II.I.4 Solar Thermochemical Hydrogen (STCH) Production – H2A Analysis

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Objectives

Support engineering cost analyses of solar thermochemical hydrogen (STCH) production cycles using the H2A central production tool for at least three cycles under development:

- Thoroughly review 2015 and 2025 cost analyses developed in H2A spreadsheets to critically assess assumptions made and cost values used to ensure that meaningful comparisons of the costs of producing hydrogen via different cycles can be made.
  - Allows DOE to make the best decisions in the cycle down-select process.
  - Identify key cost drivers to help guide research efforts to improve STCH economics.
- Work with teams to refine and develop rigorous cost analyses.

Technical Barriers

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

(U) High-Temperature Thermochemical Technology

(W) Concentrated Solar Energy Capital Cost

(X) Coupling Concentrated Solar Energy and Thermochemical Cycles

Technical Targets

This project supports all of the STCH team members' efforts to develop and refine hydrogen production cost analyses using the H2A Central Production spreadsheet, including sensitivity analyses to understand the impact of how uncertainties in key variables affect hydrogen production costs. Insights gained from these analyses will be used, for all cycles evaluated, to:

- Help select the STCH cycles with the greatest potential of reaching the DOE 2017 goal of $3.00/gasoline gallon equivalent, gge (or less) at the plant gate.
- Evaluate which STCH cycles have the potential to be competitive in the long-term (e.g., circa 2025).
- Identify key technological barriers to be overcome and opportunities for reducing the production cost to attain DOE cost targets.

Table 1 summarizes the most recent projections for the hydrogen production costs of several cycles (at the plant gate) relative to the DOE cost target of $3.00/gge:

TABLE 1. Current Hydrogen Production Cost Estimates (based on H2A Central Production Tool)

Cycle	2015 Cost*	2025 Cost*	Comments/Key Issues
Cd/CdO	Under revision	Not available	Cycle undergoing major revisions
CuCl	**$4.30** ($3.98 - $5.07)	**$2.82** ($2.65 - $3.35	Electrolyzer cost highly uncertain
Ferrite	**$5.52** (No sensitivity)	Not available	Very preliminary design and cost analysis
Hybrid Sulfur	**$4.37** ($3.86 - $4.89)	**$2.91** ($2.46 - $3.21)	Solar electric cost important
Zn/ZnO	**$5.07** ($4.58 - $6.53)	**$3.62** ($3.12 - $4.87)	Solar field + receiver cost and performance

*Sensitivity range shown in parentheses

Accomplishments

- Reviewed and provided detailed feedback to STCH teams on 11 different H2As, including identifying key issues to resolve and major uncertainties to address for each.

- Identified several "lessons learned" that were used to improve all of the H2As.
- Modified several assumptions used in the H2As used by all of the STCH teams.

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Introduction

The U.S. has vast solar resources. Indeed, a small fraction of the land in favorable locations (most notably the Southwest) could produce enough energy to meet the entire nation's annual energy demand for *all* end uses with negligible greenhouse gas emissions. At present, solar hydrogen production using electrolysis powered by solar thermal electricity is costly and not cost-competitive with conventional sources. STCH cycles, which use concentrated solar thermal energy to power chemical cycles that liberate hydrogen from water, have the potential to achieve significantly higher annual solar-to-hydrogen conversion efficiencies than solar thermal electrolysis. Because the solar collection field typically accounts for the greatest portion of the total capital cost, STCH cycles also have the potential to achieve lower hydrogen production costs than solar thermal-powered electrolysis. At present, however, STCH cycles are, in a technical sense, quite immature and, to varying degrees, have significant uncertainties related to feasibility and economic viability. Nonetheless, DOE wants to understand whether various STCH cycles have the potential to achieve economic viability even if research efforts succeed. Consequently, the teams analyzing the STCH cycles are developing H2A cost analyses for each cycle for circa 2015 and 2025.

This project critically reviews and analyzes H2A cost analyses carried out by STCH teams to enable DOE to effectively compare the hydrogen cost structures for different STCH cycles. This ensures that the analyses embody common assumptions (e.g., consistent with those used in prior H2A analyses, where appropriate) and use reasonable cost and performance assumptions for other key cycle components and variables. Ultimately, this will help to generate meaningful hydrogen production cost values. When carried out in tandem with technology development, the H2A cost modeling also helps the teams to identify key cost drivers. This, in turn, can enable the teams to understand the relative economic impact of different design choices and parameters so they can consider this information to help guide their research efforts, e.g., to decide what development pathways to pursue.

Approach

This project supports the development of H2A production spreadsheets for the STCH cycles under development by DOE. For each cycle analysis, the support effort takes the following form:

1. Receive an initial H2A spreadsheet analysis and background materials/literature from relevant team member(s) for the cycle.
2. Perform an initial, thorough review of H2A spreadsheet to critically assess the assumptions made and cost values used in the H2A analysis.
3. Discuss with the team member(s) the findings of the review, focusing on assumptions and cost values that require further explanation, appear questionable, and that deviate appreciably from typical H2A values.
4. Provide the relevant team member(s) with a punch list of issues to address/resolve and recommendations.
5. STCH Team revises the H2A analysis.
6. Review the revised H2A analysis and develop an updated list of issues to address/resolve, discuss it with the relevant team members(s) .
7. Iterate on steps 5 and 6 as necessary.

In addition, this support project also:

- Helps teams to evaluate cycle-specific issues in detail (e.g., electrolyzer costs).
- Identifies "lessons learned" and modifications to assumptions used in the H2As and disseminates them to all the teams to improve all H2As.
- Evaluates the cross-cutting issues identified by the STCH Team, Project Manager, and DOE Technology Development Manager.
- Presents the findings of the cycle analyses at the STCH Team Meetings.

Results

The project team, comprised of mechanical and chemical engineers, reviewed and provided feedback on 11 different H2A spreadsheets from several STCH teams. Figure 1 summarizes the status of the cost analyses for different STCH cycles. These reviews identified the key issues summarized in Figure 2.

The project also carried out cycle-specific analyses to help address specific issues/uncertainties with those cycles:

- Hybrid Sulfur – Compared Deutsches Zentrum für Luft- und Raumfahrt and Sandia National Laboratories (SNL) HyS analyses and evaluated differences between the analyses; reviewed electrolyzer cost assessment for the 2025 case; evaluated the likely cost impact of replacing catalysts in the sulfuric acid decomposition reactor, including preliminary modeling of expected catalysts, catalyst loadings, and catalyst replacement schedules.

	Lead	FY2008 Progress	
		2015 H2A	2025 H2A
Ammonium Sulfate	FSEC / SAIC	No H2A received	No H2A received
Cd / CdO	GA	First two iterations completed	No H2A received
CuCl	ANL	First two iterations completed	First iteration completed
Ferrite	SNL	Initial iteration completed	No H2A received
Hybrid Sulfur	SNL	One more iteration completed DLR H2A reviewed	One more iteration completed
Manganese	U. Col.	No H2A received	No H2A received
S-I	TBD	No H2A received	Preliminary H2A completed by TIAX
Zn / ZnO	U. Col.	One more iteration completed	One more iteration completed

FIGURE 1. H2A Spreadsheets Reviewed This Year

	Key Issues
Cd / CdO	Solar field design and performance, integration of solar energy with thermochemical cycle, Cd handling
CuCl	Electrolyzer design and cost highly uncertain, sensitivity cases
Ferrite	Preliminary design: system performance/efficiency and reliability
Hybrid Sulfur	Electrolyzer capital and replacement costs, integration of cycle with solar thermal heat source (vs. nuclear), backup plan if particle receiver does not work
Zn / ZnO	Solar field design and performance at very high concentration ratios used (>5,000 suns), receiver and reactor costs

FIGURE 2. Key Issues Identified for STCH Cycles Analyzed

- Ferrite Cycle – Developed initial H2A based on preliminary cost estimates from SNL.
- CuCl – Completed a preliminary bottom-up cost estimate of electrolyzer for circa 2015 design, sent to Argonne National Laboratory for review.

The reviews of the H2As yielded several "lessons learned" that were used to improve all of the H2As. Lessons learned include:

- Provide a detailed and itemized breakdown of solar field annual efficiency calculations to ensure that all losses have been accounted for: The combined efficiency of solar field, receiver, and thermochemical plant determines total heliostat area, and heliostats usually dominate capital cost, so an accurate accounting of losses is crucial for developing credible hydrogen production cost estimates.
- Use solar costing for solar components [1] and costs typical of chemical industry for thermochemical plant.
- Carefully consider and account for planned replacement costs: Initially, some analyses did not fully account for these costs, which can be substantial (e.g., for electrolyzers, catalysts).
- Carefully review capital costs used to make sure that they include all of the line items in the H2A spreadsheet (e.g., installation, site preparation, engineering and design, contingency, permitting costs, balance-of-plant, etc.).

The project also evaluated two key issues impacting all of the H2As:

- Cost of Thermal vs. Electric Energy Inputs – The current analysis framework is somewhat biased toward cycles consuming appreciable electricity because H2A uses a higher chemical industry return on investment (ROI) hurdle for solar thermal inputs but uses lower ROI electric utility economics for purchased electricity. As a result, the cost of electricity (COE) is approximately 40% greater if H2A economics are used instead of utility economics. Based on this, all teams were directed to use H2A-based COE as sensitivity case for all analyses.

- Potential Requirement for Level Production throughout the Year – Other large central hydrogen production facilities base cases use constant hydrogen production throughout the year. In contrast, STCH cycles' production will vary significantly with monthly variations in insolation (e.g., ~50% more direct normal insolation in high-insolation regions in June than in December). Consequently, a requirement for level production throughout the year would require extensive storage that could significantly increase the hydrogen price. Based on monthly variations in vehicle fuel demand that broadly track variations in fuel demand, the DOE Technology Development Manager and Team decided to not require level hydrogen production throughout the year.

The project also modified several assumptions for the STCH H2As.

- Revised heliostat capital costs based on 2007 SNL Heliostat Cost Reduction Study findings [2].
- Electric Power: Cycles using significant quantities of solar thermal energy should also obtain large quantities of electricity from solar thermal electric sources.
- Use central solar thermal electricity prices [1] instead of H2A industrial electricity prices.
- Recommended revisions to equipment installation factors in the thermochemical plant based on review of values used in literature and completed H2A central production cases.
- Revised guidance for thermochemical plant labor force and labor rates based on insights provided by the CuCl team.
- Eliminated production credit for oxygen (negligible value for oxygen in very favorable solar thermal locations).

Conclusions and Future Directions

The project has helped advance hydrogen production cost analyses for several STCH teams to realize the goal of ensuring high-quality and consistent production cost analyses. Ultimately, meaningful and consistent production cost analyses will enable effective cycle design choices and DOE programmatic decisions, i.e., cycle down select. Important conclusions from this year's effort include:

- Current analyses suggest that multiple cycles might have a chance of meeting the DOE production cost target circa 2025.
- The project reviewed and provided feedback on 11 H2As.
- The project evaluated and resolved a range of common issues that impact all of the analyses, and also contributed to the analysis of several cycle-specific issues.

In Fiscal Year 2008, the project will continue to work with the STCH teams to develop, refine, and complete H2As for the 2015 and 2025 cases for all cycles to provide the best information for cycle down-select (scheduled for the Fall of 2008). A particular focus of the 2008 effort will be to tighten up key assumptions in analysis, namely thermochemical cycle efficiency, solar field efficiency, major thermochemical plant capital costs, and to refine the sensitivity cases for factors that have a major impact on hydrogen production cost and also significant uncertainty.

FY 2008 Publications/Presentations

1. "H2A Status and Discussion," STCH Team Meeting, 12 March 2008.
2. "H2A Status and Discussion," STCH Team Meeting, 15 November 2007.
3. "Hybrid Sulfur Cycle: Comparison of DLR and SNL Analyses," STCH Team Meeting, 15 November 2007.
4. "STCH H2A Costing Analyses," STCH Team Meeting, 2 May 2007.

References

1. Sargent and Lundy, Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts, SL-5641, May 2003.
2. Kolb, G.J. et. al., Heliostat Cost Reduction Study, SAND2007-3293, Sandia National Laboratories, June 2007.