Analysis of Advanced H_2 Production Pathways

STRATEGIC ANALYSIS INC

2015 DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Brian D. James (SA)
Jennie M. Moton (SA)
Daniel A. DeSantis (SA)
Genevieve Saur (NREL)

Project ID: PD102
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Overview

Timeline

- Project start date: 3/15/2013
- Project end date: 3/14/2016
- Percent complete: 66%

Budget

- Total Funding Spent*
  - $389k thru 3/15 (SA portion)
- Total DOE Project Value
  - $609k for all 3 years (SA portion)
- Cost Share Percentage: 0%
  (not required for analysis projects)

Barriers

– **High Temperature Electrolysis using Solid Oxide Electrolysis Cell (SOEC)**
- Hydrogen (H_2) Generation by Water Electrolysis
  – F: Capital Cost
  – G: System Efficiency and Electricity Cost
  – K: Manufacturing

– **Bio-fermentation Using Corn Stover**
- Dark Fermentative Hydrogen Production
  – AX: Hydrogen Molar Yield
  – AY: Feedstock Cost
  – AZ: Systems Engineering

Partners

- National Renewable Energy Laboratory (NREL)*
- Argonne National Laboratory (ANL)*

Collaborators

- Six SOEC developers
- Bio-fermentation specialists

* National Lab work subcontracted through DOE internal funding and not included in totals.

Relevance and Impact

- Investigating production pathways selected/suggested by DOE as relevant, timely, and of value to FCTO.
- Provide complete pathway definition, performance and economic analysis not elsewhere available.
- Analysis is transparent, detailed, and made publicly available to the technical community.
- Results of analysis:
  - Identify cost drivers
  - Assess technology status
  - Provides information to DOE that may be used to help guide R&D direction

Objectives

The objectives of this project include:

1) **Analyze H_2 Production & Delivery (P&D) pathways** to determine economical, environmentally-benign, and societally-feasible paths for the P&D of H_2 fuel for fuel cell vehicles (FCEVs).

2) **Identify key "bottlenecks"** to the success of these pathways, primary cost drivers, and remaining R&D challenges.

3) **Assess technical progress, benefits and limitations, levelized H_2 costs**, and potential to meet U.S. DOE P&D cost goals of <$4 per gasoline gallon equivalent (gge) (dispensed, untaxed) by 2020.

4) Provide analyses that **assist DOE in setting research priorities**.

5) **Apply the H2A Production Model** as the primary analysis tool for projection of levelized H_2 costs ($/kg$H_2$) and cost sensitivities.

In 2014-2015, these project objectives were applied to develop two cases:

- Solid Oxide Electrolysis
- Bio-fermentation
- (These cases are in addition to the PEM electrolysis case analyzed last year)

The team gathered technical & economic data from industry/researchers and synthesized data into generalized H2A cases

- Developed a detailed, **quantitative questionnaire** soliciting engineering and economic performance data.
- **Asked Research Organizations** to independently respond to the questionnaire.
- Requested relevant **detailed information** on:
  - Current and Future cases for Central production.
- Analyzed questionnaire data, and synthesized and amalgamated data **into generalized cases/input parameters**.
- Developed accurate **process and cost models**
  - Modeled system performance in Excel® and Hysys® (SOEC Cases only).
  - Populated H2A Production Models v3.1.
  - Predicted levelized H_2 cost and identified key cost drivers and sensitivities.
- **Vetted the public cases** with the Research Organizations.

The team gathered data for two cases for each technology

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

- Case assumes high volume production that incorporates economies of scale.
- Demonstrated advances in technology are implemented.
- Potential reduction in capital cost from existing values.
- Plant lifetimes consistent with measured or reported data.

Future Case ("if you were fabricating in the future at production volume")

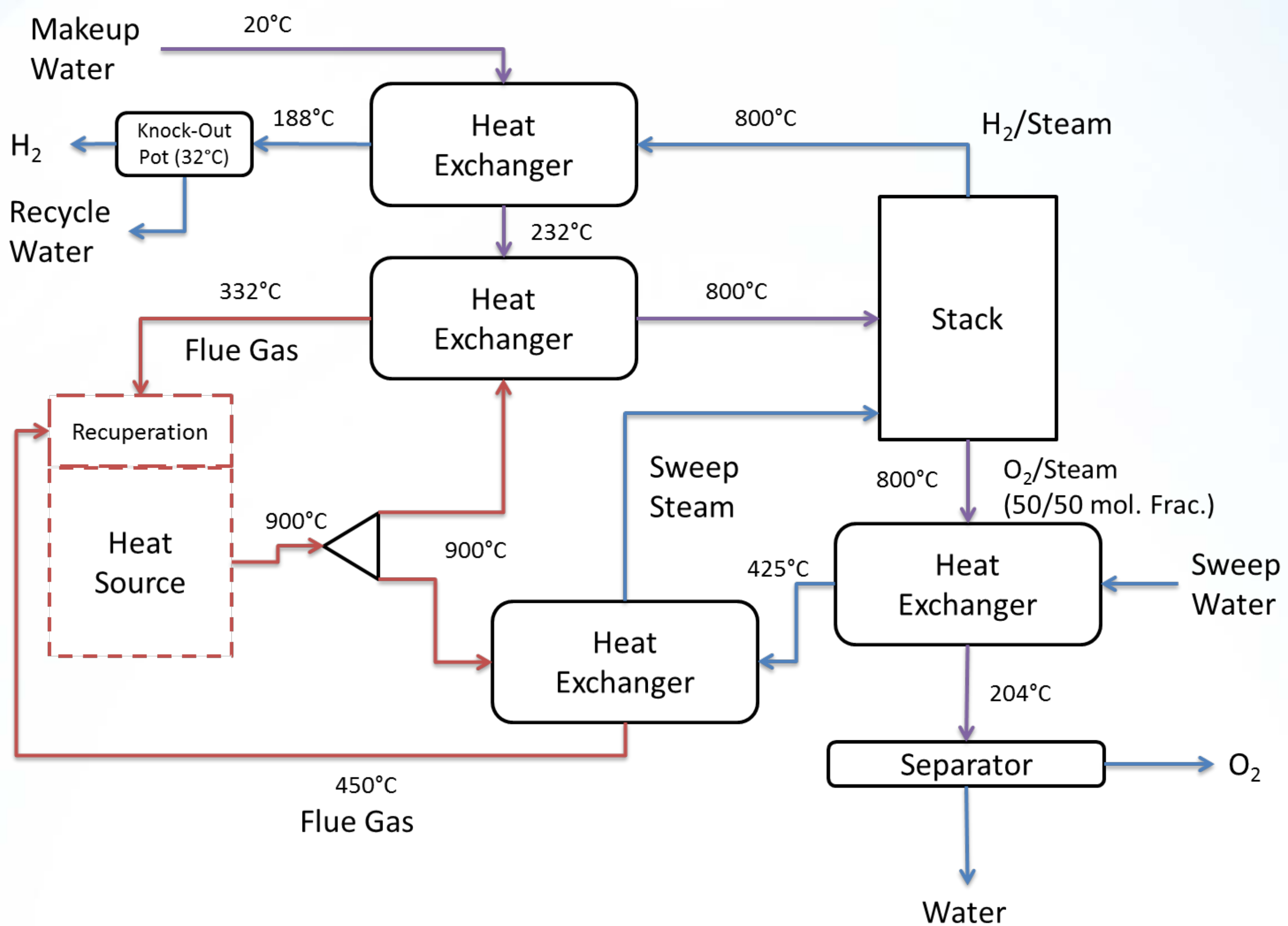
- Case assumes high volume production that incorporates economies of scale.
- Case assumes new materials and systems with higher H_2 production efficiency, longer plant lifetime, and improved replacement cost schedule.
- Case assumes greater reductions in capital cost.

Case parameters for a central H_2 production facility

Public Cases	Plant Start Date	Production of H_2 (kilograms (kg)/day)	Plant Life (years)
Current Central	2015	50,000	40
Future Central	2025	50,000	40

SOEC Cases

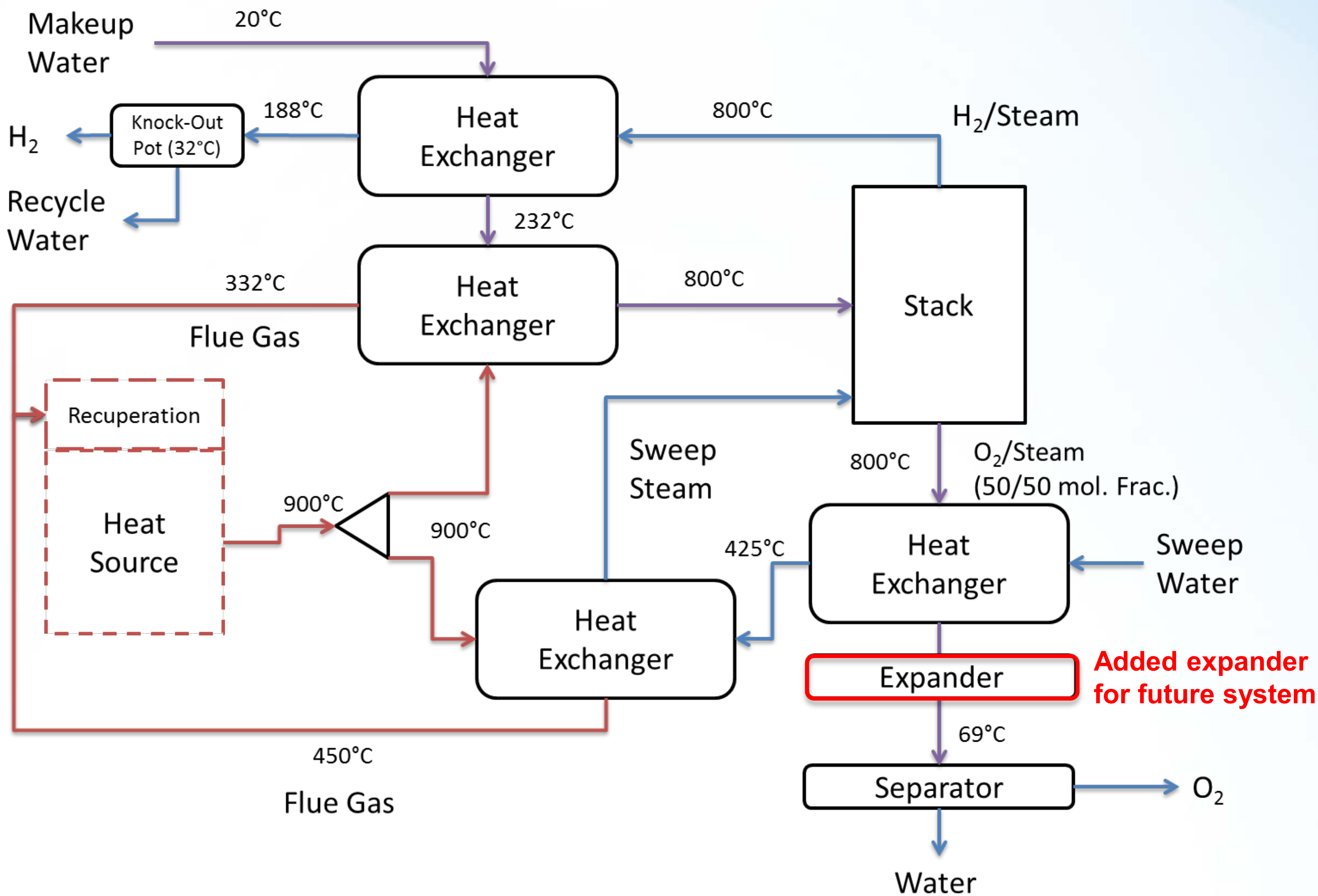
SOEC System: Current Case



- 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***

*** Heat price higher in future due to AEO projected natural gas price escalation.**

The current and future SOEC cases use input values based on feedback 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_{elec. input}$) - (w/ approx. subsys. breakdown)	**789**	**414**	**Ind. Questionnaire**
Stacks	35%	23%	Ind. Questionnaire
BoP Total	65%	77%	Ind. Questionnaire
Installation factor (a multiplier on uninstalled capital cost)	1.12	1.10	H2A/Eng. Judg.
Indirect Capital Costs			
Project contingency ($)	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 current and future SOEC cases use input values based on feedback from a six member expert panel.

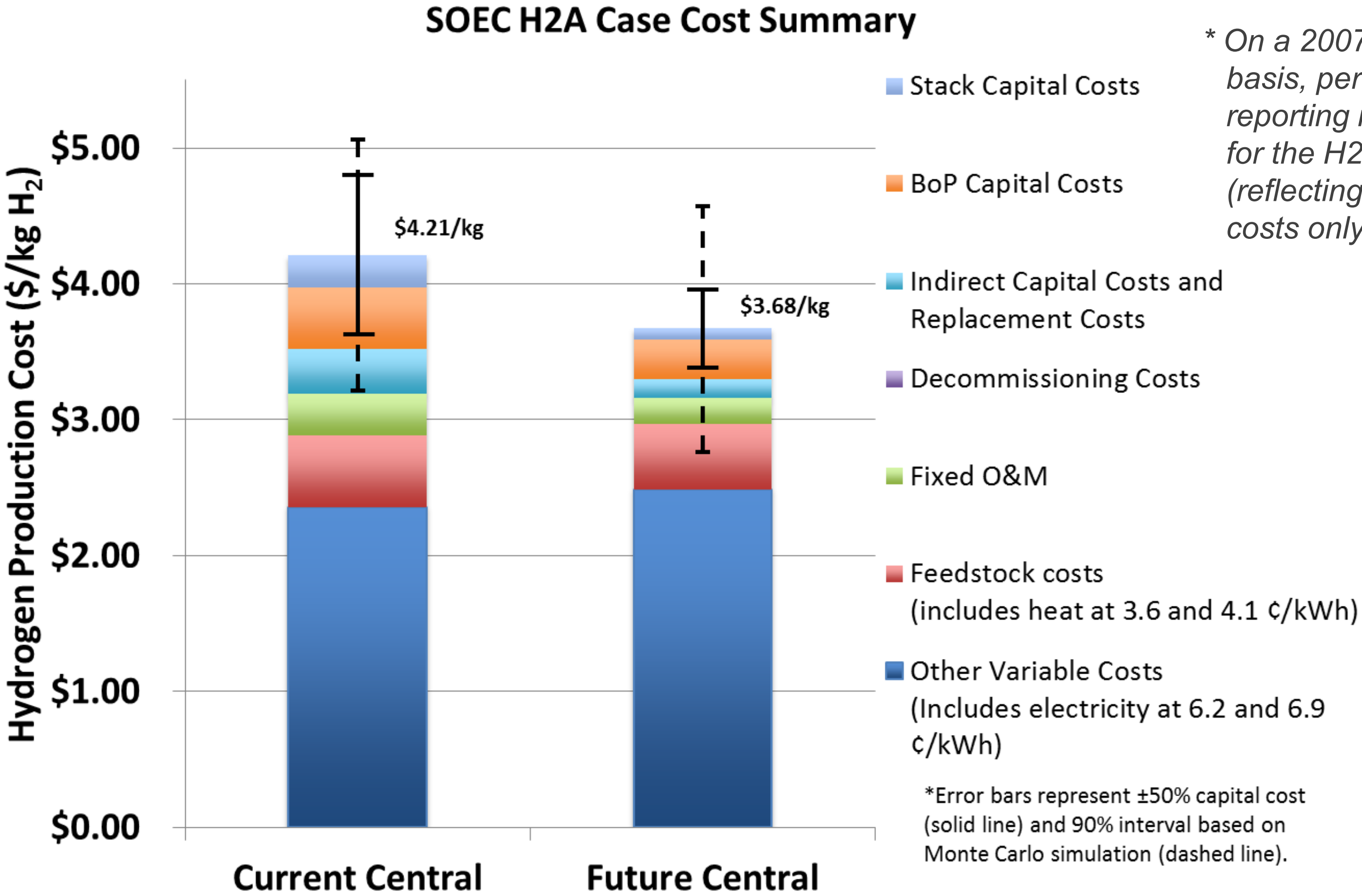
	Current	Future	Value Basis
O&M Costs-Fixed			
Yearly maintenance costs ($/kg H2) (in addition to replacement schedule)	3%	3%	H2A/Eng. Judge.
O&M Costs - Variable			
Total plant staff (total FTE's)	10	10	H2A/Eng. Judge.
Total Annual Unplanned Replacement Cost (% of total direct depreciable costs/year)	0.50%	0.50%	H2A
Feedstocks and Other Materials			
System Electricity Usage (kWh/kg H2)	**36.8**	**35.1**	**Ind. Questionnaire**
System Heat Usage (kWh/kg H2)	**14.10**	**11.50**	**Ind. Questionnaire**
Total Energy Usage (kWh/kg H2)	**50.9**	**46.6**	**Ind. Questionnaire**
Process Water Usage (gal/kg H2)	2.38	2.38	H2A/Eng. Calc.
By-Product Revenue or Input Streams			
Electricity price (2007$/kWh)	**0.062**	**0.069**	**AEO/Eng. Calc.**
Heating price (2007$/kWh)	**0.036**	**0.041**	**DOE/Eng. Calc.**
Process water price (2007$/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

Parameters of particular significance are highlighted in red.

All cases reflect a \$3.6-4.2/kg cost for H_2 production.*

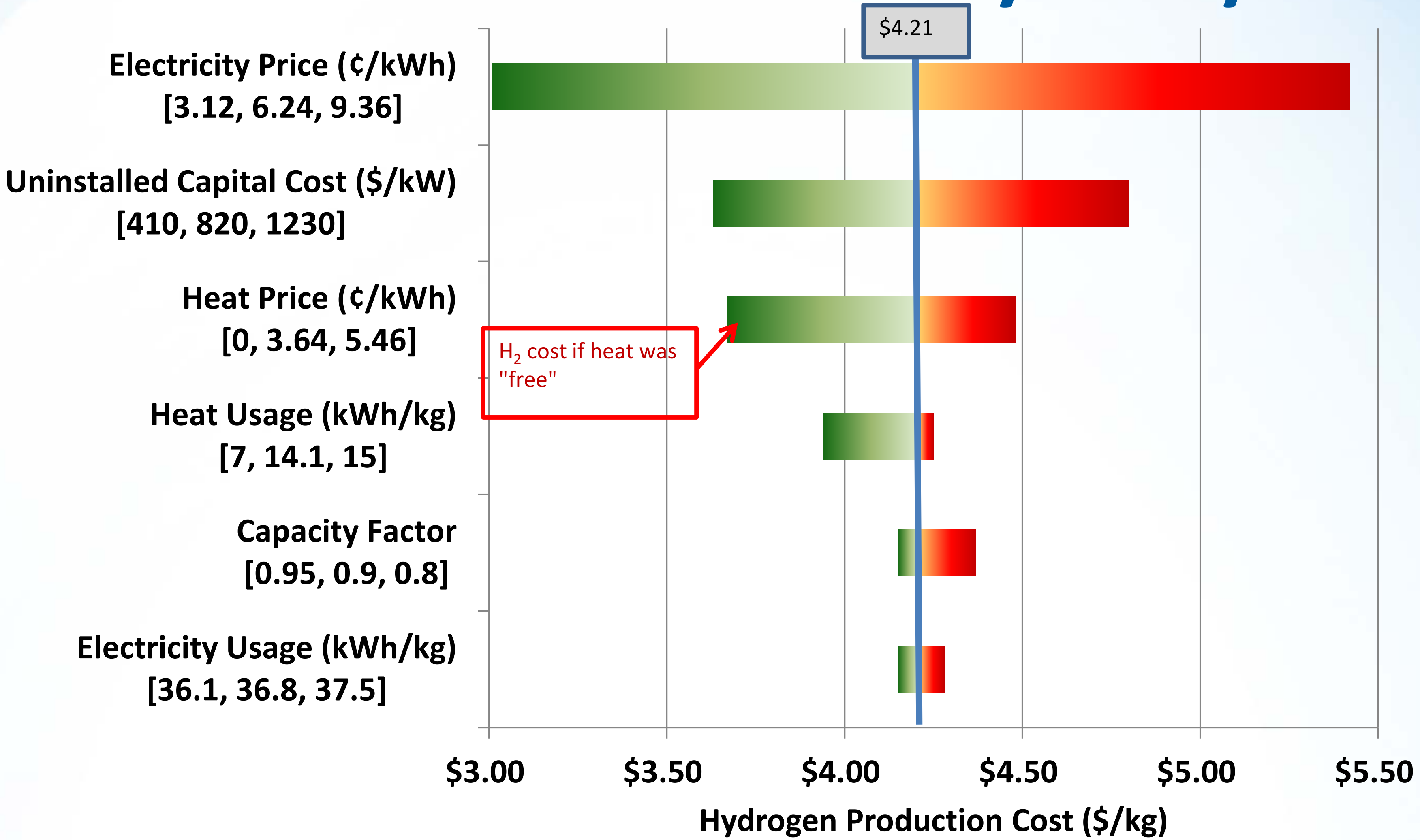
Electricity costs are the key cost driver.



** On a 2007 dollar cost basis, per standard reporting methodology for the H2A v3.1 tool (reflecting production costs only)*

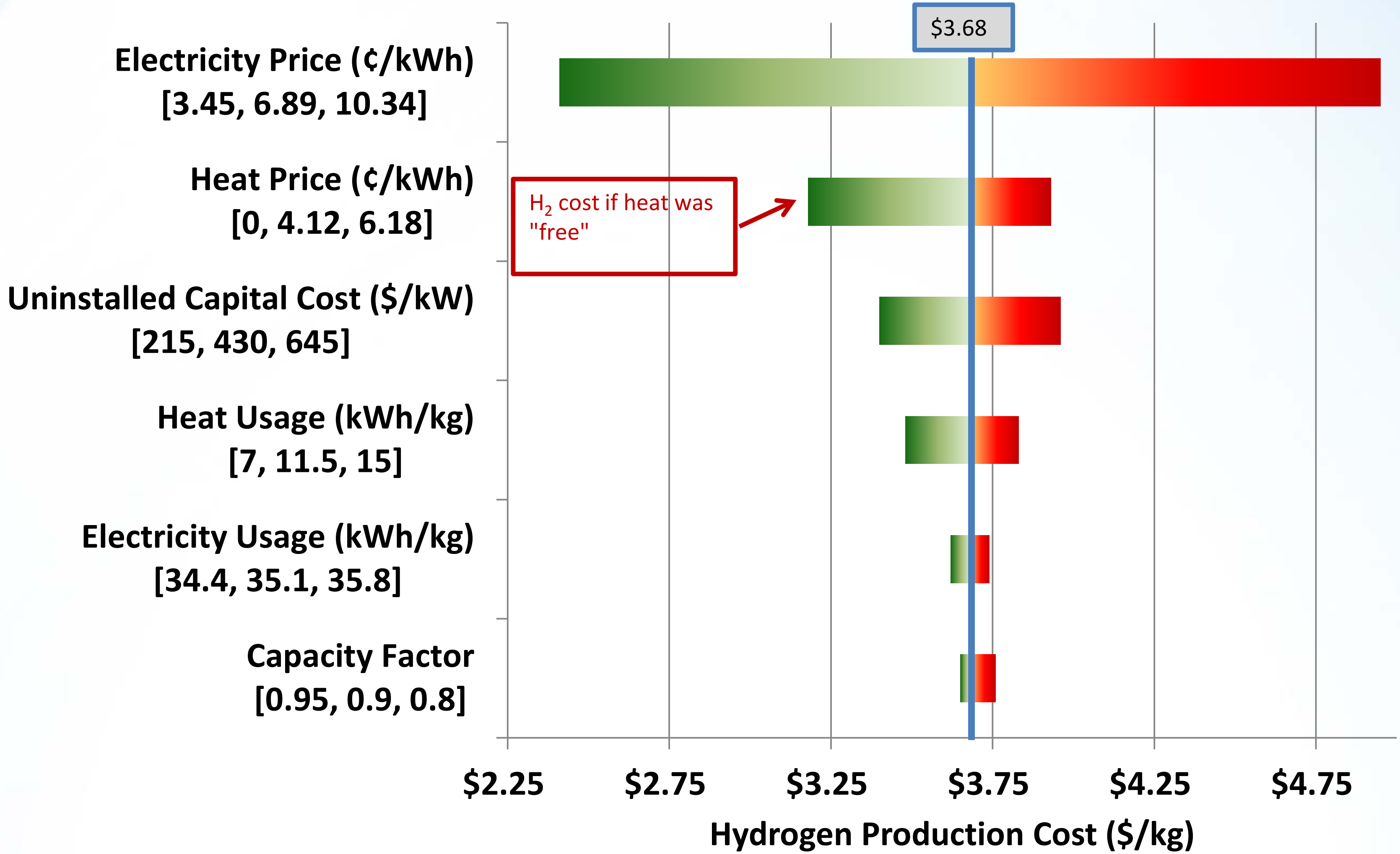
- "Other Variable Costs" consist mainly of electricity costs. "Feedstock costs" are primarily heating costs.
- "Other Variable Costs" (electricity) and "Feedstock costs" (heat) are 68% to 78% of total production costs.
- Between the current and the future case, the estimated H_2 production cost declines due to expected decreases in (1) SOEC system capital costs (primarily at the stack but also the BOP), (2) indirect capital costs and replacement costs, (3) fixed operations and maintenance (O&M) costs, and (4) system energy usage.

SOEC Current Case Sensitivity Analysis



Levelized H_2 cost is most greatly influenced by electricity price and capital cost.

SOEC Future Case Sensitivity Analysis



Levelized H_2 cost is most greatly influenced by electricity price and heat price.

SOEC Cost Drivers

1) Electricity Cost ($/GJ)

a. Like alkaline & PEM electrolysis, SOEC H_2 cost is primarily driven by electr. price.
b. Electricity price based on Annual Energy Outlook (AEO) Reference

2) Electrical Efficiency (kWh/kg H_2)

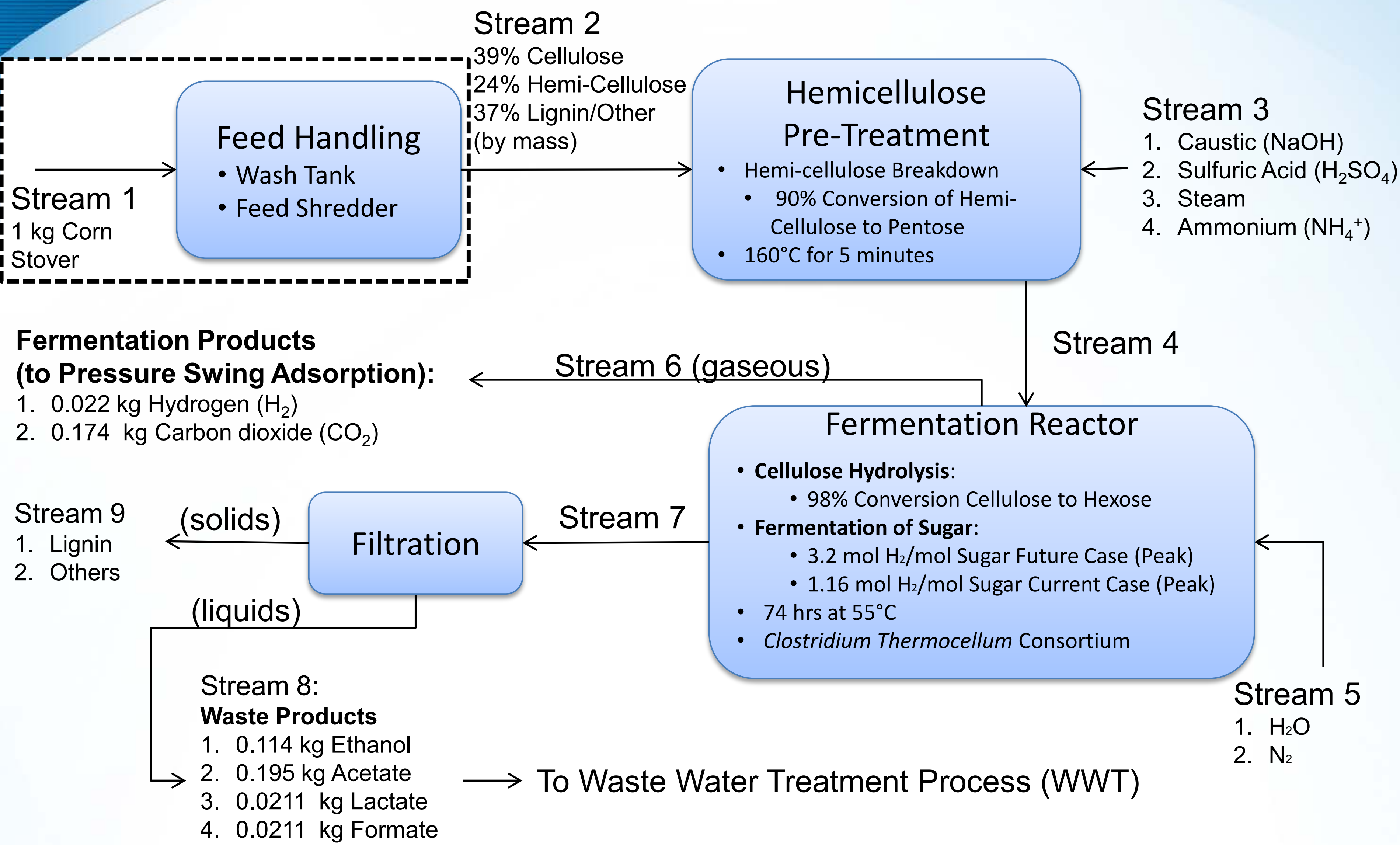
a. Stack efficiency based on operating voltage (which in turn is controlled by ASR)
b. SA selected stack operating points based on Industry input (close to thermal neutral operating point)
c. Not much change between Current and Future cases

3) Capital Cost ($)

a. Values from industry feed back have been reviewed and combined to develop the capital costs
b. Data from industry sources are considered proprietary by SA, and the numbers used in our analysis do not directly match the industry numbers
c. Major cost reductions expected between Current and Future cases

Biofermentation
Cases

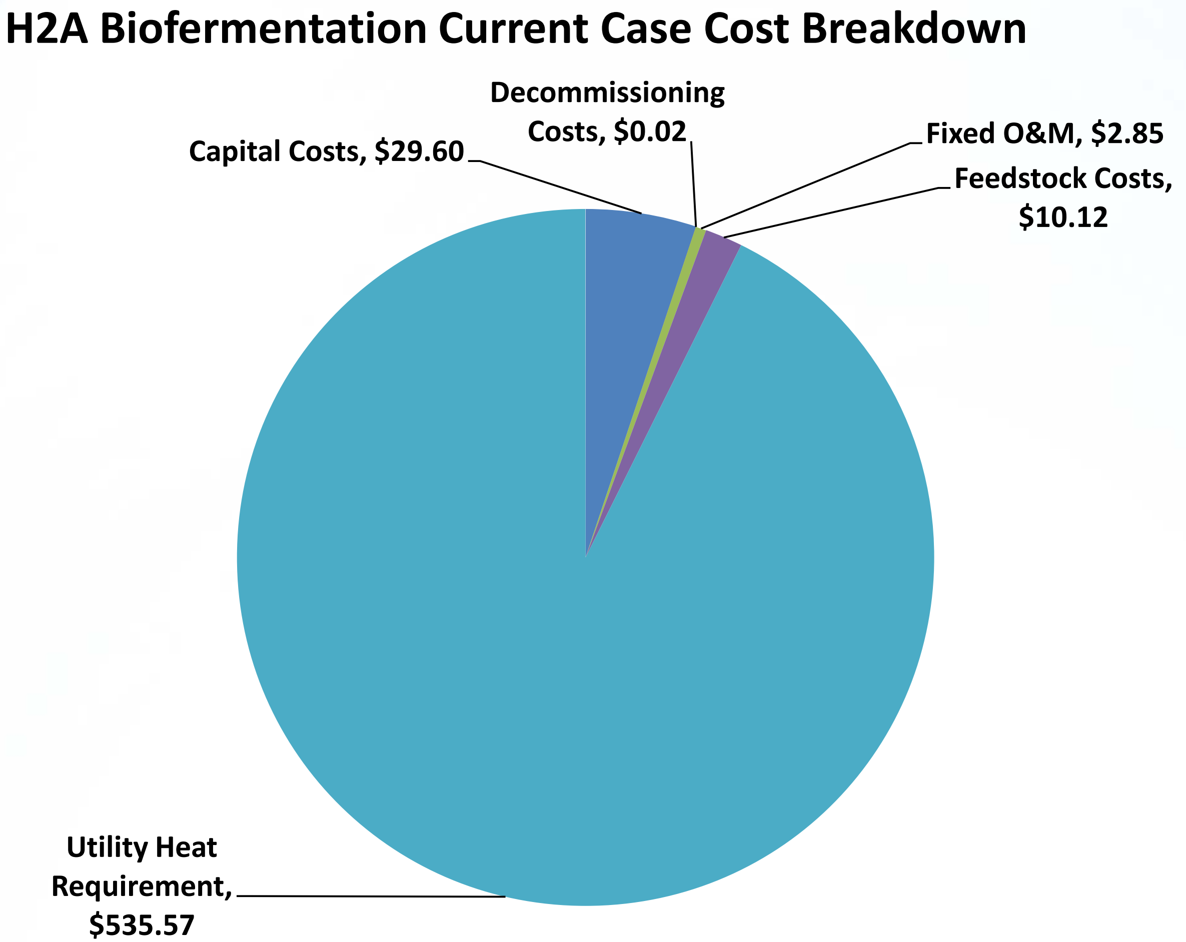
Top-Level Process Flow Diagram



Comparison of Biofermentation Current & Future Cases

		Current Case (5 g/L)	Future Case (300 g/L)
Corn Stover Usage	MT/day	2000	2000
Corn Stover Concentration	g/L	5	300
Hemi-Cellulose to Pentose Conversion	%	90%	90%
Cellulose to Hexose Conversion	%	98%	98%
Mol H_2/ Mol Pentose	mol H_2/ mol Pentose	1.16 (Exp. Data)	3.2 (Peak Yield at 74 hrs)
Mol H_2/ mol Hexose	mol H_2/ mol Hexose	1.16 (Exp. Data)	3.2 (Peak Yield at 74 hrs)
Energy Recovery		Energy Deficient (Heat/Energy req.)	Net Electricity Sales (Lignin/Bio-Gas burned to make electr.)
H_2 Production Rate (After PSA)	kgH_2/day	12,428 At 74 hours	36,749 At 74 hours
Total Installed Capital Cost	$	$1.26B	$274M
$/kg H_2 (prod. only)	**$/kg H_2**	**$577.74**	**$4.62**

H_2A Cost Summary: Biofermentation Current

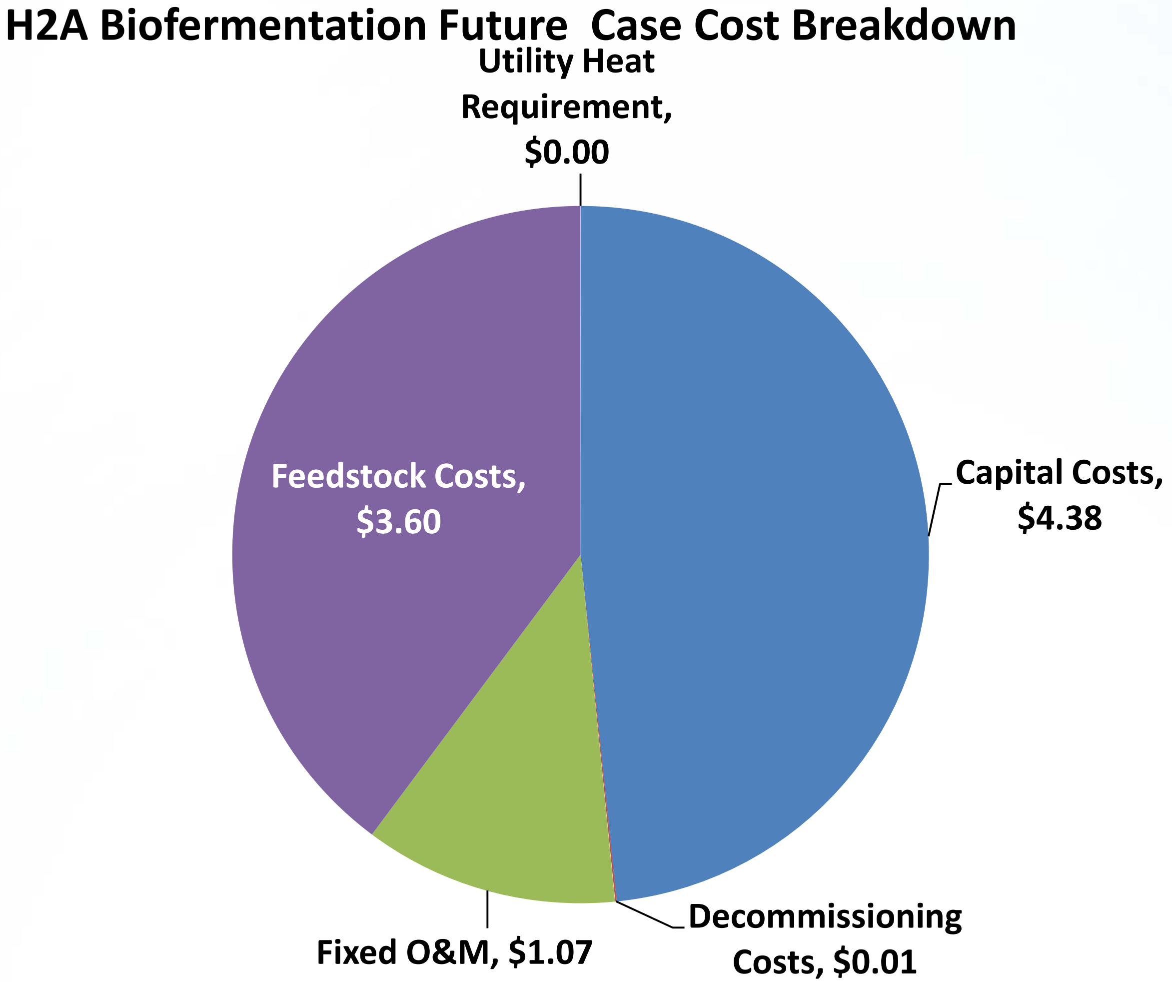


* On a 2007 dollar cost basis, per standard reporting methodology for the H2A v3 tool (reflecting production costs only)

** Byproduct credit not shown in cost breakdown

- Current Case cost is dominated by the heating requirements of the system
    - Dilute fermentation broth (5 g/L) requires excessive amounts of warm broth
- Future Case will use a more concentrated broth (300 g/L)
    - Heat requirement is off set by burning lignin from the system
    - Excess biogas and lignin can be converted to electricity for byproduct**

H_2A Cost Summary: Biofermentation Future



** On a 2007 dollar cost basis, per standard reporting methodology for the H2A v3 tool (reflecting production costs only)*

*** Byproduct credit not shown in cost breakdown*

- Current Case cost is dominated by the heating requirements of the system
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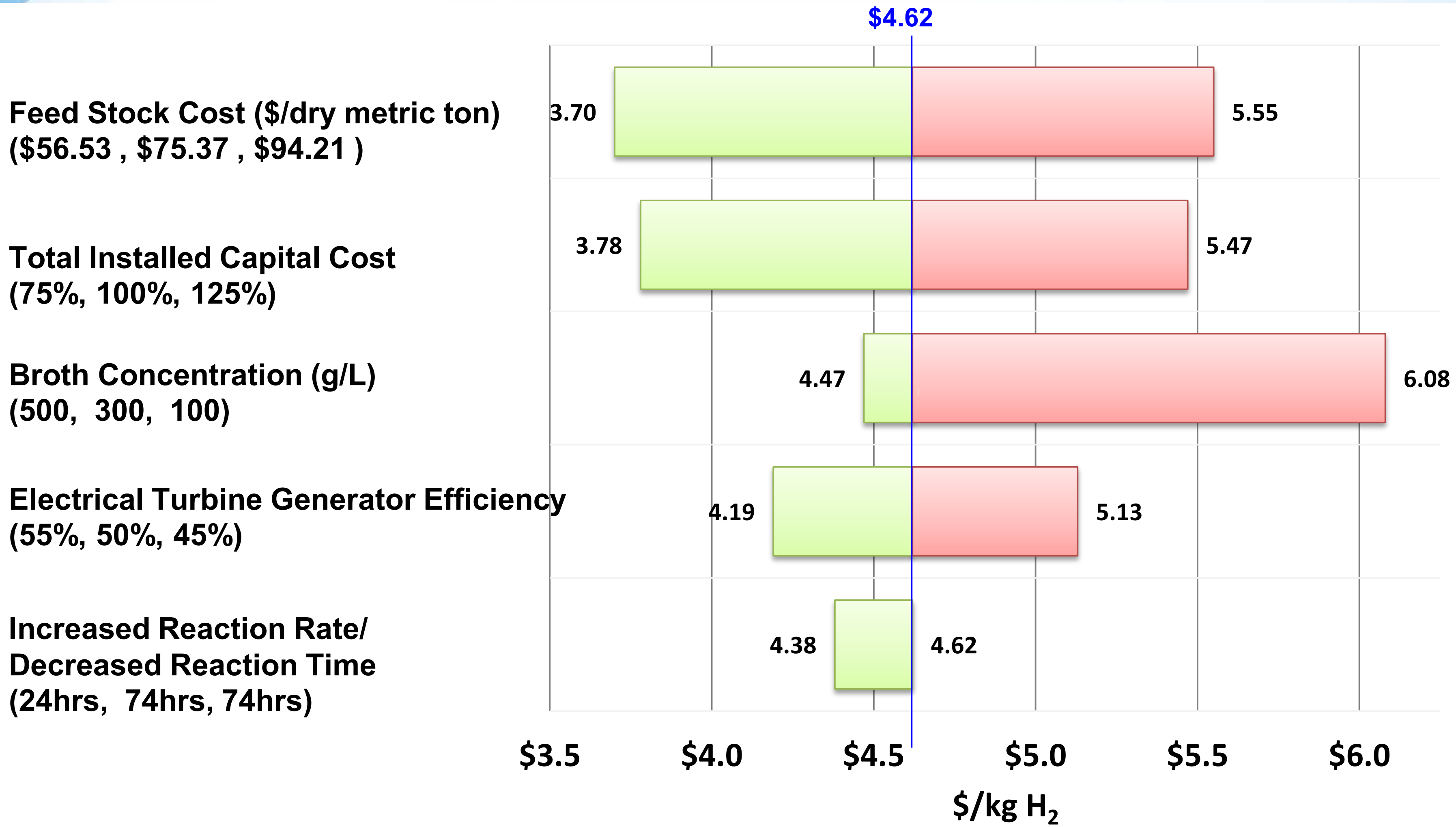
Biofermentation Cost Drivers

1) **Feed Stock Cost ($/kg)**
   a. Based on 2014 BETO MYPP values (~$75/dry metric ton)
   b. All costs taken for Corn Stover at reactor inlet

2) **Fermentation Broth Concentration (g/L)**
   a. Low concentration broth (Current Case) drives cost up due to liquid quantities, heat utilities, and waste water treatment required to produce 50,000 kg H_2/day.
      a. Cost of producing H_2 with a broth concentration of 5 g/L is over $500/kg H_2
   b. High concentration broth (Future Case) lead to a smaller, lower capital system. Also reduces heat demand leading to a system surplus (byproduct) energy.

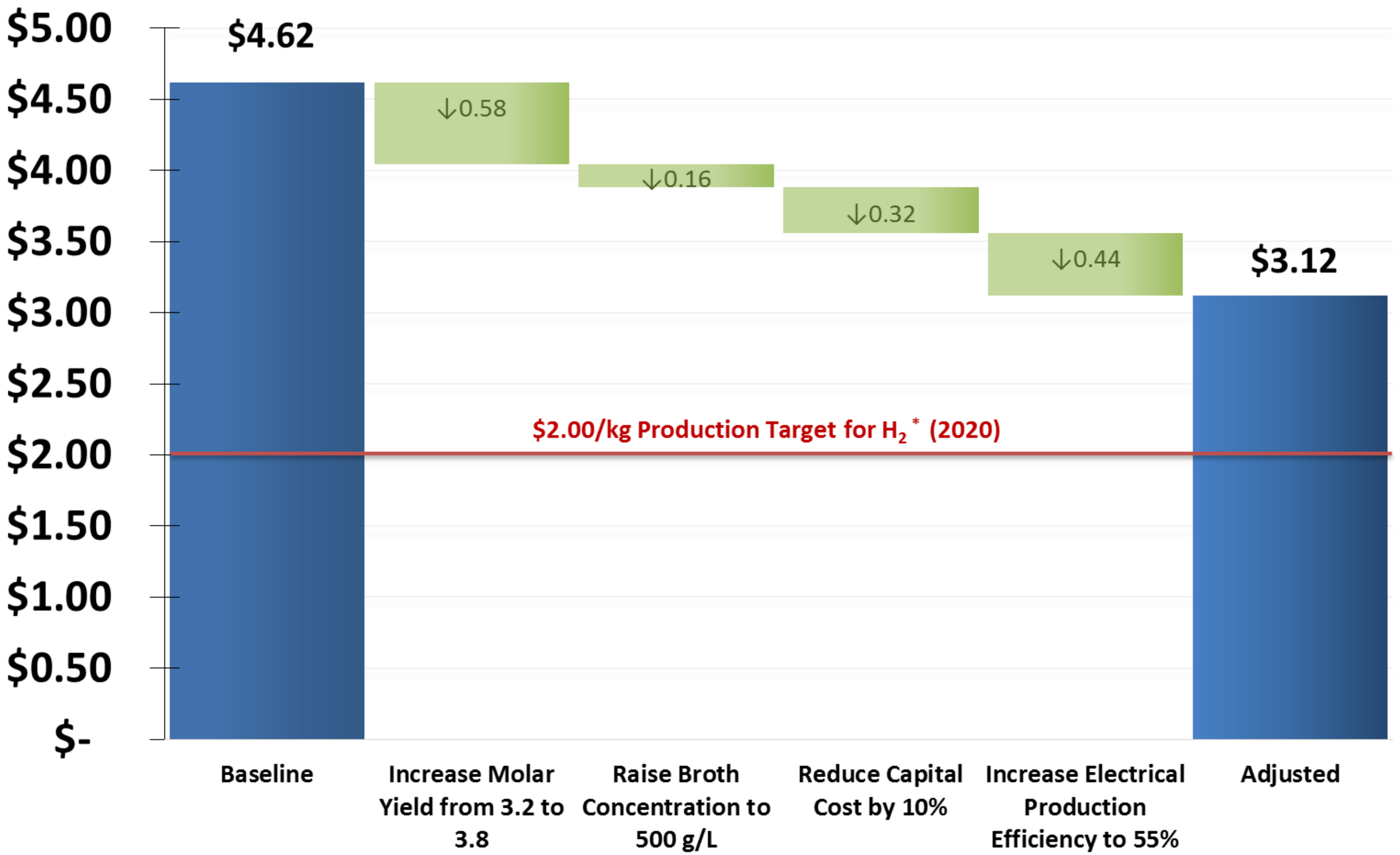
3) **Capital Cost ($)**
   a. Costs based on 2013 NREL Report: Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons
   b. Scaled to account for changes in plant design and size between original report and Current vs. Future Case

Tornado Chart shows results for single variable sensitivity analysis for Biofermentation Future Case



Levelized H_2 cost is most greatly influenced by feedstock price, capital cost, and broth concentration.

Waterfall Chart shows a progression of changes in cost in moving from the Future Case to a reduced H_2 cost



* Value based on MYRDD for target for Biomass Gasification by the year 2020

Response to Previous Year Reviewers' Comments

FY14 Reviewer Comments	FY15 Response to Comment
"Part of the reason for this work was to measure progress against DOE goals; however, this comparison was never presented."	This year's presentation compares results against DOE targets of $2/gge. The purpose of these studies is to provide DOE with information that assists them in status assessment, performance projection, and research direction formulation. The output of this analysis is enhanced understanding and is thus broader than just comparison to the DOE goals.
"I would like to see the variability of the results in the waterfall charts as opposed to just the "most likely" case and draw a horizontal line to reflect the target cost on the chart."	Uncertainty/Variability is addressed in the Tornado Chart. We added a horizontal line on the Waterfall Charts to reflect the $2/kgH2 DOE Target. A fuller description/justification for the Tornados and Waterfalls appears in the backup slides.
"The basis for the predicted [PEM electrolyzer] cost reduction in going from "existing" to "current" systems and from "current" to "future" systems should be described and justified. The exclusion of the "existing" cost case detracts from the overall usefulness of the study."	The exclusion of the existing cases is to maintain confidentiality of the companies' current system costs.

Collaborators

Institution	Relationship	Activities and Contributions
National Renewable Energy Laboratory (NREL) • Genevieve Saur • Todd Ramsden • Pin-Ching Maness	Subcontractor	• Participated in weekly project calls. • Assisted with H2A Production Model runs & sensitivity analyses • Provided laboratory data results for biofermentation • Drafted reporting materials • Reviewed reporting materials
Argonne National Lab (ANL) • Rajesh Ahluwalia • Thanh Hua	Subcontractor	• Participated in select project calls. • Scoping investigation: Evaluated four classes of technologies for producing hydrogen via high-temperature thermochemical water splitting cycles.
Industry Sources	Collaborator	• Participated in technical questionnaire • Provided extensive company-sensitive information • Clarified input data • Vetted H2A Model input data, sensitivity parameters, and results • Reviewed public documentation.

Collaborators

Institution	Relationship	Activities and Contributions
Idaho National Lab (INL) • Jim O'Brien	Collaborator	• Participated in select project calls • Provided Aspen/HYSYS® simulations for SOEC system • Supplied capital cost estimations for SOEC system
Department of Energy (DOE) • Sarah Studer • Eric Miller • Katie Randolph • David Peterson	Sponsor	• Participated in (some) weekly project calls. • Assisted with H2A Model and sensitivity parameters • Reviewed reporting materials

Proposed Future Work

- DOE Records for SOEC and Biofermentation
- Make H2A Cases publicly available (via website)
- New Pathway Cases such as
  - Bio-derived feedstock reforming
  - Solar Thermal Chemical Hydrogen (STCH)
  - Photo-electrochemical Hydrogen (PEC)

Summary Conclusions

- Case studies were completed for SOEC and Biofermentation using H2A pathways V3.1
- Future Cases reflect \$3.7 - \$4.6 per kg of H_2 production
- SOEC
  - SOEC cases are driven by electricity costs
  - Future improvements are primarily realized in lower capital cost
    - Energy usage is projected to only modestly improve
  - Alternate system configurations may yield lower H_2 cost (but our analysis suggests not by much)
  - Sale of byproduct O_2 is an option (but is not consider is this analysis)
- Biofermentation
  - Current systems are uneconomical due to low broth density and low H_2 yield
  - Future systems must operate at high(er) broth density to reduce capital & energy costs
  - An example path to reduced H_2 cost (beyond the Future case) is defined

Presentation Summary

- **Overview**
  - Exploration of selected H_2 production and delivery pathways to find most feasible
  - Transparent, objective, and internally consistent comparison of alternatives
  - In year 2 of 3 year project, added SOEC & Biofermentation Cases to our Analysis
- **Relevance**
  - Identify key "bottlenecks" to the success of these pathways, primary cost drivers, and remaining R&D challenges
  - Assess technical progress, levelized H_2 costs, benefits and limitations
  - Analyses assist DOE in setting research direction & priorities
- **Approach**
  - Input based on interviews of technical experts
  - Create engineering performance models of system operation
  - Projected cost results from use of H2A Production Model Version 3.1
- **Accomplishments**
  - Analysis of PEM electrolysis H_2 Production systems (last year)
  - Analysis of SOEC H_2 Production systems
  - Analysis of Biofermentation H_2 Production systems
- **Collaborations**
  - DOE, INL, ANL and NREL provide cooperative analysis/vetting of assumptions/results

Technology Transfer Activities

- This project was an analysis of different types of hydrogen production systems and technology transfer does not apply to this project.

Technical Backup Slides

The four H2A cases use this input data

	SOEC		Biofermentation	
	Current	Future	Current	Future
Technical Parameters				
Production Equipment Availability Factor (%)	97%	97%	97%	97%
Plant Design Capacity (kg of H_2/day)	50,000	50,000	50,000	50,000
System Energy Cost ($/kW)	$ 743.00	$ 389.00	N/A	N/A
Single Unit Size (kg/day)	500	750	500	750
System H_2 Output Pressure (psi)	450	1000	80	80
System O_2 Output Pressure (psi)	14	14	14	14
Direct Capital Costs				
Basis Year for production system costs	2007	2007	2007	2007
Uninstalled costs ($/kg H_2)	$ 56,959,567	$ 28,489,221	$ 757,603,978	$ 216,606,367
Installed Cost ($/kg H_2)	$ 63,794,715	$ 31,338,144	$ 1,258,448,873	$ 273,699,755
Indirect Capital Costs				
Site Preparation ($)	$ 1,408,213	$ 691,763	$ 2,990,174	$ 2,990,174
Engineering & Design ($ or %)	$ 7,041,067	$ 3,458,813	$ 36,543,488	$ 36,543,488
Contingency ($)	$ 9,153,393	$ 4,496,460	$ 196,401,884	$ 42,737,257
Up-Front Permitting Costs ($ or %)	$ 10,561,600	$ 5,188,219	$ 25,299,338	$ 25,299,338
Replacement Schedule				
Replacement Interval of major components (yrs)	1	1	$ 1	1
Replacement cost of major components (% of insta	0.5%	0.5%	0.5%	0.5%
O&M Costs Fixed				
Licensing, Permits, and Fees ($/year)	0	0	$ 1,000	$ 1,000
Yearly maintenance costs ($/yr)	$ 2,112,320	$ 1,037,644	$ 6,295,577	$ 136,992
O&M Costs - Variable				
Total Plant Staff (total FTE's)	10	10	68	68
Feedstocks and Other Materials				
System Electricity Usage (kWh/kg H_2)	36.8	35.1	0	0
Minimum Process Water Usage (gal/kg H_2)	4.76	3.98	11.15	11.15

H2A calculates the levelized cost of H_2, based on these inputs. Capital cost, heat usage, & electrical usage vary, and are key cost drivers.

Parameter	Current SOEC	Future SOEC	Current Biofermentation	Future Biofermentation
Levelized Cost of H_2 (2007$/kg H_2)	$4.21	$3.68	$578.16	$5.17
Plant Capacity (kg day)	50,000	50,000	50,000	50,000
Total Installed Capital (2007$/kg H_2)	$1.02	$0.52	$29.60	$4.38
Total Electrical Usage (kWh/kg H_2)	36.8	35.1	0	-55
Electricity Price (H2A Start-up year) $2007/kWh	$0.0574	$0.0659	0	$0.0659
Total Heat Usage (kWh/kg H_2)	14.1	11.5	14,372	0
Thermal Energy Price $2007/kWh	$0.0364	$0.0413	$0.0364	0
Total Feed Stock Usage (kg/kg H_2)	0	0	128.69	46.67
Feed Stock Price (H2A Start-up year) $2007/kg	0	0	$0.0870	$0.0565

Project milestones are up to date

Milestone Number	Project Milestone	Progress Notes	Percent Complete
Milestone 1	Delivery of Project Management Plan	Final version submitted to DOE	100%
Milestone 2	Delivery of Validation Case Study (on PEM Electrolysis)	Final versions of Excel models, final report, and slide presentation submitted to DOE	100%
Year 2 Milestone	Completed Year 2 Case Studies	Work nearly finished on biofermentation and solid oxide electrolysis cell (SOEC) studies.	90%
Year 3 Milestone	Completed Year 3 Case Studies		0%