HydroGEN: Benchmarking Advanced Water Splitting Technologies: Best Practices in Materials Characterization

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- Pacific Northwest National Laboratory, Richland, WA
- Arizona State University, Tempe, AZ
- H2 Technology Consulting, Alamo, CA

Project Start Date: September 1, 2017
Project End Date: February 28, 2021

Overall Objectives

- Develop a framework of protocols/standards for testing performance of materials, components, devices, and systems.
- Facilitate acceptance of community-wide technology.
- Establish an annual project meeting to share learnings and develop recommendations within and across technology areas.
- Assess capabilities and identify gaps for development of advanced water splitting technologies.
- Promote acceptance of protocols and methodologies including cost and performance assessments and database comparisons.
- Assemble roadmaps to further development of each technology pathway.

Fiscal Year (FY) 2019 Objectives

- Compile and publish Year 1 workshop results and outcome report.
- Publish draft bench-scale protocols, definitions and notations agreed on, and metrics recommended.
- Complete draft roadmap framework for each technology area.
- Complete assessment of relevant operational conditions for field use.

Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan[1]:

- C. Inconsistent Data, Assumptions, and Guidelines
- D. Insufficient Suite of Models and Tools.

Technical Targets

This project is focused on developing standards and test protocols that result in technologies to produce hydrogen consistent with the following DOE technical targets:

- Support DOE Hydrogen and Fuel Cells Program goals to sustainably produce hydrogen for <$2/kg.

FY 2019 Accomplishments

- Held the Year 1 Fall Workshop at Arizona State University on October 24–25, 2018.
- Compiled and distributed summaries of workshop breakout sessions.
- Assigned action items were assigned and created a list of test protocols to be written.

[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

- Developed and peer-reviewed test frameworks for each water splitting technology.
- Developed draft technology roadmaps for each water splitting technology.
- Developed metrics for tracking the progress of each technology.
- Conducted the Budget Period 1 Go/No Go review and decided to proceed with Budget Period 2.
- Received and integrated feedback from the HydroGEN Energy Materials Network (EMN) Consortium and international experts on draft test protocols for each water splitting technology into revised versions.
- Sent out quarterly newsletters were to the advanced water splitting technologies community.

INTRODUCTION

The high-level project goal is to create a comprehensive best-practices benchmarking framework at the materials, component, device, and systems levels for advanced water splitting technologies. All advanced water splitting pathways covered under the EMN, which include advanced high- and low-temperature electrolysis of water, photoelectrochemical (PEC) water splitting and solar thermochemical hydrogen (STCH), need these best practices to advance materials discovery. These practices will also aid the H2@Scale DOE initiative to accomplish their goals of large-scale hydrogen production.

The overall objective for this effort is to guide the development of a water splitting roadmap across the different technologies, based on the varying maturity levels and challenges of each approach, to assist DOE in maintaining a balanced R&D portfolio. To support this objective, the team is working with the EMN and water splitting community to assess and document current best practices and material standards, assess existing capabilities and needs, and recommend the next steps and priorities.

APPROACH

The overall project is divided into two major phases Budget Period (BP) 1 and BP 2, across 3 years. In BP 1, the team focused on the development of the database framework and proposed bench-scale protocols to be introduced within the community. BP 2 will pursue validation/revision of the proposed protocol through user experience and development of a vision for the “subscale” category. Strategies for stakeholder engagement throughout the project will include annual cross-technology workshops as described below, as well as the organization of conference symposia for specific technology areas for more focused, in-depth discussions and monthly virtual meetings per approach to gather stakeholder input and feedback.

RESULTS

Year 1 Workshop Outputs:

The benchmarking team held a workshop for the advanced water splitting technologies within the EMN on October 24–25, 2018, at Arizona State University in Tempe, AZ. Several breakout sessions were held for each technology area, to gather information for developing material protocols and identifying critical parameters. Report summaries were compiled (see Figure 1) and sent to the participants for each technology, as well as a cross-cutting summary. The action items were reviewed by the benchmarking team and incorporated into a prioritized list of protocols that were drafted before the end of Budget Period 1.

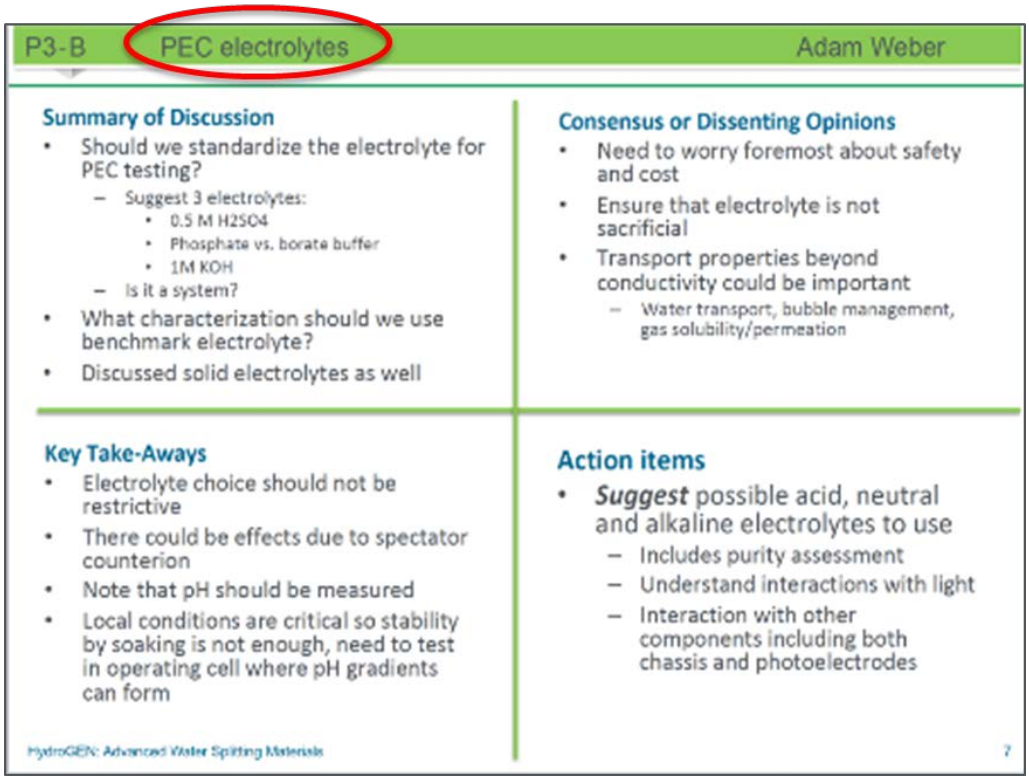

Figure 1. Example quad chart summary output from 2018 workshop breakouts

Test Protocols:

Test protocols were written and reviewed for each of the technologies based on those prioritized during the fall workshop. Each technology also included a protocol for establishing common definitions and notations. Feedback was collected from within the EMN and international communities on the following test protocols. Revisions were made to the protocols and then released as "Rev 2" for distribution to the broader water splitting community. The protocols listed in Table 1 represent completed protocols that have been reviewed and released to the EMN water splitting community.

Table 1. Written protocols to be reviewed at 2019 workshop

Number	Protocol	Component
LTE-P-1	Compressibility	Gas Diffusion Electrode
LTE-P-3	Ion Exchange Capacity	PEM
LTE-P-5	Thermal Stability	PEM
LTE-P-6	Conductivity	AEM
LTE-P-7	Ion Exchange Capacity	AEM
LTE-P-8	Gas Permeability	AEM/PEM
LTE-P-9	Chemical Stability	AEM
LTE-P-10	Rotating Disk Electrode	PGM
LTE-P-14	Electronic conductivity	Non-PGM
LTE-P-19	LTE Definitions and Notations	General
LTE-P-20	Water Uptake Measurement	PEM/AEM
HTE-P-01	Measurement of Bulk Conductivity	Electrolyte/Electrode
HTE-P-02	Ion Conductivity/Transference Numbers	Electrolyte
HTE-P-03	Mixed Ion Conductivity	Electrolyte
HTE-P-04	Density Measurement	Electrolyte
HTE-P-05	Linear Thermal Expansion	Electrolyte
HTE-P-07	Leak Test	Cell/Stack
HTE-P-00	Cell Performance Steady-State	Cell

HTE-P-10	Polarization Resistance	Electrode
HTE-P-12	HTE Definitions and Notations	General
HTE-P-13	Metal-Supported Cell Test	Cell
HTE-P-14	Bonding Strength	Contact Layer
PEC-P-1	Photoelectrodes Preparation	Device
PEC-P-2	Illumination Calibrations	Device
PEC-P-3	Tandem Light Absorber Incident Photon Conversion Efficiency Measurements	Component (photoelectrode)
PEC-P-5	Measurements of Product Crossover	Component (transport)
PEC-P-7	Band Energetics Measurement	Materials (protective layer)
PEC-P-8	Conductivity Measurements for Cation Exchange Membranes in Electrolyte	Materials (membrane electrolyte)
PEC-P-9	Outdoor, On-Sun Measurements	Device
PEC-P-10	PEC Device Fabrication/Integration and Scale Up	Device
PEC-P-11	Comparison Metrics and Terms for PEC Water Splitting	General
STCH-P-1	Metrics, Units, Definitions	General
STCH-P-2	Ceria Standard and Material Specs	Materials
STCH-P-4	Detailed Thermodynamic Screen	Materials
STCH-P-8	Detailed Kinetic Screen	Materials
STCH-P-10	Durability Level 1 Screen	Materials

AEM–anion exchange membrane, HTE–high-temperature electrolysis, LTE–low-temperature electrolysis, PEM–proton exchange membrane, PGM–platinum group metal.

Work was started on drafting the next group of test protocols. Lead writers were assigned, and progress has been made in developing the "Rev 1" drafts. All released protocols can be viewed at the following location: *https://openpoint.nrel.gov/sites/Hydrogen-AWSM/Nov17Mtg/Benchmarking/Shared%20Documents/*

Technology Roadmaps:

Technology development roadmaps were established for each of the water splitting technologies to chart a path toward reaching $2/kg hydrogen. Gaps in testing capabilities were identified, and development tasks were prioritized to focus efforts going forward. These roadmaps will be reviewed with the broader water splitting community and will be used to drive new development projects and track progress against DOE targets.

Relevant Operational Conditions:

Relevant operational conditions are being assessed for each of the water splitting technologies. These conditions will be used as a basis for the development of testing for high-level system integrations.

CONCLUSIONS AND UPCOMING ACTIVITIES

Upcoming activity will focus on holding the Year 2 workshop and developing action items and next steps as a result of discussions at the workshop to continue the development of test protocols. Test protocols will be validated and will include accelerated testing and the definition of degradation mechanisms. Gap assessment on capabilities within the EMN and R&D community for field simulations and long-term reliability testing will be completed. Field test sites and requirements for subscale testing within EMN and expert sites will be established/recommended.

FY 2019 PUBLICATIONS/PRESENTATIONS

1. K.E. Ayers, C.Capuano, P. Mani, "High Efficiency PEM Electrolysis: Potential for H2@Scale," 234th ECS, Cancun, Mexico, October 2, 2018.
2. K.E. Ayers, C. Xiang, E. Stechel, O.A. Marina, "Framework and Test Protocols for Water Splitting (LTE, PEC, HTE, STCH)," 2019 MRS Spring Meeting and Exhibit, Phoenix, AZ, April 23, 2019.
3. Benchmarking Advanced Water Splitting Technologies: Best Practices in Materials Characterization, K. E. Ayers, U.S. Department of Energy's (DOE's) Hydrogen and Fuel Cells Program 2019 Annual Merit Review and Peer Evaluation Meeting (AMR), Washington, DC, April 30, 2019.

4. K.E. Ayers, C. Capuano, A. Motz, P. Mani, "Development of Standards and Best Practices for Materials Testing in Low-Temperature Electrolysis," 235th ECS, Dallas, TX, May 27, 2018.
5. K.E. Ayers, O.A. Marina, "Benchmarking Advanced Water Splitting Technologies," 2019 International Conference on Electrolysis, Loen, Norway, June 11, 2019.
6. K.E. Ayers, K. Gross, "HydroGEN Benchmarking: Developing Best Practices for Water Splitting Technologies," 236th ECS, Atlanta, GA, October 17, 2019.