STRATEGIC ANALYSIS INC

Guidance for Filling Out a Detailed H2A Production Case Study

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The H2A Production Model described in this presentation was developed with support from the Fuel Cell Technologies Office (FCTO) within the Office of Energy Efficiency & Renewable Energy (EERE), US Department of Energy.

9 July 2013

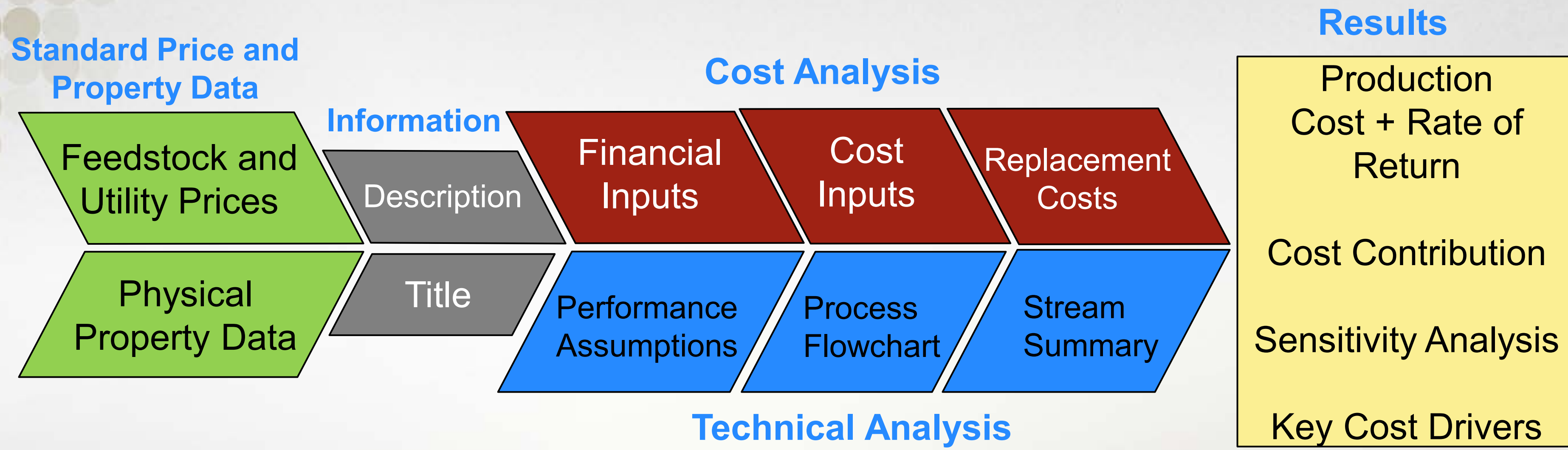
Outline and Purpose

- Explanation of H2A model capabilities, including comparing hydrogen (H_2) generation technologies and charting progress.
- As part of a DOE contract, one may be requested to prepare an H2A Case Study for a new H_2 generation technology.
- This presentation
  - Reviews elements of the H2A Excel Model;
  - Gives examples of fully detailed Case Studies;
  - Identifies key numbers, common pitfalls & errors;
  - Clarifies the level of depth, accuracy & transparency needed for a detailed analysis; and
  - Discusses metrics and common issues.

Overview of H2A

- H2A is a discounted cash flow analysis that computes the required price of H_2 for a desired after-tax internal rate of return (IRR)
- H2A uses custom macros within Microsoft Excel
- Latest analyses exist in H2A Version 3
  - Developed in 2012
- Two main types of H2A analyses:
  - production and delivery.
- Objective of H2A Analyses (production):
  - Establish a standard format for reporting the production cost of H_2, so as to compare technologies and case studies
  - Provide transparent analysis
  - Provide consistent approach

H2A Process Flow Diagram



H2A Model Description on Hydrogen and Fuel Cells Program website: http://www.hydrogen.energy.gov/h2a_analysis.html#data

Feedstock and utility prices (H2A default) linked to Annual Energy Outlook (AEO) Reference Case developed by DOE's Energy Information Administration (EIA) http://www.eia.gov/forecasts/aeo/index.cfm

Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model from Argonne National Lab: http://greet.es.anl.gov/main

Types of H2A Production Case Studies

Distributed (forecourt/filling station): 1 to 5 metric tons H_2 per day
Central: 100 to 500 metric tons H_2 per day

Current Case **("if you were fabricating today at production volume")**

- Could be a short term projection from current technology
- Assumes already identified advances in technology are implemented
- Potential reduction in capital cost from currently accepted values (due to production volume and/or identified design changes)
- Plant lifetimes assumed are consistent with either measured or reported data for equipment lifetimes installed in either the field or the laboratory.

Future Case

- More advanced materials could be used that have not been discovered
- Increased efficiency to produce H_2
- Longer plant lifetimes assumed
- Improved replacement cost schedule
- Greater reductions in capital cost

Ultimate Target Case

- Assumptions based on expected thermodynamic, physical, or economic limits of the technology.
- Generally expected to approach DOE production target of $2/kg H_2

H2A Governing Equations

Objective: Solve for required price of H_2 that returns a desired after-tax internal rate of return after adjusting for all expenses.

Method: Conduct **discounted cash flow analysis**, solving for required pump price that yields a zero net present value. (H2A spreadsheet automates entire process.)

Net Present Value (NPV) = sum of all present values (PV) of the cash flows (CF)

$$0 = NPV = \sum_{t=1}^{n} \frac{CF_t}{(1 + IRR)^t}$$

t = year
n = plant life
CF = cash flow
IRR = internal rate of return

CF_t = [**Yearly Revenues**: **H_2 Price x kg/year (i.e. H_2 Revenue)**; **Byproduct Revenue**] minus [**Yearly Expenses**: **Capital Related Costs**; **Decommissioning Costs**; **Fixed O&M**; **Feedstock Costs**; **Other Raw Material Costs**; **Other Variable Costs (including utilities)**; **Taxes**]

H2A considers the entire life of plant and accounts for inflation, and interest rates if provided. (not seen in equation above)

H2A Version 3 User Guide PDF:
https://apps1.hydrogen.energy.gov/cfm/h2a_active_folder/h2a_production/03P_H2A_Central_Hydrogen_Production_Model_User_Guide_Version_3_draft.pdf

Different Technologies Demonstrated within H2A

- **Past Production Case Studies**
  - Existing Technologies
    - Natural Gas Steam Methane Reforming (SMR) (Central/Forecourt)
    - Electrolysis (Central/Forecourt)
    - Ethanol Reforming (Forecourt)
    - Biomass (Central)
    - Coal Gasification (Central)
    - Nuclear Powered Water Splitting (Central)
  - Emerging Technologies
    - Photoelectrochemical (PEC) (Central)
    - Photo-Biological H_2 (Central)
    - Solar Thermochemical H_2 (STCH) (Central)

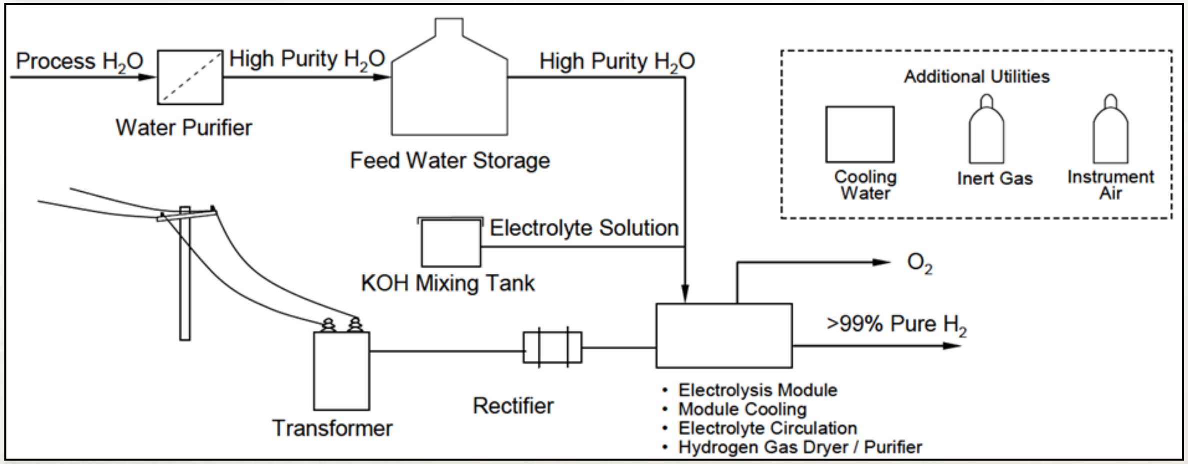
All production cases above can be found at: http://www.hydrogen.energy.gov/h2a_prod_studies.html

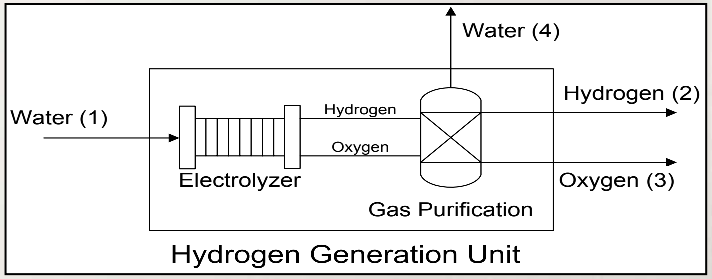
- **Type of Production Plants: Forecourt (distributed) and Central**
- **Next Generation of Production Case Studies**
  - Increased level of detail
  - Focus on Emerging Technologies
  - Uniform primary metrics (with individual sub-metrics)
  - Sensitivities (Tornado Chart)
  - May involve multiple versions to chart technology progress

➡ Today's presentation will use an electrolysis forecourt case study to illustrate issues to consider when using the model.

Electrolysis H2A Case: Current Forecourt

- Standalone grid powered electrolyzer system based on the Norsk Hydro bi-polar alkaline electrolyzer (Atmospheric Type No.5040 - 5150 Amp DC)
- Total production capacity of 1,500 kg H_2/day
- System Components:
  - Process water for electrolysis and system cooling
  - Transformer
  - Thyristor
  - Lye Tank
  - Feed Water Demineralizer
  - Hydrogen Scrubber
  - Gas Holder
  - 2 Compressor Units to 30 bar (435 psig)
  - Deoxidizer
  - Twin Tower Dryer





H2A Electrolysis Model: http://www.hydrogen.energy.gov/h2a_prod_studies.html

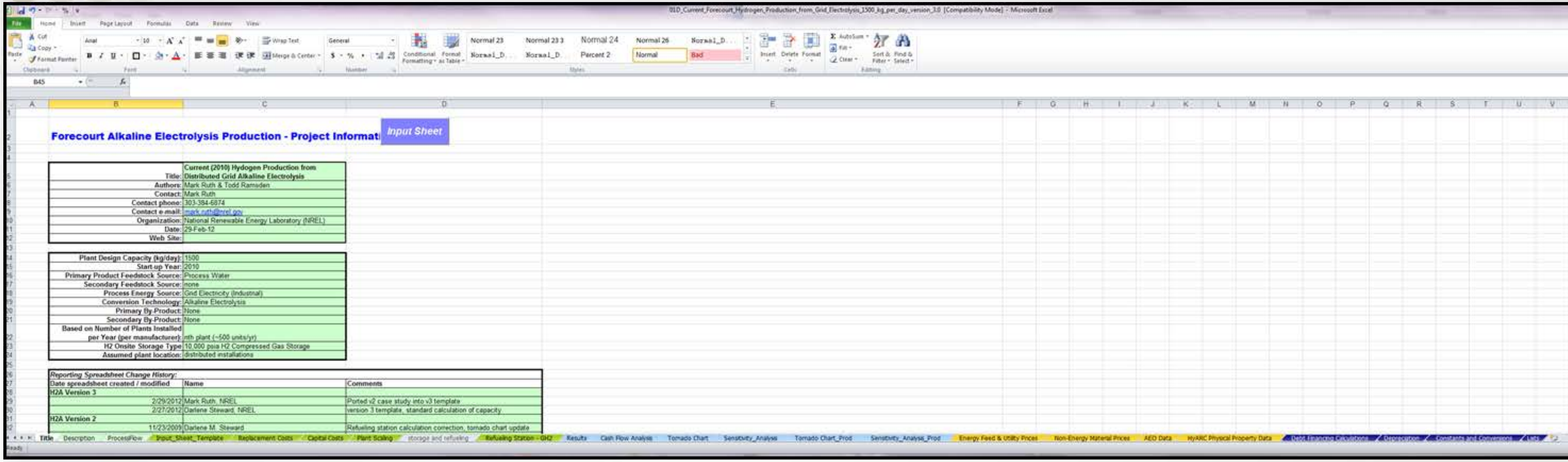
H2A Electrolysis Report (2009 Independent Review): http://www.hydrogen.energy.gov/pdfs/46676.pdf

Commonly Shared Features of H2A Across Technologies

(Using Electrolysis
Current Forecourt as an Example)

9

H2A Model Organization



Information: Title | Description | ProcessFlow

System Inputs: Input_Sheet_Template | Replacement Costs | Capital Costs | Plant Scaling

Results: Results | Tornado Chart | Sensitivity Analysis | Cash Flow Analysis

Standard Price and Property Data: Energy Feed & Utility Prices | Non-Energy Material Prices | HyARC Physical Property Data | AEO Data

Financial Calculations: Debt Financing Calculations | Depreciation | Lists | Constants and Conversions

H2A Project Information

Forecourt Alkaline Electrolysis Production - Project Information

Input Sheet

Title:	**Current (2010) Hydrogen Production from Distributed Grid Alkaline Electrolysis**
Authors:	Mark Ruth & Todd Ramsden
Contact:	Mark Ruth
Contact phone:	303-384-6874
Contact e-mail:	mark.ruth@nrel.gov
Organization:	National Renewable Energy Laboratory (NREL)
Date:	29-Feb-12
Web Site:	

Plant Design Capacity (kg/day):	1500
Start-up Year:	2010
Primary Product Feedstock Source:	Process Water
Secondary Feedstock Source:	none
Process Energy Source:	Grid Electricity (Industrial)
Conversion Technology:	Alkaline Electrolysis
Primary By-Product:	None
Secondary By-Product:	None
Based on Number of Plants Installed per Year (per manufacturer):	nth plant (~500 units/yr)
H2 Onsite Storage Type	10,000 psia H2 Compressed Gas Storage
Assumed plant location:	distributed installations

Important to report changes and version control

Reporting Spreadsheet Change History:		
Date spreadsheet created / modified	**Name**	**Comments**
H2A Version 3		
2/29/2012	Mark Ruth, NREL	Ported v2 case study into v3 template
2/27/2012	Darlene Steward, NREL	version 3 template, standard calculation of capacity
H2A Version 2		
11/23/2009	Darlene M. Steward	Refueling station calculation correction, tornado chart update
9/23/2008	Darlene Steward	Modified cooling water requirement per ASPEN modeling
9/23/2008	Darlene Steward	H2A Version 2.1 updates
5/19/2008	Todd Ramsden	Initial H2A Version 2 draft
2/21/2008	Brian D. James/DTI	H2A Forecourt Modeling tool v.2
5/27/2008	Darlene Steward	Tornado Charts added
7/2/2008	Todd Ramsden	Changes to process description

Title

Case Study Technology Description

Central Hydrogen Production - Description

Input Sheet

Purpose:

The purpose of this analysis was to analyze the technical and economic aspects of a process for production of hydrogen from the electrolysis of water using grid-based electricity.

System Description:

The system modeled is a standalone grid powered electrolyzer system with a total hydrogen production capacity of 52,300 kg/day. The system is based on the Hydro bi-polar alkaline electrolyzer system (Atmospheric Type No.5040 - 5150 Amp DC). The total electrolyzer system consists of 50 electrolyer units, each capable of producing 1,046 kg of hydrogen per day (485 Nm3 H2 per hour). The electrolyzer units use process water for electrolysis, and cooling water for cooling. KOH is needed for the electrolyte in the system. The system includes the follwing equipment: Transformer, Thyristor, Electrolyzer Unit, Lye Tank, Feed Water Demineralizer, Hydrogen Scrubber, Gas Holder, 2 Compressor Units to 30 bar (435 psig), Deoxidizer, Twin Tower Dryer

Analysis Methodology Summary:

Material and energy balances done manually, equipment costing and performance from projections and quotes.

This is generally a paragraph or two. Be as descriptive & detailed as conveniently possible.

Plant Ownership and Entity Type Assumptions:

Corporate ownership, 100% equity financed.

References:

Norsk Hydro Electrolysers Quote, Offer #: 106602, August 8, 2002

Hydro Website: http://www.electrolysers.com

Hydro "Atmospheric Electrolysers" brochure, http://www4.hydro.com/electrolysers/library/attachments/Brochures/49444_ProductSheet_2.PDF

Hydro NAS presentation, 2007. "NAS - Hydrogen" presented to NAS – Hydrogen Resource Committee, 4/19/07 (Knut Harg)

Norsk Hydro Electrolysers presentation, 2/13/2004.

PEP Yearbook 2002

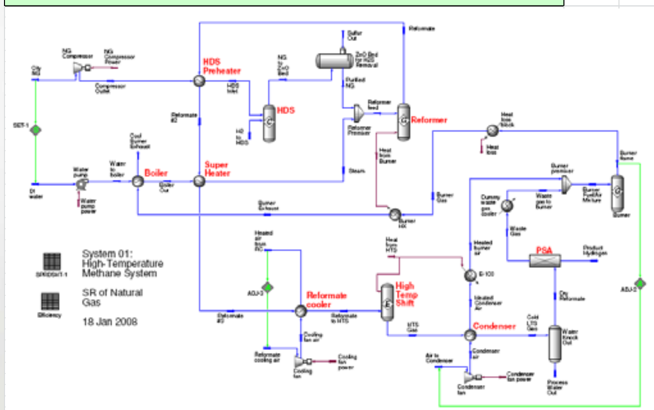
Description

System Schematic Concisely Informs Reader

Include both a diagram and table of key parameters at salient operating point.

Process Flow Diagram (PFD) (with output table) from Aspen/Hysys for Forecourt SMR

Process Flow Diagram

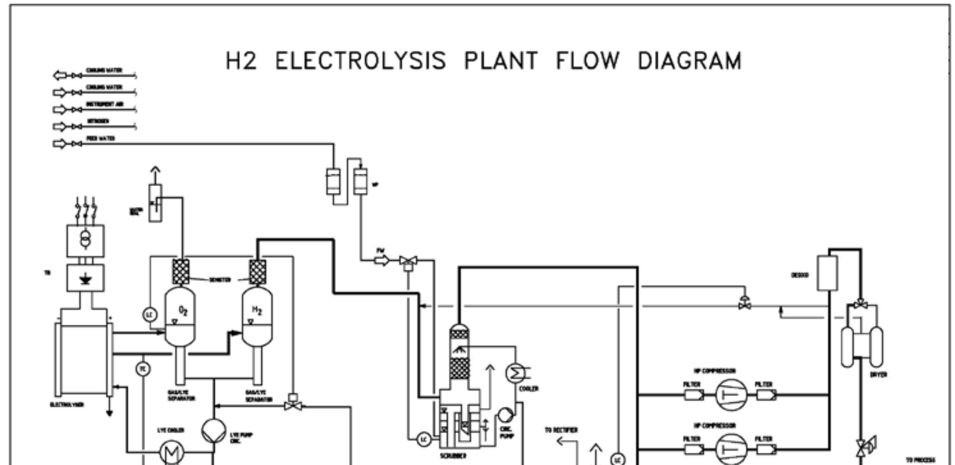


Stream Summaries

```
DIRECTED TECH                    Case Name: X:\DOE ETHANOL 2007 DISTRIBUTED REFORMING\REFORMER SYSTEMS ANALYSIS\SYSTEM 01 - SMR_PSA 2005 1
Calgary, Alberta
CANADA                           Unit Set: SI

                                 Date/Time: Thu Feb 21 17:28:46 2008
-------------------------------------------------------------------------------
Air to Condenser (Material Stream): Conditions, Properties, Composition, K Value
-------------------------------------------------------------------------------
Material Stream: Air to Condenser                          Fluid Package: Basis-1

                                                           Property Package: Peng Robinson
CONDITIONS

                                  Overall       Vapour Phase
Vapour / Phase Fraction           1.0000        1.0000
Temperature: (C)                  25.00         25.00
Pressure: (kPa)                   101.0         101.0
Molar Flow (kgmole/h)             188.5         188.5
Mass Flow (kg/h)                  5437          5437
Std Ideal Liq Vol Flow (m3/h)     6.285         6.285
Molar Enthalpy (kJ/kgmole)        -8.157        -8.157
Molar Entropy (kJ/kgmole-C)       155.7         155.7
Heat Flow (kJ/h)                  -1537         -1537
Liq Vol Flow @Std Cond (m3/h)     ---           ---
PROPERTIES

                                  Overall       Vapour Phase
Molecular Weight                  28.85         28.85
Molar Density (kgmole/m3)         4.077e-002    4.077e-002
```

ProcessFlow

Process Flow Diagram (PFD) with user created output table for Forecourt Electrolysis



Norsk Atmospheric Type No.5040 (5150 Amp DC)	Stream (1) Water			Stream (2) Hydrogen Product			Stream (3) Oxygen Product			Stream (4) Water Removal		
	l/hr	kg/hr	kmole/hr	Nm3/hr	kg/hr	kmole/hr	Nm3/hr	kg/hr	kmole/hr	l/hr	kg/hr	kmole/hr
Flowrate	0	0	0	0	0	0	0	0	0	0	0	0

Electrolyzer	
Optimum Temperature	80 C
Max Pressure	800 mm H2O g

Molecular Weight H2	2.016	kg/kmole
Molecular Weight O2	31.99	kg/kmole
Molecular Weight H2O	18.011	kg/kmole
Density of H2	0.0899	kg/Nm3
Density of O2	1.4289	kg/Nm3
Density of H2O	0.999839	kg/l

Energy Balance:

	System Energy Req't	Electro-lyzer Energy Req't	H2 Prod'n	System Power Req't	Indiv. Electro-lyzer Power Req't	LHV of H2	HHV of H2	System Energy Req't	Electrol. System Eff. (LHV)	Electrol. System Eff. (HHV)	Electrol. Stack Eff. (LHV)	Electrol. Stack Eff. (HHV)
Manufacturer Model	kWh/Nm3	kWh/Nm3	Nm3/hr	kW	kW	kWh/kg	kWh/kg	kWh/kg	%	%	%	%
Norsk Atmospheric Type No.5040 (5150 Amp DC)	4.8	4.3	485	0	2330	33.4	39.5	53.44	62.5%	73.9%	69.8%	82.6%

H2A Input Sheet

H2A Hydrogen Production Cash Flow Analysis Tool v3.0

1500 kg/day Hydrogen Production Capacity - Current Timeframe

View Description

Table of Contents

View and edit project in

H2A cell color co

H2A Color Coding

(light blue)	Calculated cell - Do not change values in these cells
(orange)	User input required
(red)	Error - Please review input
(light green)	User input information and notes. Color for detail calculation cells that are not linked to the Input Sheet.
(yellow)	H2A information and default values.

Use H2A default values — *Use Default Values*

d export data and perform analyses — *Toolkit*

Calculate Hydrogen Cost — *Calculate Cost*

Calculate Cost automatically takes you to Results tab, must be done to update model.

Input_Sheet_Template

Importance of Distinguishing Different Year $

Financial Input Values

Reference year	2007
Basis Year for production system costs	2005
Assumed start-up year	2010

Specified by DOE as 2007$

Reference year = dollar year for which results are reported (i.e. 2007$)

Basis year for costs = dollar year for entered capital costs (or feedstock prices that you manually enter)

Your choice. Use whichever year is most convenient. H2A spreadsheet will adjust to Reference year.

Assumed start-up year = year of plant start-up (used primarily in association with looking up the projected cost of feedstock and utilities)

Select year appropriate to your specific case study.

- User must be cognizant of difference between year $ values
- Easily updated in one location
- Estimated costs for equipment can be in different year $ than assumed start-up year or reference year
- General Rule of Thumb: start-up year is 5 years after technology has been demonstrated in the lab.

Input_Sheet_Template

Other Financial Parameters

When comparing technologies or case studies be consistent with these financial parameters:

- Plant life:
  - 20 years for Forecourt (H2A Default)
  - 40 years for Central (H2A Default)
- Operating capacity factor: 90% (H2A Default)
- Construction Period: 1 year
- Start up time: 0.5 years

These values may be changed (if there is a compelling reason)

- After-tax real Internal Rate of Return (IRR): 10%
- Depreciation Schedule: 7 years Modified Accelerated Cost Recovery System (MACRS)
- State Taxes: 6% (H2A Default)
- Federal Taxes: 35% (H2A Default)
- Working Capital: 1% (of yearly change in operating cost)

These values do not need to be modified

Input_Sheet_Template

Equipment and Installation Cost Calculation

PRODUCTION UNIT CAPITAL INVESTMENT (Inputs REQUIRED in basis year, (2005) $)						
Major pieces/systems of equipment	Uninstalled Costs $2005 Dollars	Baseline Uninstalled Costs $2007 Dollars	Installation Cost Factor	Baseline Installed Costs	Comments	Data Source
2 units of 1563 kW Electrolyzer systems @ 50 kWh/kg H2 (31.3 kg/hr units)		$ -		$ -		
Includes:		$ -		$ -		
Stack	663,600	$ 746,389	1.20	$ 895,667	Current cost of stack in central case is $213/kW (2005$) (65% of $327/kW). Stack costs are assumed to scale linearly so cost is kept at $213/kW resulting in 55.3% of system cost	Percentage of central cost (65%) from Electrolysis Working Group (3/8/2012)
Hydrogen Gas Management System	229,200	$ 257,794	1.20	$ 309,353	BOP costs scaled proportionally to cover non-stack portion of system cost ($384-$213=$171/kW). H2 management is 15% of the current central system cost, thus 15/35=4... of the BOP cost and scales to 19.1% of the dis...	Percentage of central cost (15%) from Electrolysis Working Group...
Electrolyte Management System	138,000	$ 155,217	1.20	$ 186,260	portion of system ... Electrolyte manag... central system cos... cost and scales to... cost	
Power Electronics				186,260	BOP costs scaled... portion of system ... Power electronics... system cost, thus... and scales to 11.5...	
Mechanical Balance...				42,111	BOP costs scaled... portion of system ... Mechanical BOP is... system cost, thus... scales to 2.6% of t...	
				-		
				-		
TOTALS				1,619,651		

Modeled Norsk Hyd...					
Number of Electrolyz...					
Maximum daily hydr...				...75 at 68F =	HyARC reports H2 density of 0.08375 kg/m3 at 1 atm, 68 F
Maximum hourly hyd...					
Maximum hourly hyd...					Calculated to meet a design capacity of 1500 kg/day with 2 units. The design capacity
kWe capacity of each electrolyzer unit (kW	1562.5				Independent review panel estimated $1.2M (2005$) purchased capital cost for a 1500kg/day distributed electrolysis system. At 50 kWh/kg (the usage reported by the independent review), the resulting electrolysis equipment cost is $384/kW (2005$).
Uninstalled capital cost of electrolyzer unit	384	432			
Total uninstalled cost (per unit)	600,000				

Looking for ~5-20 lines of capital cost breakdown.

- Use your judgment.
- Add comments to explain basis.
- Use formulas (rather than pasted-in values) to better explain logic.

Unknown Capital Costs can be based on approximate material costs of conceptual design. Good to incorporate the capital cost into a sensitivity study, bracketing the potential cost that can be drawn from analogies to similar systems.

Capital Costs

Plant Scaling is only for “Power Users”

leave this sheet as is for scaled costs

Plant Scaling Factors		
Baseline Design Capacity (kg H2/day)	**1,500**	Design capacity for input sheet
Scale Ratio	**1.00**	Ratio of new design Design Capacity. U
Scale Factor	**1.00**	Ratio of total scaled installed capital cost
Default Scaling Factor Exponent		Scaling factor expon where an individual
Lower Limit for Scaling Capacity (kg H2/day)	**100**	
Upper Limit for Scaling Capacity (kg H2/day)	**1,500,000**	

CAPITAL INVESTMENT (Inputs REQUIRED in Reference Year, (2007) $)

Major pieces/systems of equipment	Baseline Uninstalled Costs	Scaling Factor Exponent	...mments
2 units of 1563 kW Electrolyzer systems @ 50 kWh/kg H2 (31.3 kg/hr units)	$ -		
Includes:	$ -		
Stack	$ 746,389	1.0	
Hydrogen Gas Management System	$ 257,794	0.7	
Electrolyte Management System	$ 155,217	0.7	
Power Electronics	$ 155,217	0.7	
Mechanical Balance of Plant	$ 35,092	0.7	
0	$ -		
0	$ -		
0	$ -		
0	$ -		
0	$ -		
0	$ -		
0	$ -		
0	$ -		
0	$ -		
0	$ -		
0	$ -		
0	$ -		
0	$ -		
0	$ -		
0	$ -		
TOTALS (including scaling)	$ 1,349,709		

Scaling tab is an advanced feature that allows users to enter capital cost for one plant size, and then use automatic scaling to estimate capital cost at larger/smaller plant sizes.

It is for advanced users only.

It is strongly recommended that you enter capital costs only for the size plant for which you wish to compute H2 costs. In this manner, the scaling factor will be equal to 1 and the scaling feature will effectively not be used.

Thus to avoid complication, make sure the “Baseline Design Capacity” on the Plant Scaling tab is equal to the “Hydrogen Production Facility Design Capacity” entered on the Input_Sheet_Template tab.

Plant Scaling

Replacement Material Cost

Unplanned Yearly Replacement Capital (Depreciable)						
		Notes				
Total Unplanned Replacement Capital Cost Factor (% of total depreciable capital costs/year)	0.00%	The yearly replacement percentage is entered on the Input Sheet Template				
Actual Year	**Analysis Year**	**Operations Year**	**Specified Yearly Replacement Costs**	**Specified Yearly**	**Unplanned Replacement**	**Total Yearly Replacement Costs**
			Percent of Production System Direct Capital Cost			**lated to Start-up Year**
2009	2	1				$0
2010	3	2				$0
2011	4	3				$0
2012	5	4				$0
2013	6	5				$0
2014	7	6				$0
2015	8	7	25%			$428,434
2016	9	8		$0	$0	$0
2017	10	9		$0	$0	$0
2018	11	10				
		11				
		12				
		13				
		14	25%	$4		
		15				
2024	17	16				
2025	18	17		$0	$0	$0
2026	19	18		$0	$0	$0
2027	20	19		$0	$0	$0
2028	21	20		$0	$0	$0

Identify all known replacement items in this listing.
(Unknown replacements costs are captured elsewhere as an annual % of capital cost)

20 Year Life of Plant

Electrolysis Current Forecourt Case has annual replacement cost of 7 years

Replacement Costs

Total Production Capital Cost Calculation

Capital Costs - Hydrogen Production Facility				Notes
H2A Production Process Total Direct Capital Cost	$1,619,651			**Click to enter details on the Cost Detail Sheet**
Indirect Depreciable Capital Costs	**Enter values in basis year (2005) dollars**	**Combined Plant Scaling and Escalation Factor**	**Reference Year (2007) Dollars**	
Site Preparation ($)	$271,440	1.12	$305,304	H2A Default for 1500kg/day. Site Prep Using AACE* cost categories for a ">150psi, >400F Gas Process": Foundation: (% of process cost); Materials: 5% Labor: 6.65%. Miscellaneous (% of process cost); Materials:
Engineering & design ($)	$50,000			Default for 1500kg/day.
Process contingency ($)	$0			Default for 1500kg/day FC Prod.: 0%
Project contingency ($)	$216,000			Default for 1500kg/day FC Prod.: 15% of l Direct Cap. Cost
Other (Depreciable) capital ($)	$0			
One-time Licensing Fees ($)	$0			
Up-Front Permitting Costs ($)	$30,000			Default for 1500kg/day FC Prod.: $30,000. udes multiple visits to multiple agencies and blic review/ comment process.
Total Depreciable Capital Costs				
Non-Depreciable Capital Costs	**Enter values in basis year (2005) dollars**	**Co… S… Esc…**		
Cost of land ($/acre)	$50,000			
Land required (acres)		1.00	-	Land is assumed to be rented
Land Cost ($)			$0	
Other non depreciable capital costs		1.00	$0	
Total Non-Depreciable Capital Costs			$0.00	
Total Capital Costs			$2,257,883	

Most of these parameters may be computed using H2A Default values (typically a % of Capital Cost). Look in Notes column for guidance.

Input_Sheet_Template

Energy Feedstocks, Utilities, Byproducts, and Variable/Fixed Operating Costs

1. Enter Feedstock, Utility, and Byproducts

2. Enter Other Material and Byproducts

3. Enter Fixed Operating Costs

Energy Feedstocks, Utilities, and Byproduc

Select the Price Table to Use

AEO_2009_Reference_Case

AEO_2009_Reference_Case
- AEO_2009_Reference_Case
- AEO_2009_High_Price_Case
- AEO_2010_Reference_Case

Select the Use

feedstock

feedstock
- feedstock
- utility
- byproduct

Select the Feed Type

Industrial Electricity

- Residential Natural Gas
- Commercial Natural Gas
- Industrial Natural Gas
- Electric Utility Natural Gas
- Bio Methane
- Woody Biomass
- Woody Biomass B2A
- Woody Biomass MYPP
- Electric Utility Steam Coal
- Commercial Electricity
- Industrial Electricity
- Residential Electricity

feedstock	**Industrial Electricity**
Price Conversion Factor (GJ/kWh)	0.0036
Price in Startup Year ($2007)/kWh — **Use H2A Default**	$0.057
Usage (kWh/kg H2)	53.44
Cost in Startup Year	$1,444,343
Lookup Prices	yes

O

Add

Delete

If there are multiple feedstocks and need to delete one, H2A will delete all. Whatever feedstocks that need to be included must be re-entered.

Energy feedstocks, utilities, and byproducts currently in use

RT_TOP

feedstock	Price Conversion	Price in Startup Year ($2007)/kWh	Usage (kWh/kg H2)	Cost in Startup Year	Lookup Prices
Industrial Electricity	0.0036	0.057423148	50	$1,444,343	yes

Input_Sheet_Template

Energy Feedstocks, Utilities, Byproducts, and Variable/Fixed Operating Costs

1. Enter Feedstock, Utility, and Byproducts

2. Enter Other Material and Byproducts

3. Enter Fixed Operating Costs

Other Materials and Byproducts

Select the Material

Compressed Inert Gas

Feed or utility		**Con Iner**
$(2007)/kg	**Use H2A Default**	
Usage per kg H2 (kg)		
Cost in Startup Year		**$0**
Lookup Prices		**Yes**

Other Inputs and Byproducts

- Cooling Water
- Demineralized Water
- Process Water
- Oxygen
- Sulfuric Acid
- Steam
- Compressed Inert Gas

ter Price

Add

Delete

RT_NONE_TOP

Feed or utility	$(2007)/gal	Usage per kg H2 (gal)	Cost in Startup Year	Lookup Prices
Process Water	0.001807666	2.939	$2,501	Yes
Feed or utility	$(2007)/gal	Usage per kg H2 (gal)	Cost in Startup Year	Lookup Prices
Cooling Water	8.6275E-05	0.108	$4	Yes
Feed or utility	$(2007)/kg	Usage per kg H2 (kg)	Cost in Startup Year	Lookup Prices
Compressed Inert Gas	0.033086332	0.022934991	$357	Yes

Input_Sheet_Template

Energy Feedstocks, Utilities, Byproducts, and Variable/Fixed Operating Costs

1. Enter Feedstock, Utility, and Byproducts

2. Enter Other Material and Byproducts

3. Enter Fixed Operating Costs

Fixed Operating Costs - Hydrogen Production Facility	**Enter values in basis year (2005) dollars**	**Combined Plant Scaling and Escalation Factor**	**Reference Year (2007) Dollars**	
Production facility plant staff (number of FTEs)	0	1.00	0	Per Hydro "Atmospheric Electrolysers" brochure, plant is designed for automatic, unattended and continuous operation, so no labor is assumed for the production process. Labor only assumed for storage/dispensing operations (shown on Refueling tab)
Burdened labor cost, including overhead ($/man-hr)	$50	0.99	$ 49.69	
Production Facility Labor cost, $/year			$0	
G&A rate (% of labor cost)	20%	☑ H2A Default		
G&A ($/year)			$0	
Licensing, Permits and Fees ($/year)	$1,[illegible]	[illegible]	[illegible]062.20	H2A Default for 1500kg/day FC Prod.: $1000. Water, electrical, fire equipment permits but will be site specific
Property tax and insurance rate (% of total capital investment/year)	[illegible]	[illegible]		H2A Default for 1500kg/day FC Prod.: 1% insurance rate, 1% property tax.
Property taxes and insurance ($/year)			[illegible]5,158	
Rent ($/year)	$4,[illegible]	[illegible]	[illegible]002.25	Per Hydro "Atmospheric Electrolysers" broochure, electrolyzer unit requires 13.5m x 4m area including room for service and maintenance. Based on $3.23/m2/month (Square footage and rent for H2 dispensing operations are calculated on the Refueling tab.)
Material costs for maintenance and repairs ($/year)		1.12	$0.00	
Production Maintenance and Repairs ($/year)	$72,000	1.12	$80,982.53	H2A Default for 1500kg/day FC Prod.: 5% of Production Initial Cap Inv. (installed, deprec.)
Other Fees ($/year)		1.12	$0.00	
Other Fixed O&M Costs ($/year)		1.12	$0.00	
Total Fixed Operating Costs			$131,205	

Carefully consider Full Time Equivalent (FTE) employee requirements.

Input_Sheet_Template

Electrolysis Current Forecourt Case

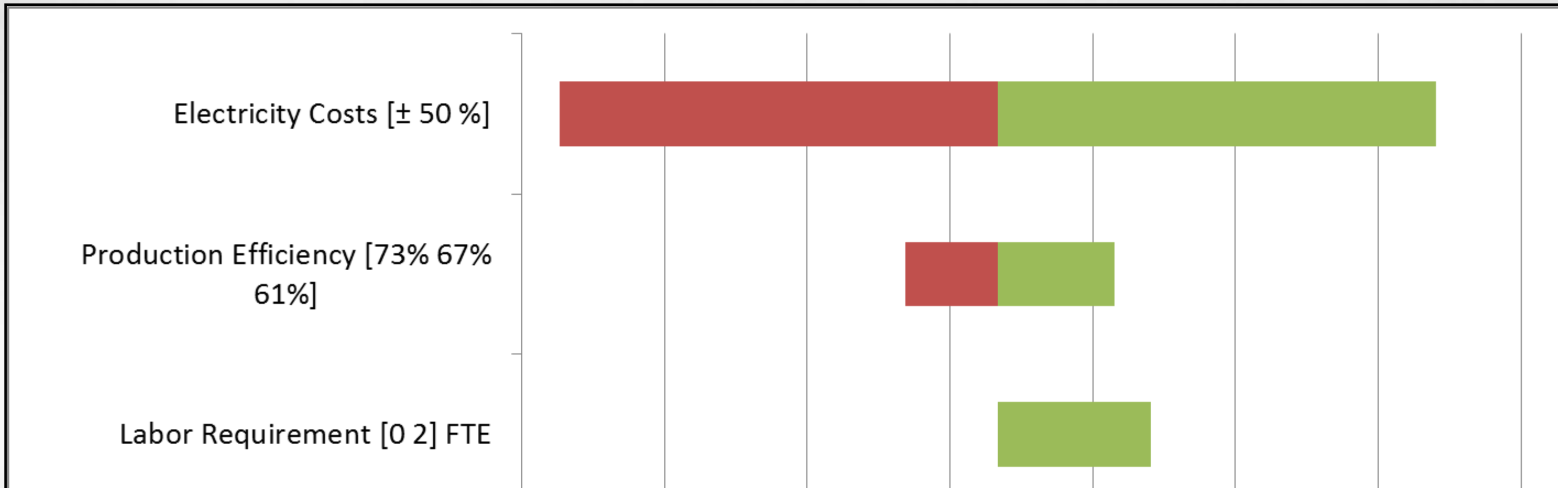
Results

Levelized Cost of Hydrogen: $6.63 / kg (2007$)
Production Cost Contribution: $4.17/kg (2007$)
Compression/Storage/Delivery (CSD) Cost Contribution: $2.46/kg (2007$)
Purchased Electrolyzer System Cost: $432/kW (2007$); $384/kW (2005$)
Installed Production Equipment Cost: $1,200,000
Total Capital Investment: $2,300,000
Lang Factor = 1.67
Production Process Energy Efficiency: 66.8% Lower Heating Value (LHV) Basis
Production & Dispensing Total Energy Efficiency: 61.4% LHV
Electricity Use: 50 kWh / kg H_2 produced
Electricity Price in Startup Year: 5.7¢/kWh
Average Electricity Price over Analysis Period: 6.3¢/kWh

Breakdown of Levelized Costs:

Specific Item Cost Calculation		***Total Cost of Delivered Hydrogen***		**$6.63 /kg$H_2$**
Cost Component	**Hydrogen Production Cost Contribution ($/kg)**	**Compression, Storage, and Dispensing Cost Contribution ($/kg)***		**Percentage of H2 Cost**
Capital Costs	$0.76	$1.53		34.5%
Decommissioning Costs	$0.01			0.1%
Fixed O&M	$0.28	$0.55		12.5%
Feedstock Costs	$3.06			46.2%
Other Raw Material Costs	$0.05			0.7%
Byproduct Credits	$0.00			0.0%
Other Variable Costs (including utilities)	$0.01	$0.39		6.0%
Total	**$4.17**	**$2.46**		

Current Forecourt Electrolysis Tornado Chart

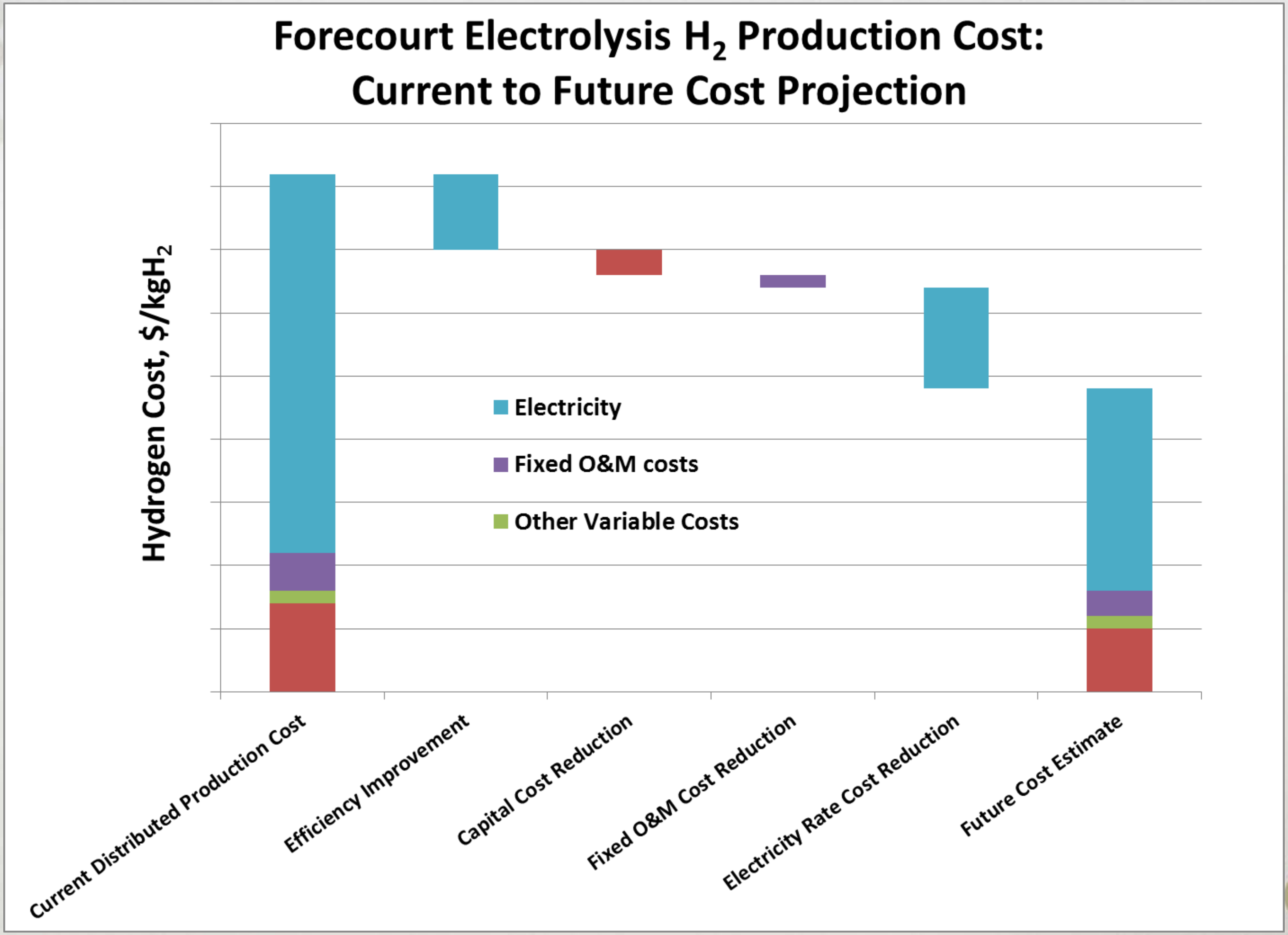


	Lower value		Nominal value		Upper value			
Variable Name	**Value**	**Minimum H2 Selling Price ($/kg)**	**Value**	**Minimum H2 Selling Price ($/kg)**	**Value**	**Minimum H2 Selling Price ($/kg)**	**Lower Difference**	**Upper Difference**
Stack Replacement Interval [10 7 5] years	10	$4.14	7	$4.17	5	$4.24	$0.03	$0.07
Stack Replacement Cost [10 25 50] % of Direct Capital Investment	10	$4.11	25	$4.17	50	$4.26	$0.06	$0.09
Total Capital Investment (Production Only) [$1.6M $2.3M $2.9M]	$1,580,518	$3.94	$2,257,883	$4.17	$2,935,248	$4.40	$0.23	$0.23
Labor Requirement [0 2] FTE	0	$4.17	0	$4.17	2	$4.70	$0.00	$0.54
Production Efficiency [73% 67% 61%]	46	$3.84	50	$4.17	55	$4.58	$0.33	$0.41
Electricity Costs [± 50 %]		$2.63		$4.17		$5.70	$1.53	$1.53

Tornado Chart

Sensitivity Analysis

Waterfall Charts will be used in Future DOE Analyses



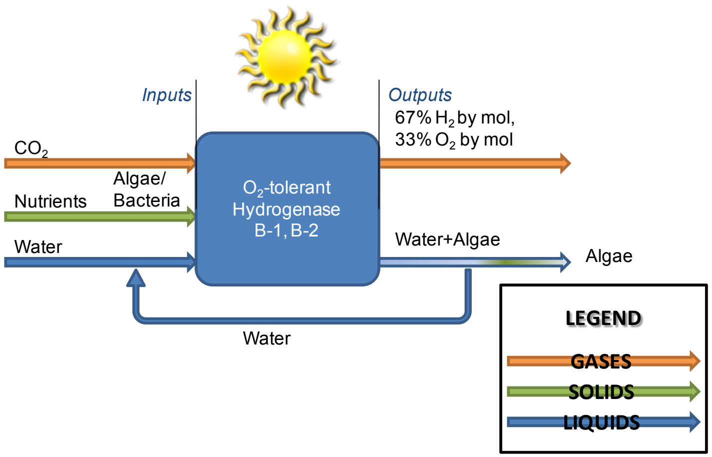
Alternative Examples for H2A Cases

(Technologies Utilizing Solar Energy for Hydrogen Production)

27

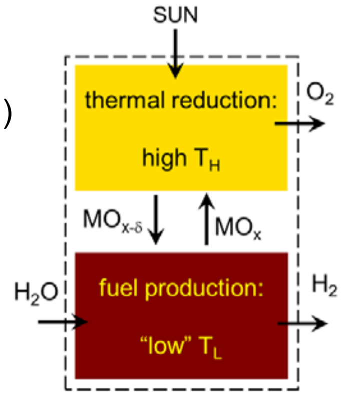
Examples of Solar Hydrogen H2A Analysis for Emerging Technologies

Photo-Bio Ponds: Algae, Bacteria



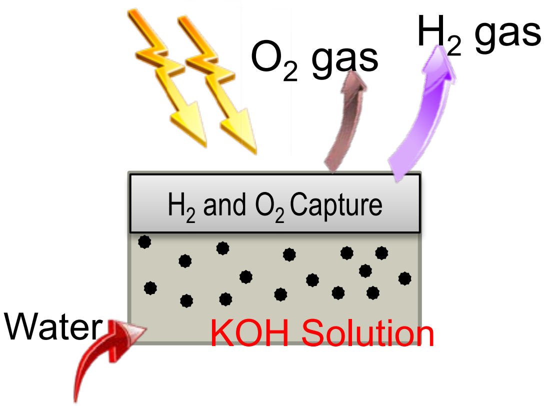
STCH Concepts

Sandia Reactor
(moving packed bed,
spatial pressure separation)

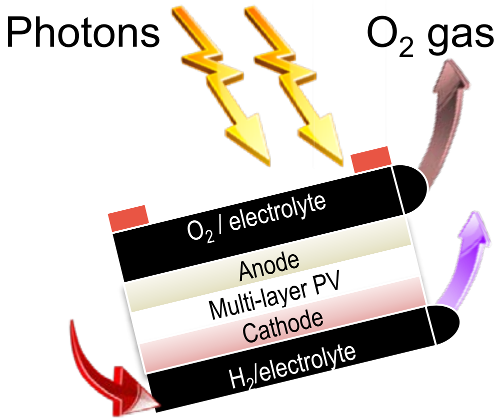


Two-step
metal oxide cycle

PEC Particle Colloidal Suspension

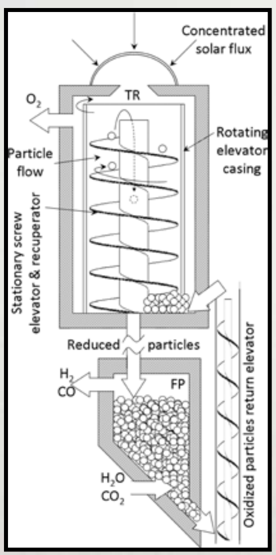


PEC Electrode Plates



STCH Concept: Solar Dishes

Envisioned design has a reactor at the focal point, which is similar to the Sandia Counter Rotating Ring Receiver Reactor Recuperator (CR5)



Latest Sandia Reactor Concept for beam down power tower (moving packed bed, spatial pressure separation)

Large field of STCH dishes:

- ~30,000 dishes (for 100TPD H_2)
- ~4,400 acres

Each dish:

- 11m (37ft) in diameter
- 88 m^2 of solar capture area
- ~3.2 kgH_2/day (average)

Line/Pipe connections for:

- H_2
- Power
- Water

Focus on Key Parameters: STH efficiency is key parameter for STCH, Bio, and PEC

STH Efficiency = Solar-to-Hydrogen Energy Conversion Efficiency

$$= \frac{\text{(LHV of Net } H_2 \text{ out of System)}}{\text{(total solar energy input into system collector)}}$$

Full spectrum energy

Full active area, not space in-between panels/beds

Key point is to make sure major terms are consistent with each other:

- solar energy/intensity ← Should consider: direct/indirect insol., tracking, blockage
- collection area
- capital cost ← Must size for hourly peak production (or have explicit alternative story)
- H_2 Production Rate ← Must reconcile hourly peak, daily & seasonal variations

Focus on Key Parameters: STCH Efficiency Example

Component Efficiency	Projected 2015 Value	Definition	Projected 2020 Value	Ultimate Target Value
Optical Efficiency	75%	Energy fraction of total solar that is reflected to receiver	75%	75%
Receiver Thermal Efficiency	82%	Energy fraction of reflected light that is absorbed by active material	89%	91%
Reactor Conversion Efficiency	10%	Energy fraction of absorbed energy that is converted to H_2 (LHV)	25%	50%
STH Efficiency	6.2%	Product of above three efficiencies.	16.7%	34.3%

- Component Efficiencies are also calculated:
  - Receiver thermal efficiency: scales with T^4 thermal radiation losses
  - Reactor conversion efficiency: based on 70% heat recovery

Calculate STH efficiency from sub-component efficiencies. Explain basis for each estimate/value.

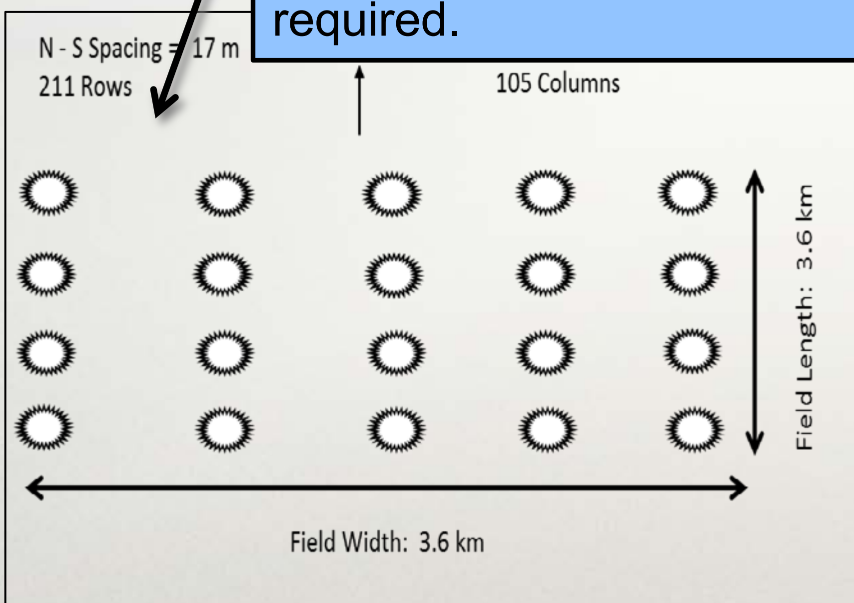
Encouraged to Include Supporting Calculations in an Added Tab at end of Workbook

- Entering calculations can facilitate scaling factors while running different cases
- Create separate tab in workbook to make calculations

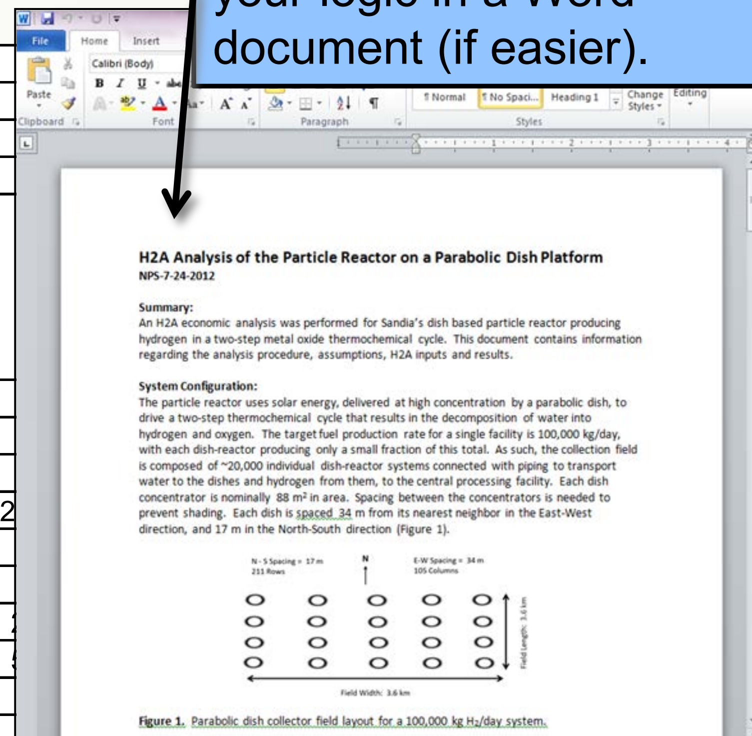
In this example, spacing of dishes is carefully computed to avoid shading.
But results of computation only show up in the H2A case in the number of acres of land required.

Example:
- # … 00 kg H_2/d
- S…

Sola…



Alternately, you can explain your logic in a Word document (if easier).



H2A Analysis of the Particle Reactor on a Parabolic Dish Platform
NPS-7-24-2012

Summary:
An H2A economic analysis was performed for Sandia's dish based particle reactor producing hydrogen in a two-step metal oxide thermochemical cycle. This document contains information regarding the analysis procedure, assumptions, H2A inputs and results.

System Configuration:
The particle reactor uses solar energy, delivered at high concentration by a parabolic dish, to drive a two-step thermochemical cycle that results in the decomposition of water into hydrogen and oxygen. The target fuel production rate for a single facility is 100,000 kg/day, with each dish-reactor producing only a small fraction of this total. As such, the collection field is composed of ~20,000 individual dish-reactor systems connected with piping to transport water to the dishes and hydrogen from them, to the central processing facility. Each dish concentrator is nominally 88 m² in area. Spacing between the concentrators is needed to prevent shading. Each dish is spaced 34 m from its nearest neighbor in the East-West direction, and 17 m in the North-South direction (Figure 1).

Figure 1. Parabolic dish collector field layout for a 100,000 kg H_2/day system.

4,406.12	Total field acres

DOE Multi-Year Research, Development, and Demonstration (MYRDD) Technical Target Tables: STCH

https://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

Table 3.1.7 Technical Targets: Solar-Driven High-Temperature Thermochemical Hydrogen Production [a]

Characteristics	Units	2011 Status	2015 Target	2020 Target	Ultimate Target
Solar-Driven High-Temperature Thermochemical Cycle Hydrogen Cost [b]	\$/kg	NA	14.80	3.70	2.00
Chemical Tower Capital Cost (installed cost) [c]	\$/TPD H_2	NA	4.1MM	2.3MM	1.1MM
Annual Reaction Material Cost per TPD H_2 [d]	\$/ yr.-TPD H_2	NA	1.47M	89K	11K
Solar to Hydrogen (STH) Energy Conversion Ratio [e,f]	%	NA	10	20	26
1-Sun Hydrogen Production Rate [g]	kg/s per m^2	NA	8.1E-7	1.6E-6	2.1E-6

Table of Targets

Table 3.1.7.A Example Parameter Values to Meet Cost Targets: Solar-Driven High-Temperature Thermochemical Hydrogen Production

Characteristics	Units	2011 Status	2015 Target	2020	Ultimate
Solar to Hydrogen (STH) Energy Conversion Ratio	%	NA	10	20	26
Cycle Time	minutes/ cycle	NA	5	3	1
Reaction Material Cost	\$/kg	270	270	270	270
Reaction Material Replacement Lifetime	years	NA	1	5	10
Heliostat Capital Cost (installed cost) [a]	\$/m^2	200	140	75	75

Supporting Assumptions

Footnotes for STCH Tables

Table 3.1.7

[a] The targets in this table are for research tracking with the Ultimate Target values corresponding to market competitiveness. Targets are based on an initial analysis utilizing the H2A Central Production Model 3.0 with standard H2A economic parameters (http://www.hydrogen.energy.gov/h2a_production.html). Projections assume a ferrite high-temperature cycle with a central production capacity of 100,000 kg H_2/day. Further analysis assumptions may be found in "Support for Cost Analyses on Solar-Driven High Temperature Thermochemical Water-Splitting Cycles, TIAX LLC, Final Report to U.S. Department of Energy, 22 February 2011" (http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/solar_thermo_h2_cost.pdf).

[b] Hydrogen cost represents the complete system hydrogen production cost for purified, 300 psi compressed gas. System level losses such as heliostat collector area losses, replacement parts, operation, and maintenance are included in the cost calculations which are documented in the H2A v3 Future Case study for Solar-thermochemical Production of Hydrogen (http://www.hydrogen.energy.gov/h2a_prod_studies.html).

[c] The chemical tower capital cost is the projected total installed cost for the ferrite cycle conversion of water into hydrogen.

[d] Reaction material cost is defined as the effective annual cost of the active (ferrite) material within the thermochemical process per metric ton rated hydrogen capacity of the system. The value is calculated as the expected annual purchase price of the material in its usable form (e.g., ferrite coated on a substrate) divided by the material lifetime under expected use condition (i.e., nearly continuous usage during the sunlight hours with an annual capacity factor of 90%); divided by the net rated hydrogen production capacity of the system [in metric tons per day (TPD)] (For example, 100,000 kg H_2/day = 100 TPD). Material cost improvements are expected to result from a combination of decreased material usage, improved cycle time, and increased material lifetime.

[e] STH energy conversion ratio is defined as the energy of the net hydrogen produced (LHV) divided by full-spectrum solar energy consumed. For systems utilizing solar energy input only, the consumed energy is calculated based on the incident irradiance over the total area of the solar collector. For hybrid systems, all additional non-solar energy sources (e.g., electricity) must be included as equivalent solar energy inputs added to the denominator of the ratio.

[f] Due to the developmental nature of the technology, the STH energy conversion ratio has not yet been measured for the complete solar to hydrogen reaction. Consequently, STH targets are calculated based on partial laboratory measurements using artificial light sources with extrapolation to overall system performance.

[g] The hydrogen production rate in kg/s per total area of solar collection under full-spectrum 1-sun incident irradiance (1,000 W/m^2). Under ideal conditions, STH can be related to this rate as follows: STH = H_2 Production Rate (kg/s per m^2) * 1.23E8 (J/kg) / 1.00E3 (W/m^2). Measurements of the 1-sun hydrogen production rate can provide an invaluable diagnostic tool in the evaluation of loss mechanisms contributing to the STH ratio.

Table 3.1.7.A

[a] Heliostat capital costs encompass all capital costs, including installation, with the solar reflector system needed to focus solar energy onto the chemical tower reactor. Cost is stated per square meter of solar capture area. Heliostat capital cost status for 2010 and the capital cost targets for 2015 and 2020 are consistent with the current viewpoint of the EERE Solar Program as reflected in the "Power Tower Technology Roadmap and Cost Reduction Plan" SAND2011-2419, April 2011, (http://prod.sandia.gov/techlib/access-control.cgi/2011/112419.pdf) and the DOE SunShot Vision Study (http://www1.eere.energy.gov/solar/pdfs/47927_chapter5.pdf), respectively.

DOE MYRDD Plan Technical Target Tables: Bio H_2

https://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

Table 3.1.10 Technical Targets: Photolytic Biological Hydrogen Production [a]

Characteristics	Units	2011 Status	2015 Target [c]	2020 Target [d]	Ultimate Target [e]
Hydrogen Cost [b]	$/kg	NA	NA	9.20	2.00
Reactor Cost [f]	$\$/m^2$	NA	NA	14	11
Light utilization efficiency (% incident solar energy that is converted into photochemical energy) [g]	%	25 [h]	28	30	54
Duration of continuous H_2 production at full sunlight intensity [i]	Time Units	2 min [j]	30 min	4 h	8 h
Solar to H_2 (STH) Energy Conversion Ratio [k]	%	NA	2%	5%	17%
1-Sun Hydrogen Production Rate [l]	kg/s per m^2	NA	1.6E-7	4.1E-7	1.4E-6

Table 3.1.11 Technical Targets: Photosynthetic Bacterial Hydrogen Production [a]

Characteristics	Units	2011 Status	2015 Target	2020 Target [b]
Efficiency of Incident Solar Light Energy to H_2 (E0*E1*E2) [c] from organic acids	%	NA	3	4.5
Molar Yield of Carbon Conversion to H_2 (depends on nature of organic substrate) E3 [d]	% of maximum	NA	50	65
Duration of continuous photoproduction [e]	Time	NA	30 days	3 months

Footnotes for Bio Tables

Table 3.1.10

[a] The targets in this table are for research tracking with the Ultimate Target values corresponding to market competitiveness. Targets are based on an initial analysis utilizing the H2A Central Production Model 3.0 with standard H2A economic parameters (www.hydrogen.energy.gov/h2a_production.html.)

[b] Hydrogen cost represents the complete system hydrogen production cost for purified, 300 psi compressed gas. Projections assume photolytic production of hydrogen gas by genetically engineered organisms (algal or bacterial) suspended in a water solution under solar illumination, modeled as algae, with an O_2-tolerant hydrogenase, grown in large, raceway-type, shallow bed reactors that are covered by a thin, optically transparent film, and provided with nutrients, CO_2, and sunlight. The evolved gas will be collected, purified to 99.999+ hydrogen purity by pressure swing adsorption (PSA), and compressed to 300 psi for hydrogen pipeline transport. Plant capacity is 50,000 kg H_2/day for all years. All targets are expressed in 2007 dollars. Cost calculations are documented in the H2A v3 Future Case Study for Photolytic Biological Production of Hydrogen (http://www.hydrogen.energy.gov/h2a_prod_studies.html). Further analysis assumptions may be found in "Technoeconomic Boundary Analysis of Biological Pathways to Hydrogen Production," Directed Technologies, Inc., Final Report to U.S. Department of Energy, 31 August 2009 (http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/46674.pdf).

[c] The 2015 target is based on analysis of the best technologies projected to be available in 2015 and assumes integration into a single, non-hybrid organism. Specifically, the 2015 target is based on a model of a *Chlamydomonas reinhardtii* strain with an O_2-tolerance hydrogenase system and a reduced chlorophyll antennae light harvesting complex (LHC), in which all the improvements listed in the table have been integrated.

[d] For 2020, all assumptions of the 2015 target system apply (such as reactor system design and organism type) except the organism is assumed to be further improved in the target parameters indicated in the table.

[e] For the 2015 and 2020 targets, the organism modeled is assumed to be an algal strain with a native photosynthesis system (i.e., with Photosystems I and II). For the Ultimate Target, previous assumptions (such as reactor system design) apply, but the modeled organism is both optimized and has a genetically modified hybrid photosynthetic system combining the native algal Photosystem II with a bacterial Reaction Center, achieving greater hydrogen production rates by extending the light spectrum that can be collected and improving the efficiency of other conversion steps. Fundamental genetic engineering advances are required to reach the hybrid organism's ultimate target efficiency values. If the hybrid organism was not successfully genetically engineered, performance would be limited to a light utilization efficiency of 34%, an STH ratio of 9.8%, and a cost of \$2.6/kg H_2.

[f] Installed cost per square meter of organism bed reactor equipment includes the containment structure, film covering, and any reactor interior flow control equipment. It does not include cost of complementary equipment

Footnotes for Bio Tables

Table 3.1.10 (continued)

such as compressors, PSA, Control Room, etc. Square meters are defined as the solar capture area. Future designs for the reactors will need to address safety measures to deal with the co-production of hydrogen and oxygen (e.g., replacing PSA systems with Temperature Swing Apparatus systems), which may increase costs. Due to the early stage of development, photobioreactor designs and the required organismal characteristics will likely undergo modifications before widespread commercial use to address issues such as temperature, salinity, and pH control.

g The light utilization efficiency is the conversion efficiency of incident solar energy into photochemically available energy and is the product of two values: the light collection efficiency and the photon use efficiency at full sunlight intensity. The first value, light collection efficiency, is the fraction of solar incident light that is within the photosynthetically active radiation (PAR) wavelength band of the organism. For green algae, the light collection efficiency is estimated to be 45% ("Light and photosynthesis in aquatic ecosystems," Kirk, Cambridge University Press, 1994), and is considered fixed for the 2015 and 2020 targets; the hybrid organism modeled for the ultimate target is estimated to have a light collection efficiency of up to 64% ("Integrated biological hydrogen production," Melis and Melnicki, International Journal of Hydrogen Energy, September 2006) http://www.sciencedirect.com/science/article/pii/S0360319906002308). The second value, photon use efficiency, is the efficiency of converting the absorbed photon energy into chemical energy through photosynthesis at full sunlight intensity (2,500 micromol photons per square meter per second). At low-light conditions (i.e., with no light saturation), the average photon use efficiency for algae is 85% ("Absolute absorption cross sections for photosystem II and the minimum quantum requirement for photosynthesis in *Chlorella vulgaris*." Ley and Mauzerall, Biochim. Biophys. Acta 1982). Experimentally, photon use efficiency is determined by measuring the rate of photosynthesis (via oxygen evolution) per photon at different light intensities and comparing the rates at full sunlight and at sub-saturating light levels, with the maximum value set at the 85% efficiency level.

h "Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures," Melis, 2008 Annual Progress Report for DOE's Hydrogen Program (http://www.hydrogen.energy.gov/pdfs/progress08/ii_f_2_melis.pdf).

i For purposes of conversion efficiencies and duration reporting, full sunlight (2,500 micromol photons per square meter per second) conditions are assumed. Since in actual practice light intensity varies diurnally, only 8 hours of continuous duration is needed for a practical system. The duration values assume a system where the enzyme is regenerated at night with respiration scavenging oxygen.

j Brand et al., 1989, Biotechnol. Bioeng.

k STH energy conversion ratio is defined as the energy of the net hydrogen produced (LHV) divided by net full-spectrum solar energy consumed. For systems utilizing solar energy input only, the consumed energy is calculated based on the incident irradiance over the total area of the solar collector. For hybrid systems, all additional non-solar energy sources (e.g., electricity) must be included as equivalent solar energy inputs added to the denominator of the ratio. For photolytic biological hydrogen production, this can be thought of as the product of three components: $E_0*E_1*E_2$. The maximum potential value is calculated by determining the highest possible conversion efficiencies at three steps: E_0, the percent of solar energy (at sea level) that is absorbed by the organism; E_1, the percent of absorbed energy that is utilized for charge separation by the photosystems; and E_2, the energy for charge separation that is utilized for water splitting. The E_2 value is reduced by 20% to account for the fact that some photon energy will go to other processes, such as cellular maintenance, rather than hydrogen production. The hydrogen cost calculation takes into consideration reductions due to reactor light transmittance (10% loss) and the loss of production over a full production day due to durations less than 8 h. Cost calculations are documented in the H2A v3 Future Case Study for Photolytic Biological Production of Hydrogen (http://www.hydrogen.energy.gov/h2a_prod_studies.html).

l The hydrogen production rate in kg/s per total area of solar collection under full-spectrum 1-sun incident irradiance (1,000 W/m^2). Under ideal conditions, STH can be related to this rate as follows: STH = H_2 Production Rate (kg/s per m^2) * 1.23E8 (J/kg) / 1.00E3 (W/m^2). Measurements of the 1-sun hydrogen production rate can provide an invaluable diagnostic tool in the evaluation of loss mechanisms contributing to the STH ratio.

DOE MYRDD Technical Target Tables: PEC (Photoelectrode)

https://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

Table 3.1.8 Technical Targets: Photoelectrochemical Hydrogen Production: Photoelectrode System with Solar Concentration [a]

Characteristics	Units	2011 Status	2015 Target	2020 Target	Ultimate Target
Photoelectrochemical Hydrogen Cost [b]	\$/kg	NA	17.30	5.70	2.10
Capital cost of Concentrator & PEC Receiver (non-installed, no electrode) [c]	\$/m^2	NA	200	124	63
Annual Electrode Cost per TPD H_2 [d]	\$/ yr-TPDH$_2$	NA	2.0M	255K	14K
Solar to Hydrogen (STH) Energy Conversion Ratio [e, f]	%	4 to 12%	15	20	25
1-Sun Hydrogen Production Rate [g]	kg/s per m^2	3.3E-7	1.2E-6	1.6E-6	2.0E-6

Table 3.1.8.A Example Parameter Values to Meet Cost Targets: Photoelectrochemical Hydrogen Production (Photoelectrode System)

Characteristics	Units	2011 Status	2015	2020	Ultimate
Solar to Hydrogen (STH) Energy Conversion Ratio	%	NA	15	20	25
PEC Electrode cost [a]	\$/m^2	NA	300	200	100
Electrode Cost per TPD H_2 [b]	\$/ TPD	NA	1.0M	510K	135K
Electrode Replacement Lifetime [c]	Years	NA	0.5	2	10
Balance of Plant Cost per TPD H_2 [d]	\$/ TPD	NA	420K	380K	310K

Footnotes for PEC (Photoelectrode) Tables

Table 3.1.8

[a] The targets in this table are for research tracking with the Ultimate Target values corresponding to market competitiveness. Targets are based on an initial analysis utilizing the H2A Central Production Model 3.0 with the standard H2A economic parameters (www.hydrogen.energy.gov/h2a_production.html). Targets are based on photoelectrode-type PEC systems wherein a solar trough collector concentrates light onto a PEC receiver assembly. The PEC receiver consists of a flat panel PEC electrode (submerged in an electrolyte bath) and the collection housing and manifolds to collect and separate the evolved hydrogen and oxygen gases. Solar concentration is assumed to be 15:1 for the ultimate target case and 10:1 for all others. Further analysis assumptions may be found in "Technoeconomic Analysis of Photoelectrochemical (PEC) Hydrogen Production", Directed Technologies Inc., Final Report to the Department of Energy, December 2009 (http://www.hydrogen.energy.gov/pdfs/review09/pd_23_james.pdf). Plant assumed capacity is 50,000 kg H_2/day for all years. All targets are expressed in 2007 dollars.

[b] Hydrogen cost represents the complete system hydrogen production cost for purified, 300 psi compressed gas. System level losses and expenses due to solar collection/concentration, window transmittance/refraction, replacement parts, operation, and maintenance are included in the cost calculations which are documented in the H2A v3 Future Case study for Type 4 (Photoelectrode System with Concentration) Photoelectrochemical (PEC) Production of Hydrogen (http://www.hydrogen.energy.gov/h2a_prod_studies.html).

[c] Capital cost includes solar concentration and associated tracking (if any), the optical window, and the water/electrolyte/gas containment subsystem. The cost of the PEC electrode is not included. All areas refer to total solar capture area. While improvements beyond the current status are needed to meet these cost goals, this area is not presently a research focus of the Fuel Cell Technologies Program.

[d] Annual electrode cost refers to the annual replacement cost of the PEC photoelectrode panel normalized by the design capacity of the system (in metric tons H_2 per day). Electrode cost includes both the material and manufacturing cost of the PEC electrode used within the reactor.

[e] STH energy conversion ratio is defined as the energy of the net hydrogen produced (LHV) divided by full-spectrum solar energy consumed. For systems utilizing solar energy input only, the consumed energy is calculated based on the incident irradiance over the total area of the solar collector. For hybrid systems, all additional non-solar energy sources (e.g., electricity) must be included as equivalent solar energy inputs added to the denominator of the ratio.

[f] The 2011 Status of STH ratio is in the range of 4% and 12% for different semiconductor material systems exhibiting different levels of operational durability. Thin film material systems have been demonstrated with STH > 4% for hundreds of hours (A. Madan, Fuel Cell Technologies Program 2011 Annual Progress Report: http://www.hydrogen.energy.gov/pdfs/progress11/ii_g_5_madan_2011.pdf); Crystalline material systems have been demonstrated with STH > 12% for tens of hours. [O. Khaselev, J.A. Turner, Science 280, 425 (1998)].

[g] The hydrogen production rate in kg/s per total area of solar collection under full-spectrum 1-sun incident irradiance (1,000 W/m^2). Under ideal conditions, STH can be related to this rate as follows: STH = H_2 Production Rate (kg/s per m^2) * 1.23E8 (J/kg) / 1.00E3 (W/m^2). Measurements of the 1-sun hydrogen production rate can provide an invaluable diagnostic tool in the evaluation of loss mechanisms contributing to the STH ratio.

Table 3.1.8.A

[a] PEC photoelectrode cost refers to the material and manufacturing cost of the PEC electrode. Area is based on the actual area of the electrode itself.

[b] This parameter is the PEC photoelectrode cost (as defined above) normalized by the metric tons per day of hydrogen design capacity of the electrode.

[c] Electrode replacement lifetime denotes the projected total duration of the electrode being immersed in electrolyte and under cyclic solar illumination until process energy efficiency drops to 80% of its original values. Thus, a 10 year electrode replacement lifetime refers to 10 years of operation under diurnal cycles and approximately 5 years of actual hydrogen production.

[d] This parameter denotes non-electrode, non-concentrator/PEC receiver, non-installation balance of plant costs normalized by the metric tons per day of hydrogen design capacity of the electrode.

DOE MYRDD Technical Target Tables: PEC (Colloidal, Dual Bed)

https://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

Table 3.1.9 Technical Targets: Photoelectrochemical Hydrogen Production: Dual Bed Photocatalyst System [a]

Characteristics	Units	2011 Status	2015 Target	2020 Target	Ultimate Target
Photoelectrochemical Hydrogen Cost [b]	$/kg	NA	28.60	4.60	2.10
Annual Particle Cost per TPD H_2 [c]	$/ yr-TPD$H_2$	NA	1.4M	71K	4K
Solar to Hydrogen (STH) Energy Conversion Ratio [d,e]	%	NA	1	5	10
1-Sun Hydrogen Production Rate [f]	kg/s per m^2	NA	8.1E-8	4.1E-7	8.1E-7

Table 3.1.9.A Example Parameter Values to Meet Cost Targets: Photoelectrochemical Hydrogen Production (Dual Bed Photocatalyst)

Characteristics	Units	2011 Status	2015	2020	Ultimate
Solar to Hydrogen (STH) Energy Conversion Ratio	%	NA	1	5	10
PEC particle cost [a]	$/kg	NA	1000	500	300
Particle Replacement Lifetime [b]	Years	NA	0.5	1	5
Capital cost of reactor bed system (excluding installation and PEC particles) [c]	$/$m^2$	NA	7	7	5
Balance of Plant Cost per TPD H_2 [d]	$/ TPD	NA	6.4M	1.0M	0.6M

Footnotes for PEC (Dual Bed) Tables

Table 3.1.9

[a] The targets in this table are for research tracking with the Ultimate Target values corresponding to market competitiveness. Targets are based on an initial analysis utilizing the H2A-Central Production Model 3.0 with standard H2A economic parameters (www.hydrogen.energy.gov/h2a_production.html). Targets are based on a dual-bed PEC nanoparticle slurry-type system wherein clear thin film polymer bag-style reactors are filled with water and photocatalytically active nanoparticles. The hydrogen evolution half-reaction occurs in one bag reactor section and the oxygen evolution half-reaction occurs in an adjacent reactor section. The reactor sections are connected by a porous ionic bridge which permits ion exchange to complete the electrochemical circuit but prevents gas mixing. Solar energy energizes both reactions. No solar concentration is used. Further analysis assumptions may be found in "Technoeconomic Analysis of Photoelectrochemical (PEC) Hydrogen Production," Directed Technologies Inc., Final Report to the Department of Energy, December 2009 (http://www.hydrogen.energy.gov/pdfs/review09/pd_23_james.pdf). Plant capacity is 50,000 kg H_2/day for all years. All targets are expressed in 2007 dollars.

[b] Hydrogen cost represents the complete system hydrogen production cost for purified, 300 psi compressed gas. System level losses and expenses due to solar window transmittance/refraction, replacement parts, operation, and maintenance are included in the cost calculations which are documented in the H2A v3 Future Case study for Type 2 (PEC Dual Bed Photocatalyst System) Photoelectrochemical Production of Hydrogen (http://www.hydrogen.energy.gov/h2a_prod_studies.html).

[c] PEC particle cost refers to the annual replacement cost of the PEC nanoparticles normalized by the design capacity of the system (metric tons H_2 per day). Particle cost includes both the material and manufacturing cost of the PEC nanoparticles used within the reactor. Although different chemical reactions occur in the two bed sections, particle cost is combined for purposes of cost reporting.

[d] STH energy conversion ratio is defined as the energy of the net hydrogen produced (LHV) divided by full-spectrum solar energy consumed. For systems utilizing solar energy input only, the consumed energy is calculated based on the incident irradiance over the total area of the solar collector. For hybrid systems, all additional non-solar energy sources (e.g., electricity) must be included as equivalent solar energy inputs added to the denominator of the ratio. In a dual bed system, this requires two material systems each with half reactions operating at twice the stated net STH energy conversion ratio.

[e] Dual bed systems are less mature than photoelectrode PEC systems. The current status STH energy conversion ratio is still under investigation.

[f] The hydrogen production rate in kg/s per total area of solar collection under full-spectrum 1-sun incident irradiance (1,000 W/m^2). Under ideal conditions, STH can be related to this rate as follows: STH = H_2 Production Rate (kg/s per m^2) * 1.23E8 (J/kg) / 1.00E3 (W/m^2). Measurements of the 1-sun hydrogen production rate can provide an invaluable diagnostic tool in the evaluation of loss mechanisms contributing to the STH ratio.

Table 3.1.9.A

[a] PEC particle cost refers to the material and manufacturing cost of the PEC nanoparticles used within the reactor. While different chemical reactions occur in the two bed sections, the particle costs are combined for purposes of cost reporting. Particle mass is based on the total particle mass (including inert substrate if used).

[b] Particle replacement lifetime denotes the projected total duration of the nanoparticles being immersed in electrolyte and under cyclic solar illumination until process energy efficiency drops to 80% of its original values. Thus, a 5 year particle replacement lifetime refers to 5 years of operation under diurnal cycles and approximately 2.5 years of actual hydrogen production.

[c] Reactor system capital cost includes only the high density polyethylene clear plastic film reactor bed assembly and its associated ionic transfer bridges. Installation, fluid piping, and the photocatalytic nanoparticles are not included. All areas refer to total solar capture area.

[d] This parameter denotes the non-installed balance of plant costs exclusive of reactor beds and PEC particles. It includes piping, controls, sensors, pumps, and compressors and is normalized by the metric tons per day of hydrogen design capacity of the system.

Reference Information

This presentation available after WebEx.

H2A Model Description on Hydrogen and Fuel Cells Program website:
http://www.hydrogen.energy.gov/h2a_analysis.html#data

H2A Production Models and Case Studies
http://www.hydrogen.energy.gov/h2a_production.html

H2A Version 3 User Guide PDF:
https://apps1.hydrogen.energy.gov/cfm/h2a_active_folder/h2a_production/03P_H2A_Central_Hydrogen_Production_Model_User_Guide_Version_3_draft.pdf

Feedstock and utility prices (H2A default) linked to Annual Energy Outlook (AEO) Reference Case developed by DOE's Energy Information Administration (EIA)
http://www.eia.gov/forecasts/aeo/index.cfm

Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model from Argonne National Lab: http://greet.es.anl.gov/main