Techno-Economic Analysis:
Water splitting technologies and metrics

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Arlington VA

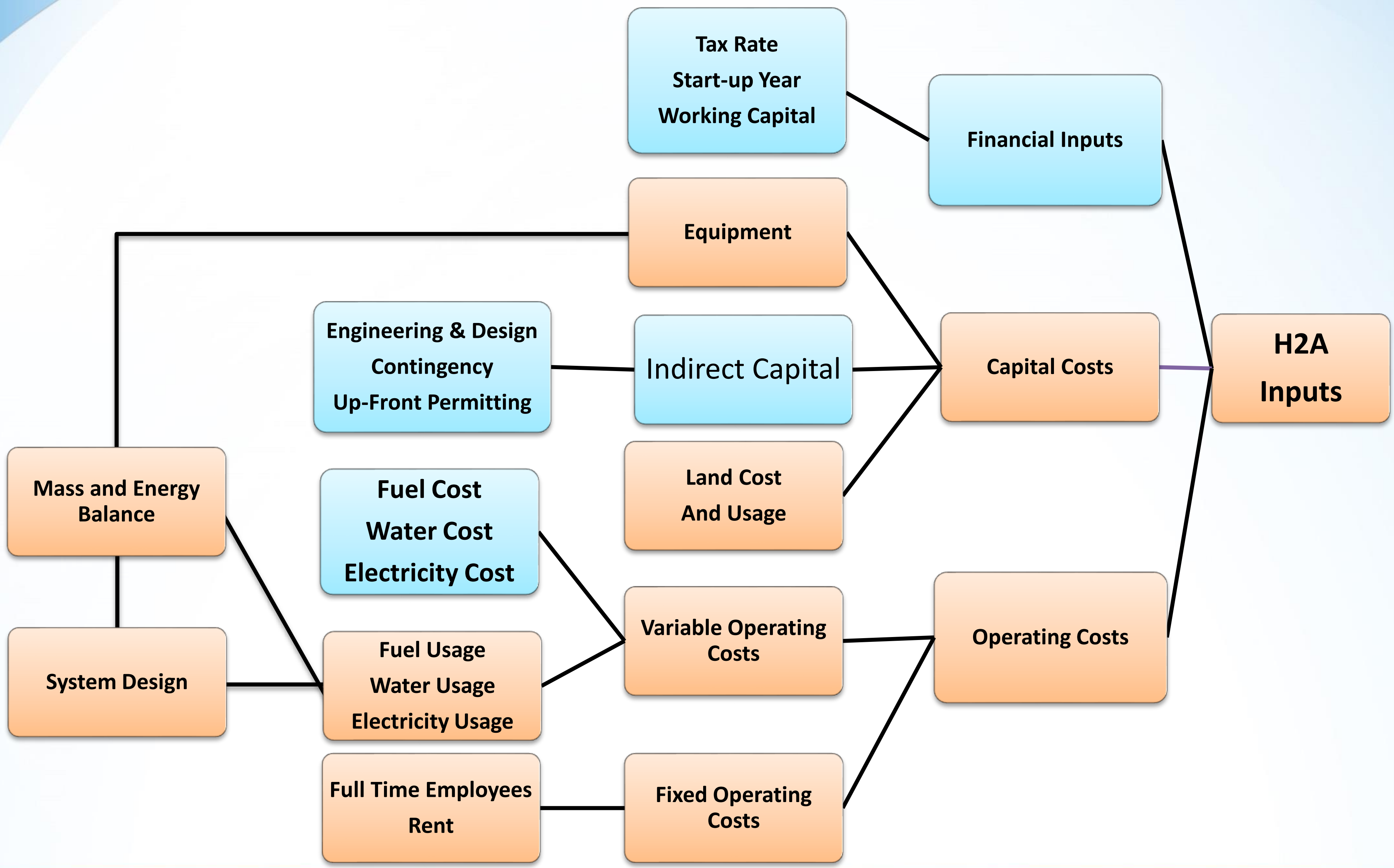
Overview

- Overview of H2A
- Past H2A techno-economic analyses of water splitting technologies
  - High Temperature Solid Oxide Electrolysis Cell (SOEC)
  - Photoelectrochemical (PEC)
  - Solar Thermochemical Hydrogen (STCH)
- System and Component Metrics
  - Tiered technology metrics
    - Common metrics for technologies
    - Local metrics for developmental technologies

Overview of H2A

- H2A is a discounted cash flow analysis that computes the required pump price of H_2 for a desired after-tax internal rate of return (IRR)
- SA uses the H2A tool along with a blend of TEA approaches
- Uses custom macros within Microsoft Excel
- NREL developed H2A
  - Latest analysis conducted in H2A Version 3.101 (updated 2015)
  - https://www.hydrogen.energy.gov/h2a_analysis.html
- Objective:
  - Establish a standard format for reporting the price of H_2 to compare technologies and case studies
  - Analyze H_2 cost from new technologies in transparent manner
  - Apply a consistent approach to analysis

H2A Inputs


Tax Rate
Start-up Year
Working Capital
Financial Inputs
Equipment
Engineering & Design
Contingency
Up-Front Permitting
Indirect Capital
Capital Costs
H2A
Inputs
Land Cost
And Usage
Mass and Energy
Balance
Fuel Cost
Water Cost
Electricity Cost
Variable Operating
Costs
Operating Costs
System Design
Fuel Usage
Water Usage
Electricity Usage
Full Time Employees
Rent
Fixed Operating
Costs

Technology Readiness Level (TRL)

- Technology Readiness Level
  - A.K.A. Technology Readiness Assessment
  - Measure of development status of a given technology
- Various TRL definitions
  - NASA
  - DOD
  - DOE
  - European Space Agency
  - Oil and Gas Industry
  - And More!
- Use in H2A
  - Future case TRL is generically assumed to be higher than the Current case
    - May estimate parameters that raise the TRL for Future case
  - If the Current case TRL is low enough, only Future case analysis might be conducted

TRL Descriptions

1	Basic Concepts Conceived and Reported
2	Technology Concept and Application Formation
3	Analytical and Experimental Critical or Proof of Concept
4	Component or System Validation in Laboratory Environment
5	Bench Scale or Similar System Validation in Relevant Environment
6	Engineering Scale, system validation in a Relevant Environment
7	Full-scale, similar system demonstrated in Relevant Environment
8	Actual System Completed and Qualified
9	Actual System Operation

DOE TRL Descriptions

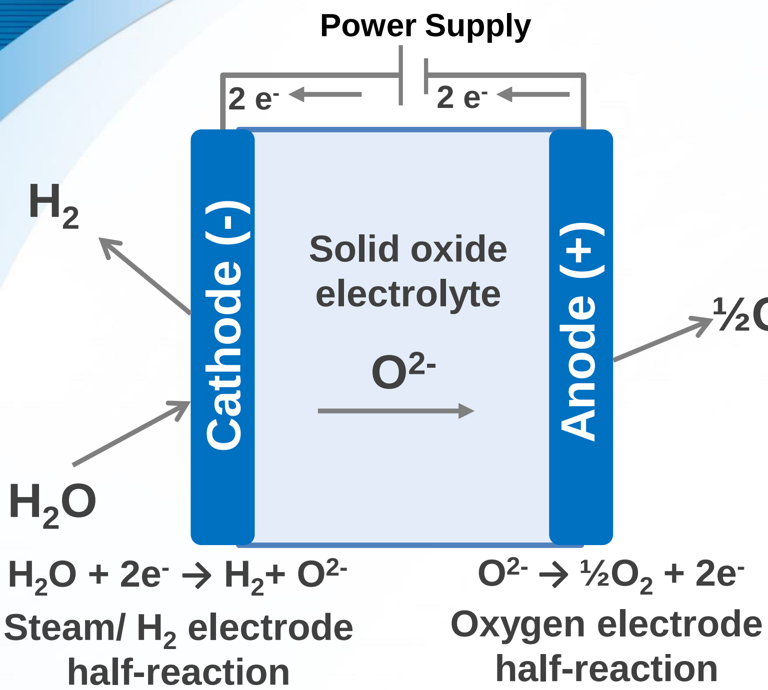
Table 1 Technology Readiness Levels

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	**TRL 9**	Actual system operated over the full range of expected conditions.	Actual operation of the technology in its final form, under the full range of operating conditions. Examples include using the actual system with the full range of real wastes.
System Commissioning	**TRL 8**	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with real waste in hot commissioning.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in a relevant environment	Prototype[a] full scale system. Represents a major step up from TRL 6, requiring demonstration of a system prototype in a relevant environment. Examples include testing the prototype in the field with a range of simulants and/or real waste and cold commissioning.
Technology Demonstration	**TRL 6**	Engineering scale, similar (prototypical) system validation in a relevant environment	Representative engineering scale system, which is well beyond the scale tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness and system integration. Examples include testing a prototype with real waste and a range of simulants.
Technology Development	**TRL 5**	Laboratory/bench scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity system in a simulated environment and/or with a range of real wastes and simulants.
	TRL 4	Component and/or system validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in a laboratory and testing with a range of simulants.[b] Laboratory/bench scale testing may not be appropriate for all systems. For example, mechanical systems, such as robotic retrieval technologies, may require full scale prototype testing to meet TRL 4.
Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory/bench scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. Components may be tested with simulants. For some applications, such as mechanical systems, this may include computer and/or physical modeling to demonstrate functionality.
	TRL 2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.
Basic Technology Research	**TRL 1**	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.

http://energy.gov/sites/prod/files/2014/03/f12/ATTACHMENT-TRA%20Guide%20%20%209-3-13.pdf

High Temperature Solid Oxide Electrolysis Cells

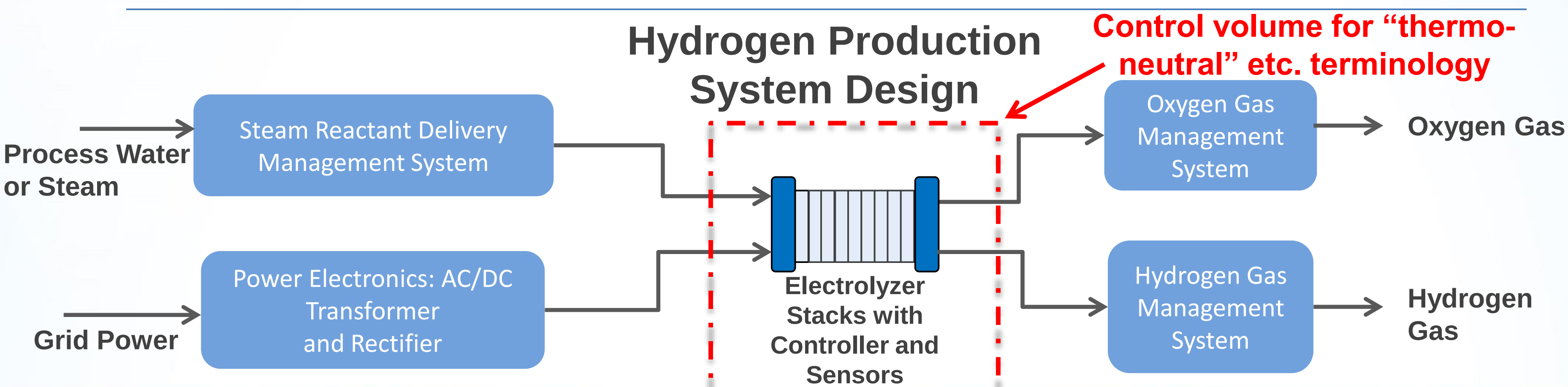
SOEC Technology



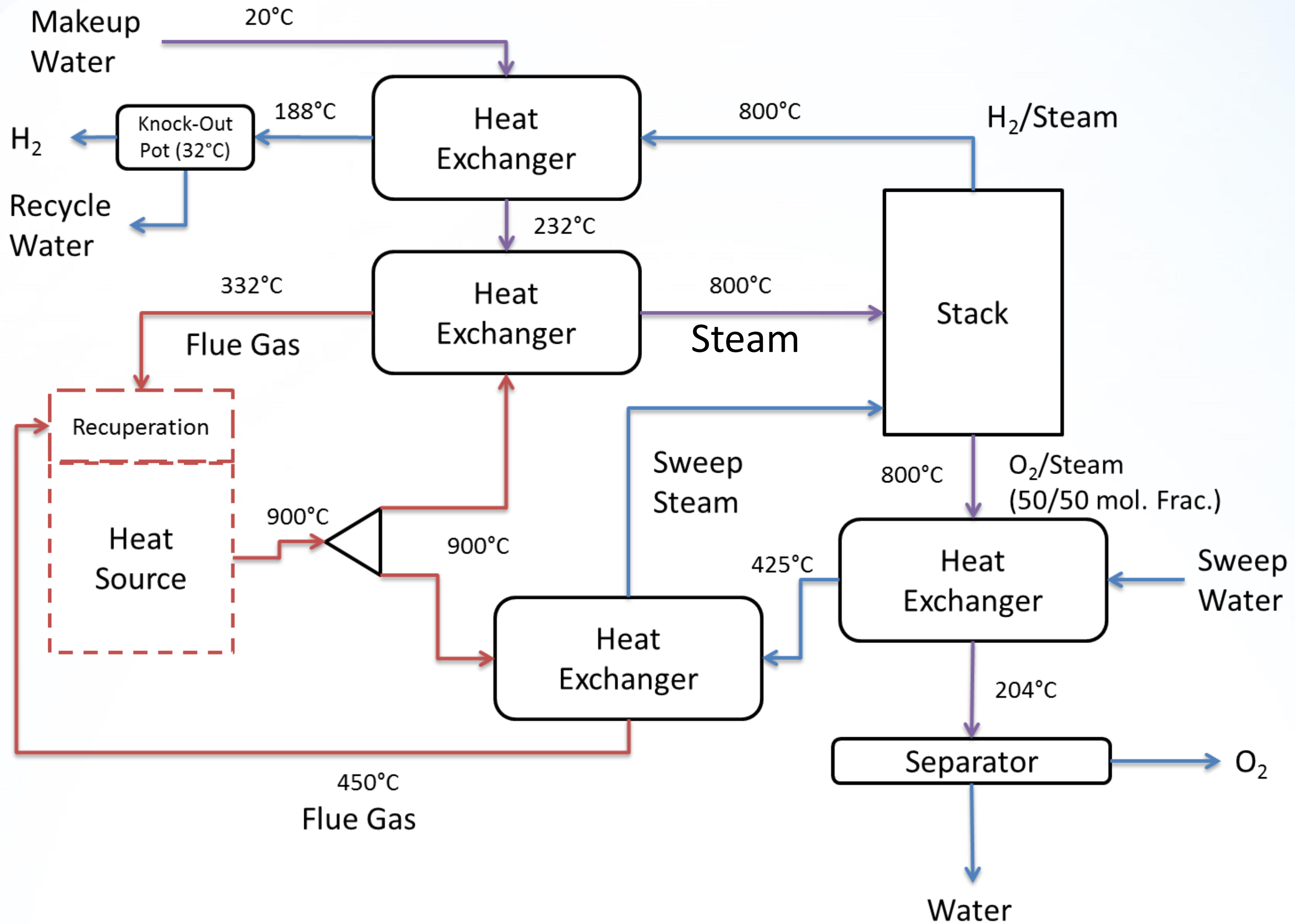
SOEC water electrolysis uses electricity to split water (H_2O) into oxygen (O_2) and hydrogen (H_2).

- Overall endothermic reaction: **Energy + $H_2O \rightarrow H_2 + ½O_2$**
- Power: An external power supply delivers direct current (DC) electricity such that electrons (e^-) flow through an external electric current.
- Cathode (negative terminal): Steam (H_2O) reacts with electrons (e^-) in the presence of catalyst to form negatively charged oxygen ions (O^{2-}) (or anions) and hydrogen gas (H_2).
- Electrolyte: Oxygen ions (O^{2-}) traverse the electrolyte.
- Anode (positive terminal): In the presence of catalyst, oxygen ions (O^{2-}) release their electrons (e^-) to the external circuit and form oxygen gas (O_2).

Hydrogen Production System Design

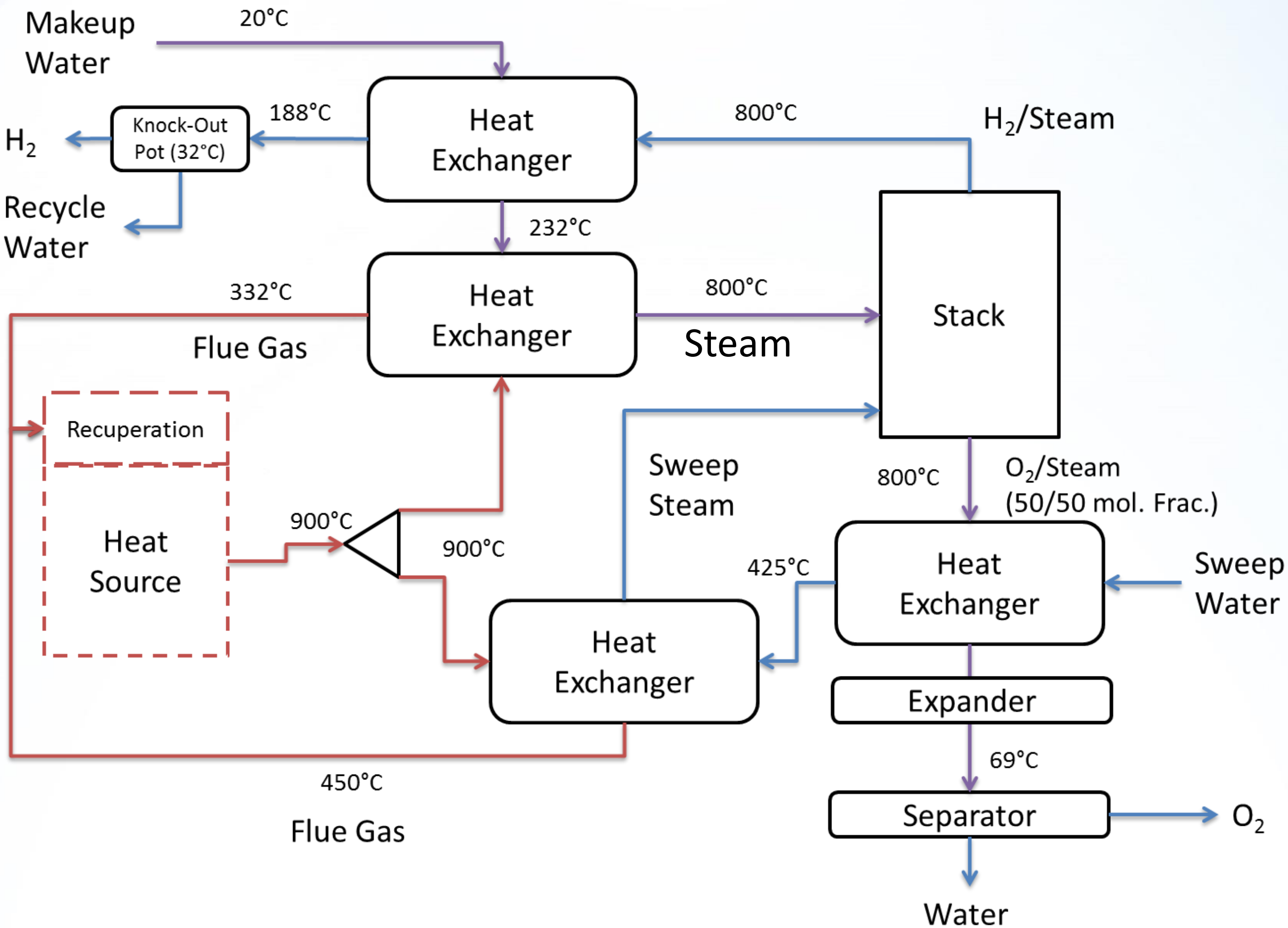


SOEC System: Current Case



- 66% H_2O Consumption in stack
- Natural Gas Burner at 900°C
- System Pressure = 300 psi
- Electrical Usage = 36.8 kWh/kg
- Heat Usage = 14.1 kWh/kg
- Heat Price = $10.11/GJ

SOEC System: Future Case



- 66% H_2O Consumption in stack
- Natural Gas Burner at 900°C
- **System Pressure = 700 psi**
- **Electrical Usage = 35.1 kWh/kg**
- **Heat Usage = 11.5 kWh/kg**
- **Heat Price = $11.47/GJ**

The two public H2A cases use this input data, which is based on performance data from a six member expert panel.

	Current	Future	Value Basis
Technical Parameters			
Production Equipment Availability Factor (%)	90%	90%	H2A
Plant Design Rated Hydrogen Production Capacity (kg of H2/day)	50,000	50,000	H2A
System Design Rated Electric Power Consumption (MWe)	76.7	73.1	Eng. Calc.
System H2 Output pressure (MPa)	2	5	Ind. Questionnaire
System O2 Output pressure (MPa)	2	5	Ind. Questionnaire
Stack operating temperature range (°C)	600 to 1,000	600 to 1,000	Ind. Questionnaire
Direct Capital Costs			
Basis Year for production system costs	2007	2007	H2A
Uninstalled Cost (2007$/kW) - (with approx. subsystem breakdown)	**789**	**414**	**Ind. Questionnaire**
Stacks	35%	23%	Ind. Questionnaire
BoP Total	65%	77%	Ind. Questionnaire
Installation factor (a multiplier on uninstalled capital cost)	1.12	1.10	H2A/Eng. Judg.
Indirect Capital Costs			
Project contingency ($)	20%	20%	H2A
Other (depreciable capital) (%) (Site Prep, Eng&Design, Permitting)	20%	20%	H2A
Land required (acres)	5	5	H2A/Eng. Judg.
Replacement Schedule			
Replacement Interval of stack (yrs)	4	7	Ind. Questionnaire
Replacement Interval of BoP (yrs)	10	12	Ind. Questionnaire
Replacement cost of major components (% of installed capital)	15%	12%	Ind. Questionnaire

Parameters of particular significance are highlighted in red.

The two public H2A cases use this input data, which is based on performance data from a six member expert panel.

	Current	Future	Value Basis
O&M Costs-Fixed			
Yearly maintenance costs ($/kg H2) (in addition to replacement schedule)	3%	3%	H2A/Eng. Judge.
O&M Costs - Variable			
Total plant staff (total FTE's)	10	10	H2A/Eng. Judge.
Total Annual Unplanned Replacement Cost (% of total direct depreciable costs/year)	0.50%	0.50%	H2A
Feedstocks and Other Materials			
System Electricity Usage (kWh/kg H2)	**36.8**	**35.1**	**Ind. Questionnaire**
System Heat Usage (kWh/kg H2)	**14.10**	**11.50**	**Ind. Questionnaire**
Total Energy Usage (kWh/kg H2)	**50.9**	**46.6**	**Ind. Questionnaire**
Process water usage (gal/kg H2)	2.38	2.38	H2A/Eng. Calc.
By-Product Revenue or Input Streams			
Electricity cost (2007$/kWh)	**0.0624**	**0.0689**	**AEO/Eng. Calc.**
Heating cost (2007$/kWh)	**0.036**	**0.041**	**DOE/Eng. Calc.**
Process water cost (2007$/gallon)	0.00181	0.00181	H2A
Sale Price of Oxygen ($/kg O2)	O_2 not re-sold		Eng. Judgment

Ind. Questionnaire = values based on SOEC industry questionnaire results
H2A = parameter default values used within H2A model
Eng. Judgment/Calc. = values based on engineering judgment or calculation

Degradation Values

	Units	Current Case	Future Case
Current Density (BOL)	A/cm	1.0	1.5
Cell Voltage	V/cell	1.28	1.28
Voltage Degradation	%/1000h	0.9%	0.25%
Voltage Degradation	mv/1000h	11	3.15
Ohmic Degradation Rate	mOhm-cm^2/1000h	11	2.1
Stack Service Lifetime	years	4	7
% of Design Capacity at End of 1 Year Service due to degradation	%	83.2%	94.5%
H2A Plant Capacity Factor	%	90%	90%
Overall Effective Plant Capacity Factor (Linear Average per year)	%	82.4%	87.5%
BoP Service Lifetime	years	20	20
BoP Replacement Cost	%	100%	100%

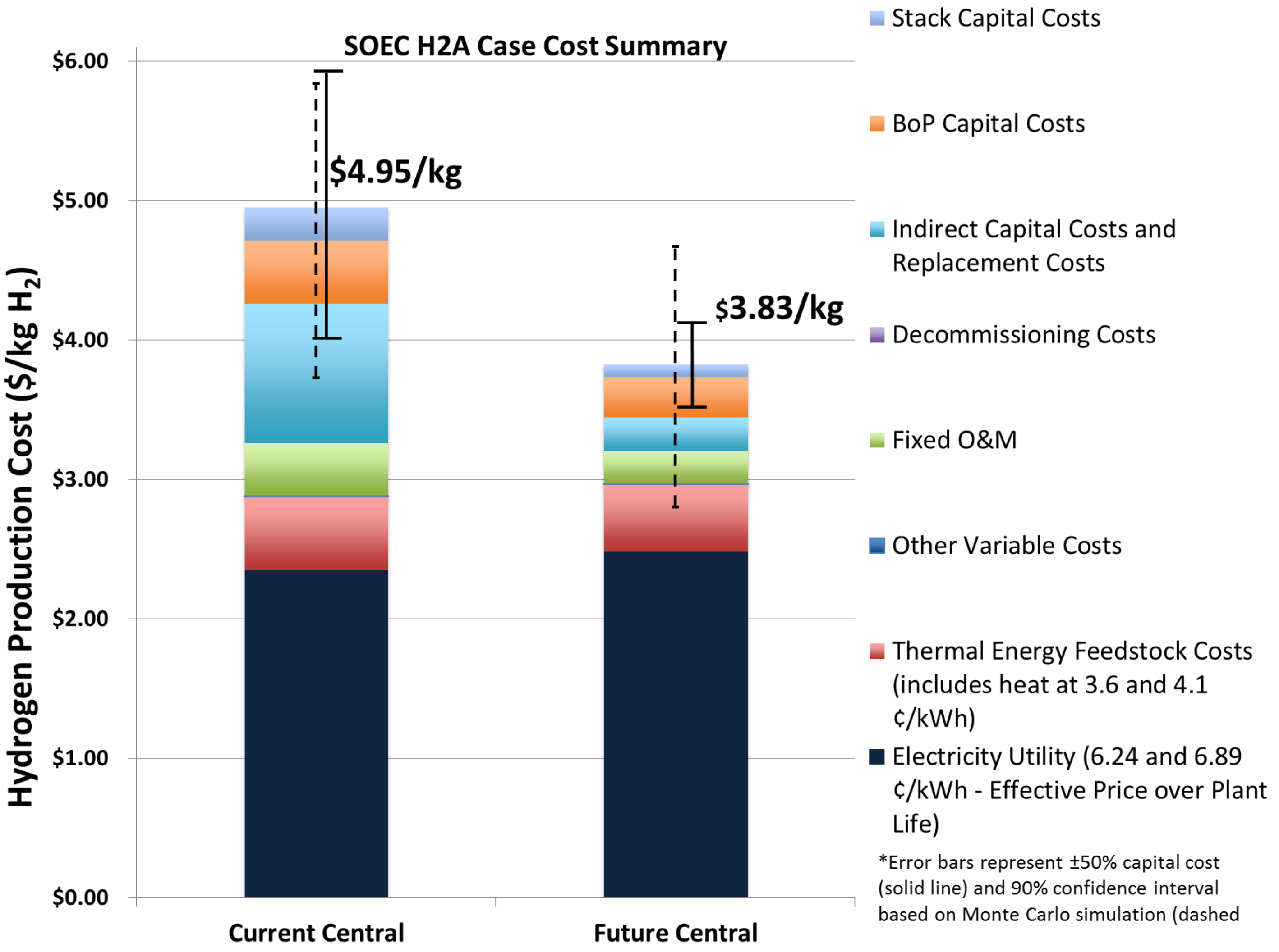
We use Ohmic degradation rate to assess the annual impact on H_2 production rate. Rates calculated by methods described in Hjelm[3]

[1] BOL = Beginning of Life

[2] Absolute ASR degradation rate computed using secant method based on 0.85V open circuit voltage, BOL conditions and voltage degradation as stated.

[3]"Degradation Testing- Quantification & Interpretation", Johan Hjelm, Riso National Laboratory for Sustainable Energy, Technical University of Denmark

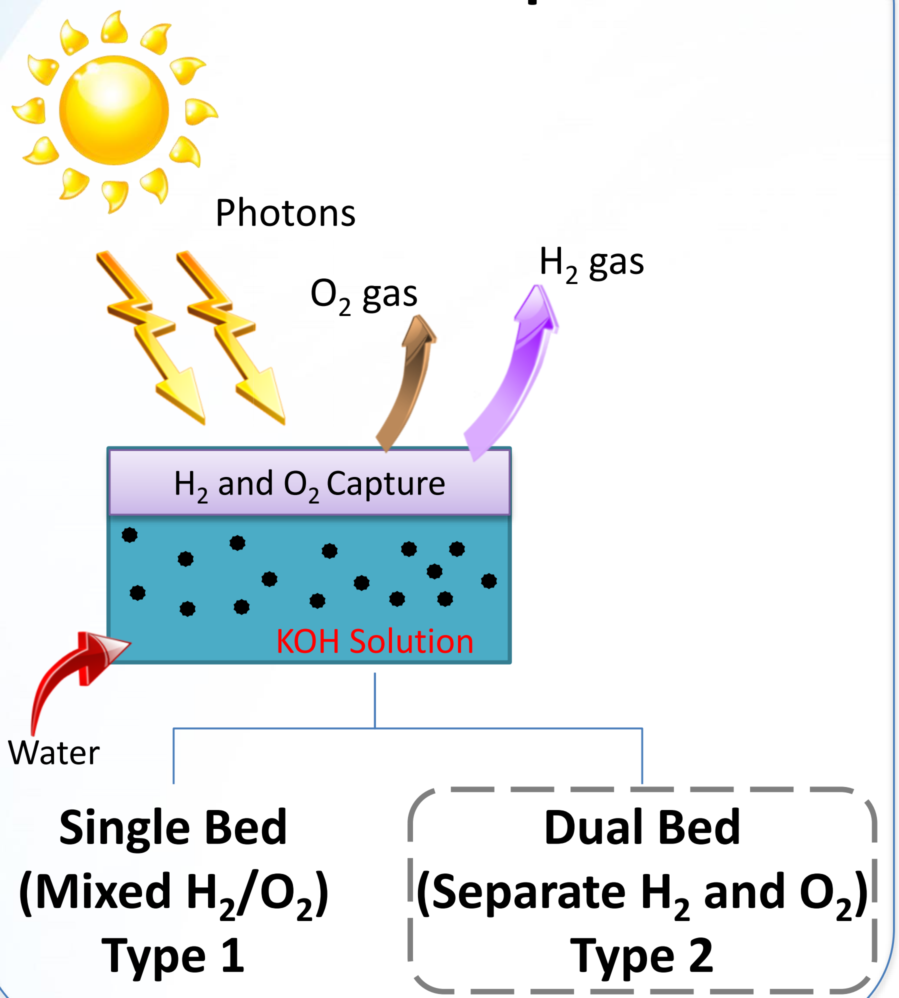
SOEC Costs


SOEC H2A Case Cost Summary
Hydrogen Production Cost ($/kg H2)
$6.00
$5.00
$4.00
$3.00
$2.00
$1.00
$0.00
$4.95/kg
$3.83/kg
Current Central
Future Central
Stack Capital Costs
BoP Capital Costs
Indirect Capital Costs and Replacement Costs
Decommissioning Costs
Fixed O&M
Other Variable Costs
Thermal Energy Feedstock Costs (includes heat at 3.6 and 4.1 ¢/kWh)
Electricity Utility (6.24 and 6.89 ¢/kWh - Effective Price over Plant Life)
*Error bars represent ±50% capital cost (solid line) and 90% confidence interval based on Monte Carlo simulation (dashed

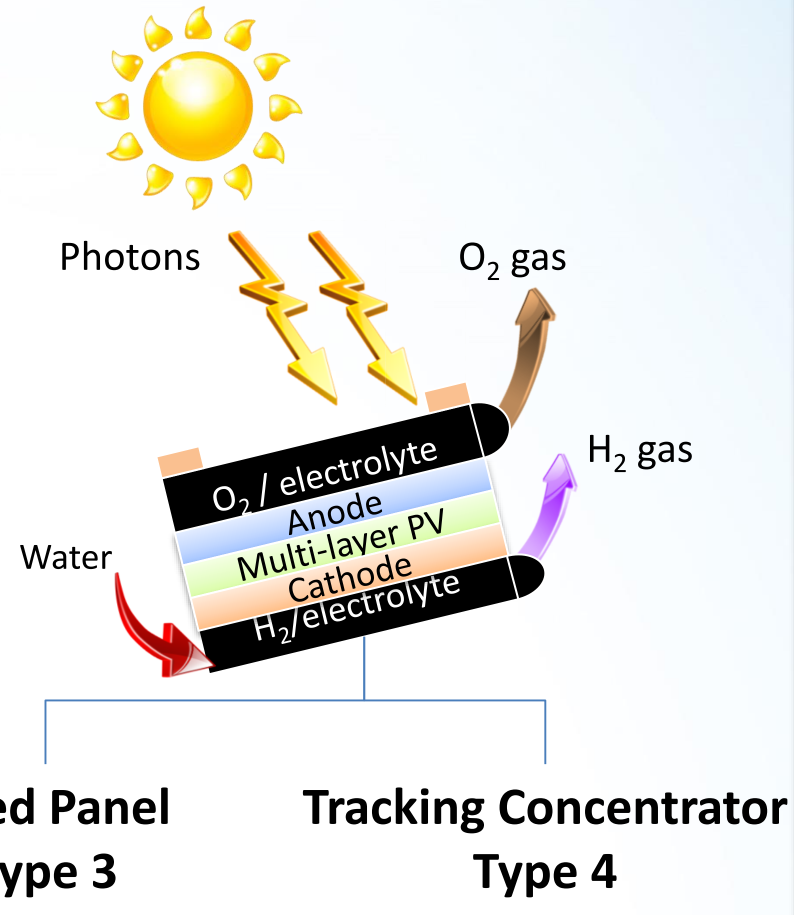
Photoelectrochemical

PEC Design Concepts

Colloidal Suspensions



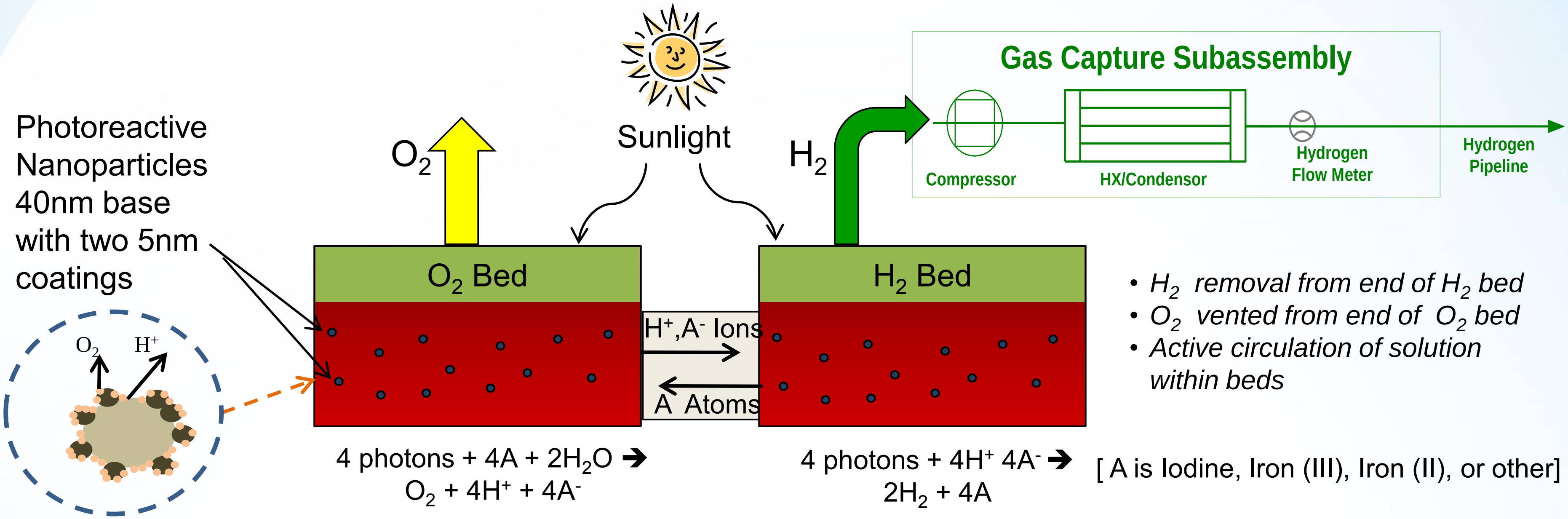
PEC Electrode

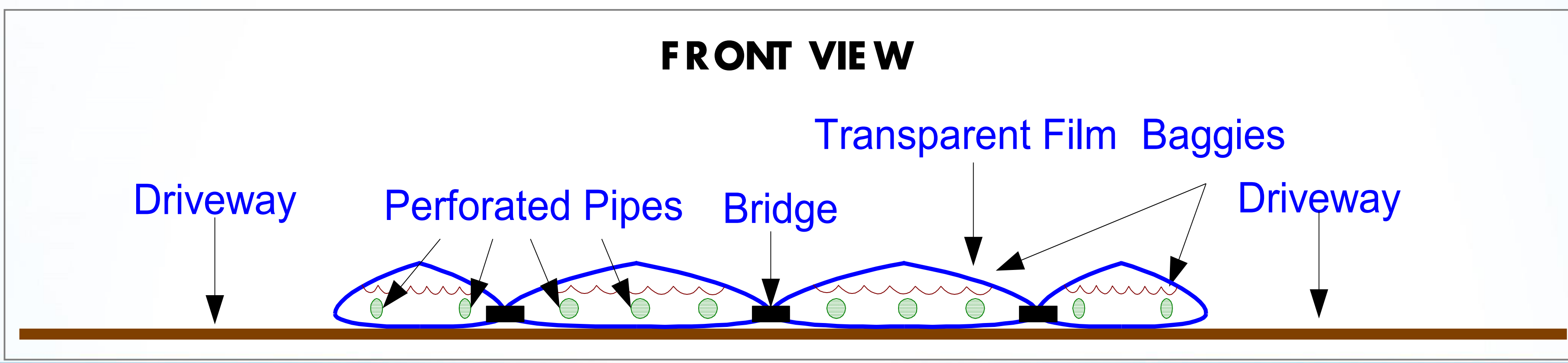


Basic PEC System Design

Type 2 Colloidal Suspension System

Plant Capacity = 1 TPD Module x 10





Basic Assumptions:
Type 2 Colloidal Suspension System: Dual Bed Photocatalyst

- Coated Nanoparticles in in shallow plastic (HDPE) bags of 0.1M KOH Electrolyte Solution
- Two bed system: one for H_2 generation, one for O_2 generation
- 5% (2020) Solar-to-Hydrogen Efficiency
- Product Gas after condenser: 99% H_2, 1% water
- H_2 compression to 300psi (external compressor)
- LDPE fibrous mat is liquid permeable "window" between beds
- 6 mil HDPE transparent bags (90% optical transparency)
- Fabricated in factory: unrolled in field
- Perforated PVC pipes for mixing

Example Parameter Values to Meet Cost Targets

Characteristics	Units	2020 Target
Solar to Hydrogen (STH) Energy Conversion Ratio	%	5%
PEC particle cost	$/kg	500
Particle Replacement Lifetime	Years	1
Capital cost of reactor bed system (excluding installation and PEC particles)	$/m^2	$7
Balance of Plant Cost per TPD H_2	$/TPD	$1.0M

Bottom-Up Technology Status: Type 2 PEC 2020 Target

- Levelized Cost of Hydrogen: **$4.07 / kg (2007$)**
- Installed Equipment Cost: **$2.7M** (for 1 TPD module)
- Total Capital Investment: **$3.7M** (for 1 TPD module)
- Capital Costs represent the majority (70.4%) of H_2 cost.

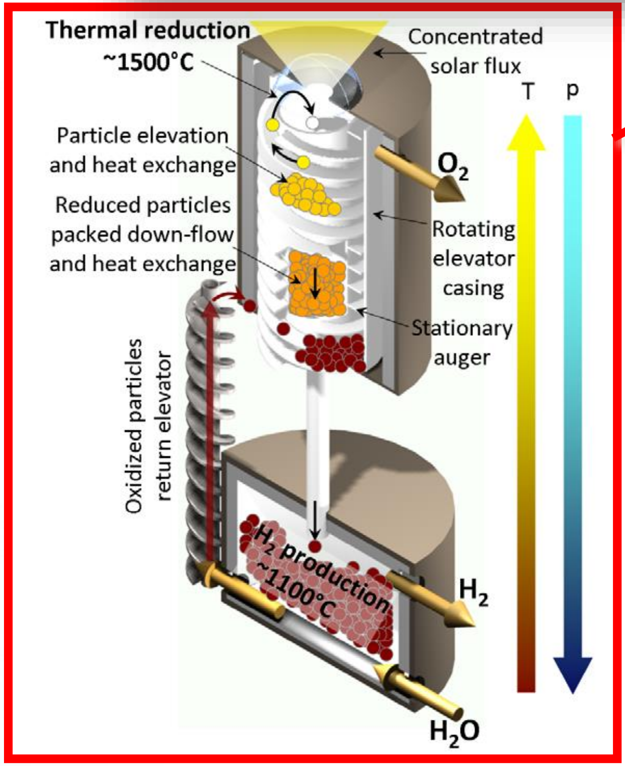
Specific Item Cost Calculation		
Cost Component	**Cost Contribution ($/kg)**	**Percentage of H2 Cost**
Capital Costs	$2.87	70.4%
Decommissioning Costs	$0.00	0.1%
Fixed O&M	$1.06	26.1%
Feedstock Costs	$0.00	0.0%
Other Raw Material Costs	$0.00	0.0%
Byproduct Credits	$0.00	0.0%
Other Variable Costs (including utilities)	$0.14	3.4%
Total	**$4.07**	

Capital cost is majority cost contributor

Fixed O&M is mostly labor.

Solar Thermochemical Hydrogen Production

STCH Concept: Solar Dishes

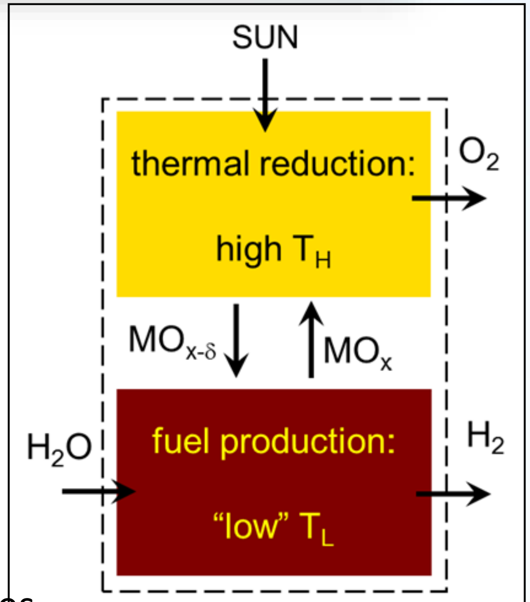


Latest Sandia Reactor Concept
(moving packed bed, spatial pressure separation)

Large field of STCH dishes:
- ~30,000 dishes (for 100TPD H_2)
- ~4,400 acres

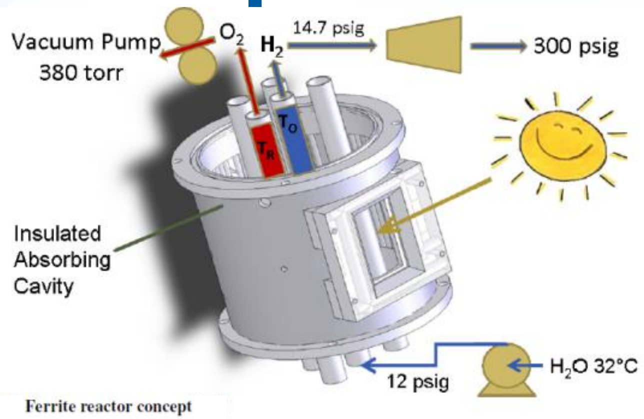
Each dish:
- 11m (37ft) in diameter
- 88 m^2 of solar capture area
- ~3.2 kgH_2/day (average)

Line/Pipe connections for:
- H_2
- Power
- Water (although one variant uses abs. chillers to capture environmental water vapor)



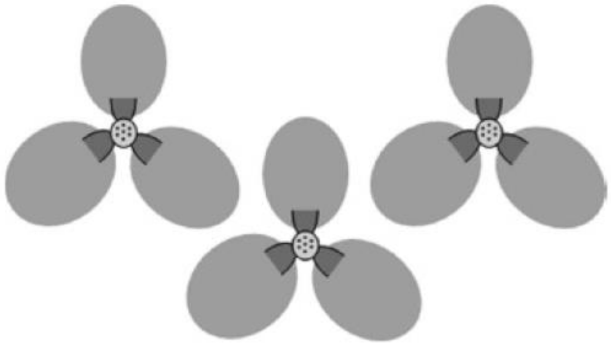
Two-step
metal oxide cycle

Example STCH System Configuration



Ferrite reactor concept

Figure from TIAX 2009.



Schematic of ferrite solar field layout (not to scale)

Figure from TIAX 2009.

Figure from NREL/SR-550-34440, 2003.

Three H2A Case Studies on STCH

Nominal plant size for Central cases is 100 metric tons H_2 per day (enough to support ~131,000 vehicles). Intent is to be a "large" plant.
The H2A analysis reviews a STCH system producing 100,000 kg of H_2 per day

2015 Case

- The 2015 case is a projection from current STCH technology
- Assumes the optimal performance of the Ceria redox cycle
- Increased solar to H_2 conversion efficiency
- Reduction in capital cost from currently accepted values

2020 Case (Data in this presentation represents this case)

- More advanced material used for redox cycle, some type of perovskite
  - Shorter cycle time (time to split H_2O into O_2 and H_2)
  - Longer lifetime
  - Increased H_2 evolution (moles of H_2 produced per gram of ceria).
- The solar to H_2 conversion efficiency increases
- Reductions in capital cost.

Ultimate Target Case

- Assumptions based on expected limit of technology.
- Generally expected to reach/approach DOE target of $2/kg$H_2$.

2020 Case Study Results

Levelized Cost of Hydrogen (production only): $8.83/kg (2007$)
Uninstalled STCH System Cost: $783,405,000
Total Installed Capital Investment: $1,177,742,181
Lang Factor = 1.5
STH Efficiency of System: 16.7%
Electricity Use: 6.855 kWh / kg H_2 produced
Electricity Price in Startup Year: 5.9¢/kWh

Breakdown of Levelized Costs:

Specific Item Cost Calculation		
Cost Component	**Cost Contribution ($/kg)**	**Percentage of H2 Cost**
Capital Costs	$6.48	73.4%
Decommissioning Costs	$0.01	0.1%
Fixed O&M	$1.86	21.1%
Feedstock Costs	$0.00	0.0%
Other Raw Material Costs	$0.00	0.0%
Byproduct Credits	$0.00	0.0%
Other Variable Costs (including utilities)	$0.48	5.4%
Total	**$8.83**	

Focus on Key Parameters: STCH Efficiency Example

	2015		2020	Ultimate Target
Component Efficiency	**Value**	**Definition**	**Value**	**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.**	**16.7%**	**34.3%**

- 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. Explanation of basis is good for each estimate/value.

STH Efficiency Is a Key Parameter

STH Efficiency = Solar-to-Hydrogen 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

(If STH efficiency varies with light intensity, report average conversion.)

Solar Insolation assumptions can be tricky.

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

- solar energy/intensity ← Generally 7.46 kWh/m^2/day (yearly average)
  1 kWh/m^2 (hourly peak)
  Also consider: direct/indirect insol., tracking, blockage
- collection area
- capital cost ← Sized for hourly peak production (or have explicit alternative story)
- H_2 Production Rate ← Must reconcile hourly peak, daily & seasonal variations

Metrics

Metrics

- Metrics must be meaningful and useful
- Two types
  - System metrics to assess the planned final large-scale operation
    - System metrics/performance are what ultimately matter
  - Local/Component metrics to assess narrow-field progress
    - Are a means to an end (to achieve high system performance)
    - Can “miss” one (or more) local metrics to achieve high system performance
    - Don’t have to capture all performance aspects in each metric
    - Ideally applies to multiple technologies (but doesn’t have to)
    - Ideally will be easy to measure

It’s surprisingly hard to come up with clear, concise, workable metrics.

Common System Metrics

Metric	Unit	Ultimate Target	PEC	STCH	SOEC
Cost of H_2	$/kg	2.00	✓	✓	✓
Electrical Usage	kWh/kg H_2	Not listed	✓	✓	✓
Solar to H_2 Conversion	%	25-26	✓	✓	✗
Green House Gas	$KgCo_2eqiv/kgH_2$	-	✓	✓	✓
Active Material (Electrode) Cost	$/(TPD H_2·yr)	Varies	✓	✓	✓
H_2 production rate	kg $H_2/(s \cdot m^2)$	Varies	✓	✓	✓

- Cost is King and can be calculated in H2A with normalized and transparent assumptions
- System efficiency includes all energy provided to the system (thermal, solar, electrical, etc.) ratioed to the LHV of H_2
- Values for Active Material provide accounting for useful life span
- Units with a per area basis may help in selecting technologies based on land available

Values taken from 2015 MYRDD. https://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

Local Metrics

Category	Metric	Units	STCH	PEC	SOEC
Subsystem/Component Cost	Particle/Electrode Cost	\$/kg	✓	✓	✗
	Stack Cost	\$/stack	✗	✗	✓
	Active Mat. Cost per kg H_2	\$/kg H_2	✓	✓	✓
	Active Material to H_2	kg mat/kg H_2	✓	✓	✓
Material Lifetime	Particle/Electrode Lifetime	Yrs	✓	✓	✗
	Stack Lifetime or Voltage degrad./1000 hrs	Yrs	✗	✗	✓
	Active Mat. Degrad. Rate	%/hr	✓	✓	✓
Performance	H_2 production efficiency	%	✓	✓	✓
	Component Elect. Usage	kWh/kg	✓	✓	✓
	Cycle time	min/cycle	✓	✗	✗
	Reactor Conv. Efficiency	%	✓	✗	✗
	O2 Transfer	Mol O/mol act. Mat.	✓	✗	✗
	Power Density/Current	mW/cm^2, A/cm^2	✗	✓	✓

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

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

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

Conclusions

- New materials for H_2 production are a high priority for DOE
  - SOEC
  - PEC
  - STCH
- Metrics must be meaningful and useful
  - System metrics for assessment of final large-scale operations
    - System metrics/performance are what ultimately matter
  - Local/Component metrics for assessment of narrow-field progress
    - Are a means to an end (good system performance)
    - Must be fair but don't have to capture all performance and cost aspects
    - Ideally apply to multiple technologies (but don't have to)
    - Ideally will be easy to measure

Thank You