increase linearly. Most of the cost benefit is gained in the initial increase in plant size so a 10 TPD plant size was chosen. All of the systems used condensers and pressure swing adsorber (PSA) units, as necessary, to separate the H_2 from the O_2 and water vapor present in the gas stream. For three of the systems, a compressor with intercoolers was needed to compress the reactor output gases.

A sensitivity analysis for each PEC system was conducted to examine the cost effect of three parameters, namely; efficiency, PEC particle or cell cost and particle or cell lifetime. Each of the systems and the parameter boundaries explored are listed in Table 1. Efficiency is defined as the solar-to-hydrogen conversion efficiency i.e., net hydrogen lower heating value divided by total solar energy input.

Results

1. The Single Bed system using colloidal particles has a 'baggie' transparent plastic tube design to contain the water/particle mix and the product gases. This system raised hazard issues as to the stoichiometric mix of H_2 and O_2.
2. The Dual-Bed system using colloidal particles has a dual 'baggie' design, shown in Figure 1, using separate bags for H_2 and O_2 generation. The ion bridge between bags allows ion transport, but prevents gas bubble transport. The slurry is circulated through perforated pipes to promote mixing within the bed and across the bridge.
3. The PEC Panel system uses thin film multilayer photovoltaic (PV) components with water and gas manifolds, mounted on 1 m x 2 m fixed geometry panels. The PEC system for 1 TPD H_2 output contains 30,000 panels (60,000 m^2).
4. The Concentrator PEC system uses solar collectors with a 10:1 concentration ratio steerable in azimuth and elevation. Each PEC receiver unit mounted on a collector uses a multilayer PV cell with water and gas manifolds and is operated at 300 psi to allow elimination of the compressor.

TABLE 1. Sensitivity Parameters and Boundary Conditions

	Low Cost	Baseline	High Cost
Type 1 - Single Reactor Bed Colloidal Suspension System			
Efficiency	20%	10%	5%
Particle Life	10 yr	5 yr	1 yr
Particle Cost	$152/kg	$304/kg	$9120/kg
Type 2 - Dual Reactor Bed Colloidal Suspension System with Ion Bridge			
Efficiency	20%	10%	5%
Particle Life	10 yr	5 yr	1 yr
Particle Cost	$152/kg	$304/kg	$9120/kg
Type 3 - Thin Film PV System with Fixed Positioning			
Efficiency	20%	10%	5%
PV Life	20 yr	10 yr	5 yr
PV Cost	$40/m^2	$100/m^2	$200/m^2
Type 4 - Thin Film PV System with Tracking and Concentrators			
Efficiency	25%	15%	10%
PV Life	20 yr	10 yr	5 yr
PV Cost	$40/m^2	$100/m^2	$200/m^2

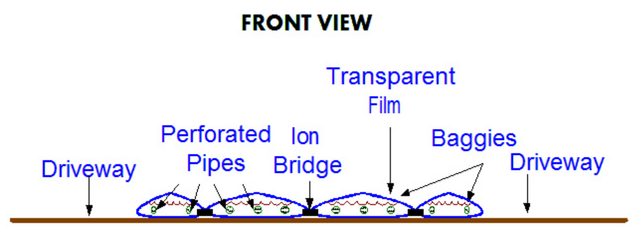

FIGURE 1. Type 2 Reactor Bed Conceptual Design

For the systems above, the feasibility, performance, capital cost, and resultant $/kg H_2 were evaluated using each of the given sensitivities. Production costs are summarized in Table 2.

Conclusions and Future Directions

The analyses for Types 1 – 4 are essentially complete. Further work needs to be done on control system costs and other system cost details. This analysis

TABLE 2. H_2 Production Costs

Type 1		Type 2	
Baseline (10% efficiency, 5 year particle lifetime, $304/kg particle cost)	$ 1.89	Baseline (10% efficiency, 5 year particle lifetime, $304 /kg particle cost)	$ 3.56
5% efficiency	$ 2.39	5% efficiency	$ 7.63
20% efficiency	$ 1.63	20% efficiency	$ 2.02
1 year particle lifetime	$ 2.00	1 year particle lifetime	$ 3.71
10 year particle lifetime	$ 1.88	10 year particle lifetime	$ 3.49
$152 particle cost	$ 1.86	$152 particle cost	$ 3.48
$9120 Particle cost	$ 3.18	$9120 Particle cost	$ 5.74
Type 3		**Type 4**	
Baseline (10% efficiency, 10 year PV lifetime, $100/m^2 PV cost)	$10.20	Baseline (15% efficiency, 10 year PV lifetime, $100/m^2 PV cost)	$ 3.84
5% efficiency	$19.39	10% efficiency	$ 5.61
20% efficiency	$ 5.61	25% efficiency	$ 2.47
5 year particle lifetime	$13.30	5 year particle lifetime	$ 4.02
20 year particle lifetime	$ 8.81	20 year particle lifetime	$ 3.77
$40/m^2 PV cost	$ 5.55	$40/m^2 PV cost	$ 3.62
$200/m^2 PV cost	$13.52	$200/m^2 PV cost	$ 4.21

produced several key findings which are listed below about PEC systems and how they can be used to generate H_2.

Type 1 System Findings:

- The product gas in this system is a stoichiometric mixture of H_2 and O_2 which raises safety issues.
- Lowest predicted H_2 costs.
- Composite nanoparticles with requisite voltages yet to be demonstrated.
- Indeterminate life of particles.

Type 2 System Findings:

- Low H_2 costs.
- Ion transport issues.
- Composite nanoparticles with requisite voltages yet to be demonstrated.
- Indeterminate life of particles.

Type 3 System Findings:

- Highest H_2 costs – large areas of PV component.
- Relies on low cost thin film PV material.
- Lifetime issues due to corrosion.

Type 4 System Findings:

- Low H_2 costs.
- Increased efficiency possible with PV development, and high temperature operation.
- Lifetime issues due to corrosion.

Based on the aforementioned findings, future work recommendations for each system are listed.

Type 1 System Recommendations:

- Resolve H_2/O_2 mixture issues.
- Develop nanoparticles with requisite photovoltage.

Type 2 System Recommendations:

- Develop ion-bridge between beds.
- Develop ionic charge carriers (I, Br, Fe, etc.).
- Develop nanoparticles with requisite photovoltage.
- Develop water circulation system.

Type 3 System Recommendations:

- Delay development until ultra-low cost multi-layer PV realized.

Type 4 System Recommendations:

- Develop low cost composite structures.
- Develop high pressure PEC operation.
- Investigate concentrator ratio ~20.
- Investigate high temperature operations, to increase efficiency or lower voltage requirement.

FY 2009 Publications/Presentations

1. 2009 DOE Hydrogen Program Review - Washington, D.C. – May, 2009. Presentation PD# 23.

2. H_2 Production Tech Team Mtg – Las Vegas, NV – 21 January 2009. Status Presentation.

3. PEC Program Review Meeting. Honolulu, Hawaii – 18 October 2008. Status Presentation.

References

1. Deutsch, Todd. “Photoelectrochemical Production of Hydrogen.” Presentation at NHA Fall Forum, Golden, CO., 22 Sep 2008.

2. Turner, John, “Photoelectrochemical Water Splitting” Presentation at 2008 DOE Program Review, June 2008.

3. McFarland, Eric, “Development and Optimization of Cost Effective Material Systems For Photoelectrochemical Hydrogen Production,” June 12, 2008.