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DOE Hydrogen Program
2024 Annual Merit Review and Peer Evaluation Meeting

Benchmarking, Protocol Development and Community Engagement of Advanced Water Splitting Technologies

Olga A. Marina[1], Kathy Ayers[2], Ellen B. Stechel[3], CX Xiang[4], Karl Gross[5]

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AMR Project ID # P170

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Project Goal

Development of extensive benchmarking practices that do not exist or need significant improvement

Advanced Water Splitting Technologies (AWST) of Hydrogen production:

Low Temperature Electrolysis (LTE) – Kathy Ayers

High Temperature Electrolysis (HTE) – Olga Marina

Photoelectrochemical (PEC) – CX Xiang

Solar Thermochemical (STCH) – Ellen Stechel

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Overview

Timeline and Budget

- Project Start Date: 10/20/2021
- FY24 DOE Funding: $1M
- FY24 DOE Planned Funding: $1M
- Total DOE Funds Received to Date**: $2M

** Since the project started

Barriers and Targets

- Hydrogen generation by different technologies
- Improve energy resiliency and sustainability
- Establish a universal system for Benchmarking
- Provide access to Benchmarking results to community

Project Partners

- Pacific Northwest National Laboratory
- Nel Hydrogen
- Arizona State University
- California Institute of Technology
- H2 Technology Consulting LLC

Relevance and Impact

Renewable hydrogen generation via AWST is a critical part of the US strategy to reduce reliance on fossil fuels and improve energy resiliency and sustainability.

To produce significant advances in AWST, limited RD&D resources must be used in the most effective way. Accurately quantifying progress against the target goals requires consistent measurement methods and benchmarking standards. Without this, RD&D efforts can easily become mired in dead-end pathways and/or wasted or duplicative efforts.

For this reason, the establishment of a universal system for benchmarking is critical for the DOE hydrogen program and AWST progress in general.

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Benchmarking Team Mission

- **Strategic coordination of Benchmarking in the water splitting community**
  - Annual meetings with both plenary and technology-specific breakout sessions, and report outs for cross-technology communications
  - Structured dialogue on best practices and priorities for the field
  - Promote community participation in creating Benchmarking Protocols
  - Connection to the broader international community to leverage synergies and avoid contradicting protocols
- **Advancement of Protocols**
  - Prioritization for development and verification of Protocols
  - Universal accessibility through open source publication
  - Launching of key Protocol Validation Centers
- **Critical review and direction-setting**
  - Advisement of DOE consortia and academic teams funded by DOE on AWST needs and directions
  - Expert evaluation of techno-economic analyses

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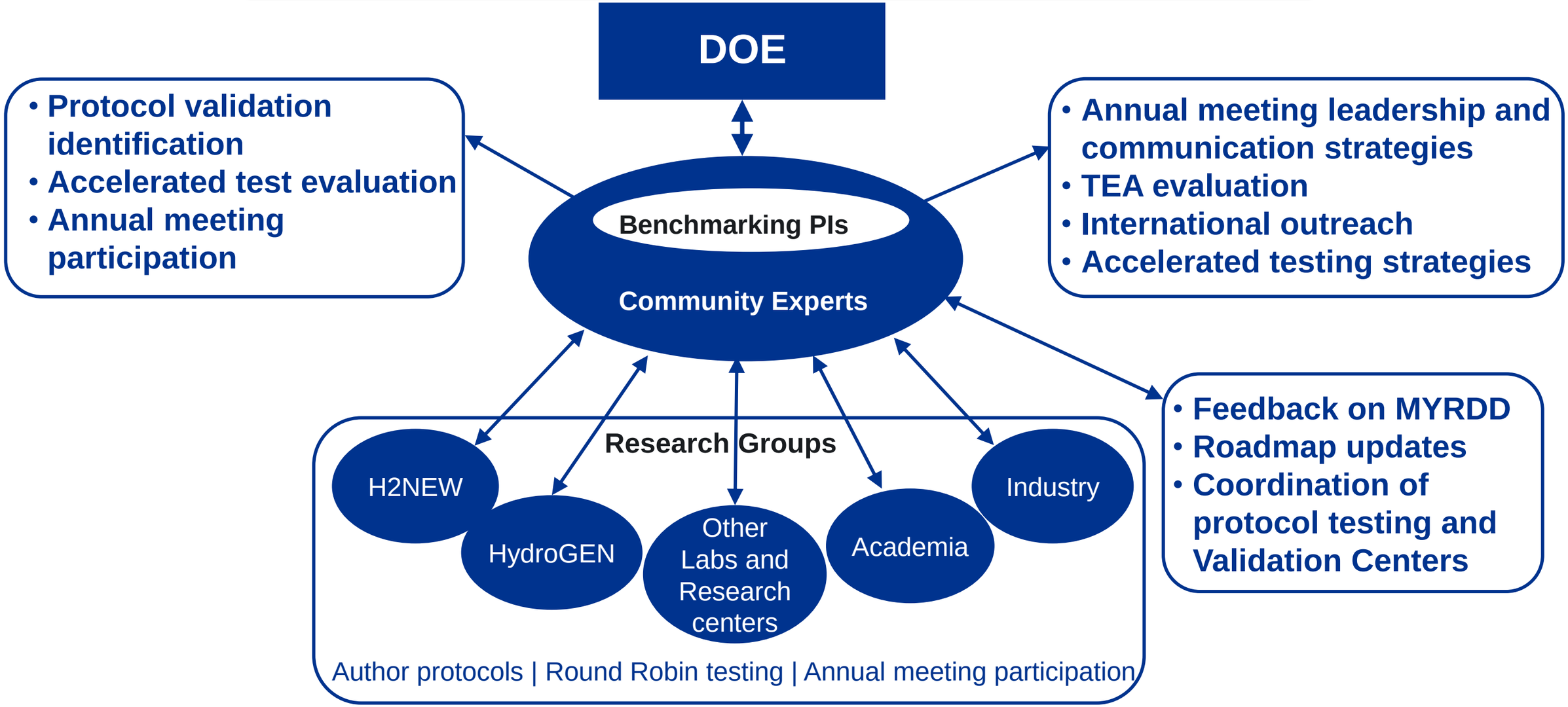
Approach: Organizational Structure



Approach: Deliverables

The urgent and growing demand for large scale, sustainable hydrogen production requires advancements in Benchmarking Practices to accelerate the RD&D development cycle. This project has and will continue to address this need through:

- Extensive portfolio of ***Measurement Protocols*** for Advanced Water Splitting Materials testing
- ***Validation*** and improvement of these protocols by experts in the AWST fields
- ***Publish*** the protocols in an open source environment available to the entire AWST community.
- Overseeing a selective community ***Round Robin*** testing verification program
- Development of accepted testing materials and system ***Standards*** with universally accessible data sets
- Organization of ***Annual Meetings*** to engage the community and create dialogue within and between the technology areas, and for better leveraging of technical advancements
- Work on ***Advanced Protocols*** development and protocol verification and validation
- Work with H2NEW Consortia to assist in ***Accelerated Aging Protocols*** development
- Update AWST ***Roadmaps*** to identify current priorities and missing protocols
- Update recommendations on ***Priority Research Opportunities*** based on near and long term needs

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Approach: Safety Planning and Culture

- Project was not required to submit a safety plan to HSP
- Project follows strict PNNL/Nel/Caltech/ASU safety requirements
  - Approved SOPs must be created, approved, and followed
  - Activities must be created, approved, and followed for any work in the lab
  - Safety training must be completed to gain active access to the lab space
  - Safety training needs to be retaken following specific class requirements

Approach: Tasks & Milestones Timeline

FY2024 Milestones	Date	Goal	Progress
Benchmarking/Protocols Volume II publication for world-wide utilization	Q1	Finalize the agreement with the journal Frontiers in Energy Research for a 2nd Benchmarking volume	100%
Next Generation Protocol Publication	Q2	Identify articles to be published in Frontiers in Energy Research	85%
Protocol Validation	Q3	Develop detailed protocol validation plan	50%
Hold 6th Annual Workshop	Q4	Complete 6th Annual Benchmarking Meeting with progress summary	30%
Submit Annual Report	Q4	Complete Annual Report summarizing project progress	0%

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Accomplishments and Progress Summary:
Project Tasks Completed / Currently in Progress

Completed

- **59** AWST Protocols completed
- **20** Protocols published in Volume 1 of publicly accessible on-line Journal Frontiers in Energy Research
- Next level protocols to be written has been decided
- Protocol validation prioritization completed, and validation started
- AWST 2023 Benchmarking Meeting held in September with 100+ US and International active participants
- Accomplishments/agreements of Benchmarking Meeting compiled and distributed to participants

In Progress

- Protocols being uploaded to DOE DataHub
- Publication of Volume 2 of Protocols in Frontiers in Energy Research Started
- Development of next level protocols underway
- Protocol validation prioritization completed, and validation started
- Re-evaluation of alignment of Lab nodes current capabilities to support program needs has started
- 2024 AWST Benchmarking Meeting in planning stage

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Accomplishments and Progress:
Protocols Development Details

Measurement Protocols

- Provide Standardized Test Methods and Benchmarks
- Allow for direct comparisons of materials and AWST

Completed:

- Completed revisions to first set of draft protocols with feedback from EMN and International experts
- Published first-priority protocols in open journals and on the NREL Sharepoint AWSM website
- Presented results at scientific conferences
- Created prioritized plans for protocol validation testing
- Initiated next level of protocols planning for materials, scaled-up components and accelerated tests

Test Protocol Table of Contents

1.Procedures
- a. Scope and Applicability
- b. Summary of Method
- c. Definitions
- d. Health & Safety Warning
- e. Cautions
- f. Interferences
- g. Personnel Qualifications / Responsibilities
- h. Equipment and Supplies
- i. Step by Step Procedure
  - Instrument or Method Calibration and Standardization
  - Sample Collection
  - Sample Handling and Preservation
  - Sample Preparation and Analysis
  - Troubleshooting
  - Data Acquisition, Calculations & Data Reduction Requirements
  - Computer Hardware & Software
- j. Data and Records Management

2.Quality Control and Quality Assurance Section
3.General Notes
4.Reference Section

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Accomplishments and Progress:
Completed **59** Test Protocols Across AWST

DOE Datahub (LTE at this time): https://datahub.h2awsm.org/dataset/lte-benchmarking-protocols

LTE	HTE	PEC	STCH
LTE-P-1 GDL Compressibility	HTE-P-O1 Conductivity Measurement	PEC-P-1 Photoelectrode Fabrication and Area	STCH-P-1 Metrics
LTE-P-3 IEC PEM SOPx	HTE-P-02 Ion Conductivity/Transference Numbers	PEC-P-2 Light Sources Calibration	STCH-P-2 Standards
LTE-P-5 PEM Thermal Stability	HTE-P-04 Density Measurements	PEC-P-3 Tandem IPCE	STCH-P-4 Detailed Thermo
LTE-P-6 AEM Conductivity	HTE-P-05 Linear Thermal Expansion	PEC-P-5 Product Crossover	STCH-P-8 Detailed Kinetics
LTE-P-7 IEC AEM SOP	HTE-P-07 Leak Test	PEC-P-7 Band Energetics	STCH-P-10 Durability First Screen
LTE-P-8 AEM Gas permeability	HTE-P-09 Button Cell Test	PEC-P-8 Membrane Conductivity	
LTE-P-10 RDE	HTE-P-10 Polarization Resistance	PEC-P-9 On Sun Testing	
LTE-P-13 3-Electrode Cell for Screening OERHER Electrocatalyst Activity	HTE-P-11 Impedance Spectroscopy Test	PEC-P-10 for Fabrication Integration and ScaleUp	
LTE-P-14 Non PGM Conductivity measurement	HTE-P-13 Metal supported Cell Test	PEC P-11 Metrics SOP PEC	
LTE-P-17 PTL Resistance and Water Properties	HTE-P-14 Bonding Strength	PEC-P-12 Band-gap and Light Absorptions	
LTE-P-19 Comparison Metrics and Terms for Low Temperature Electrolysis	HTE-P-15 Mechanical Strength	PEC-P-13 OER and HER Activitys for Water Splitting	
LTE-P-20 Water Content	HTE-P-18 Interconnect Resistance Measurements	PEC-P-14 Minority Carrier Diffusion Length	
LTE-P-21 Post Test Teardown Analysis	HTE-P-19 Area Specific Resistance	PEC-P-16 Check List for Beyond 1000h Testing	
LTE-P-22 Alkaline stability AEMs	HTE-P-21 Cell Thermal Cycling	PEC-P-17 Flat Band Potentials	
LTE-P-23 AEM alkaline-oxidative stability SOP	HTE-P-22 Measurement of Faradaic Efficiency	PEC-P-18 Spatially Resolved PEC SECM	
	HTE-P-23 SOEC Stack Testing	PEC-P-19 Protective Layer Conductivity	
	HTE-P-24 Cell Durability Testing	PEC-P-20 Protective Layer Optical	
	HTE-P-25 Large Area Cell Testing	PEC-P-21 Doping Type and Doping Density	
	HTE-P-27 H2 Production Rate and Electronic Leakage		

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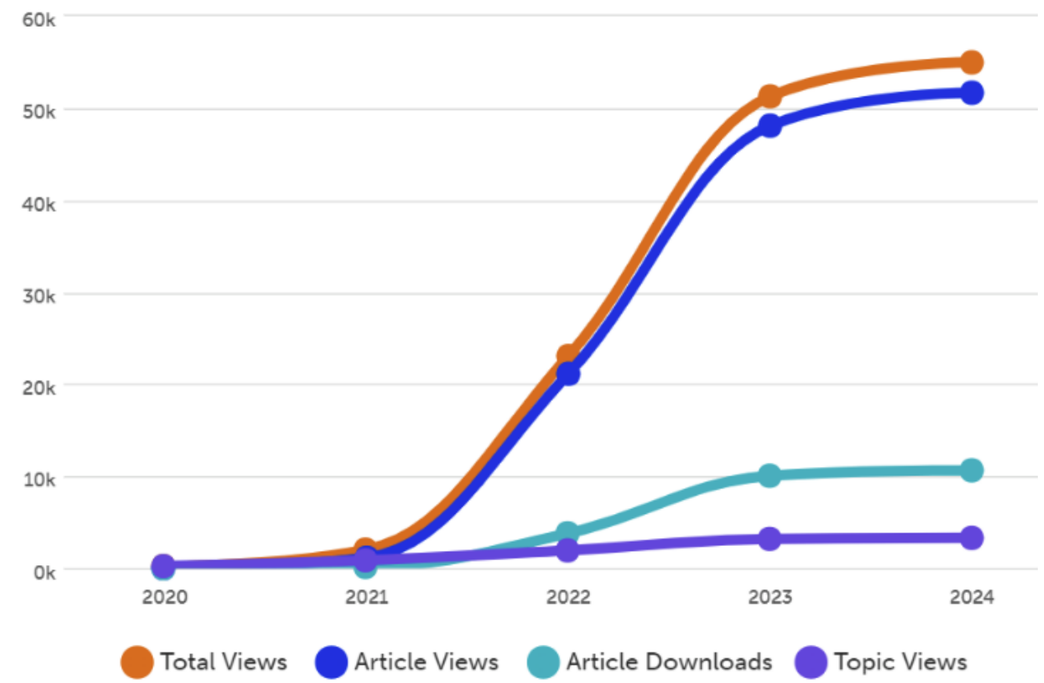
Accomplishments and Progress:
Publication in Frontiers in Energy Research: Hydrogen Storage and Production: Research Topics

"Advanced Water Splitting Technologies Development: Best Practices and Protocols"

Volume 1:

https://www.frontiersin.org/research-topics/16823/advanced-water-splitting-technologies-development-best-practices-and-protocols



Volume 1:

54,970 Views and 10,644 Total Downloads

20 published articles with 96 authors

From list of most viewed Research Topics this volume is #35 out of 592 issues

Volume 2:

The project team members are currently planning for Volume 2 which will publish new and next level protocols

Accomplishments and Progress:
Protocols Have Been Prioritized for Validation, and Validation Has Started

Currently Being Validated

LTE

Number	Protocol	Component	Priority
LTE-P-7	Ion Exchange Capacity	AEM	1
LTE-P-22	**Alkaline stability**	AEM	1
LTE-P-8	Gas Permeability	AEM/PEM	1
LTE-P-9	Chemical Stability	AEM	1
LTE-P-10	RDE	PGM	1
LTE-P-20	Water Uptake Measurement	PEM/AEM	1
LTE-P-3	Ion Exchange Capacity	PEM	2
LTE-P-5	Thermal Stability	PEM	2
LTE-P-6	Conductivity	AEM	2
LTE-P-14	Electronic conductivity	Non-PGM	2
LTE-P-1	Compressibility	GDL	3
LTE-P-19	LTE Definitions and Notations	General	N/A

HTE

Number	Protocol	Component	Priority
HTE-P-01	Measurement of Bulk Conductivity	Electrolyte/ Electrode	1
HTE-P-02	Ion Conductivity / Transference Numbers	Electrolyte	1
HTE-P-03	Mixed Ion Conductivity	Electrolyte	1
HTE-P-07	Leak Test	Cell/Stack	1
HTE-P-09	Cell Performance Steady-State	Cell	1
HTE-P-05	Linear Thermal Expansion	Electrolyte	2
HTE-P-10	Polarization Resistance	Electrode	2
HTE-P-04	Density Measurement	Electrolyte	3
HTE-P-13	Metal-Supported Cell Test	Cell	3
HTE-P-14	Bonding Strength	Contact Layer	3

PEC

Number	Protocol	Component	Priority
PEC-P-3	Tandem light absorber IPCE	Photo-electrode	1
PEC-P-5	Product crossovers	Transport	1
PEC-P-9	Outdoor, on-sun measurements	Device	1
PEC-P-2	Illumination calibrations	Device	2
PEC-P-7	Interfacial band energetics	Protective layer	2
PEC-P-8	Membrane separators conductivity	Membrane electrolyte	2
PEC-P-10	Device fabrication, integration, scale up	Device	2
PEC-P-1	Photoelectrodes preparation	Photo-electrode	3
PEC-P-0	Comparison Metrics and Terms for PEC Water Splitting	General	N/A

STCH

Number	Protocol	Component	Priority
STCH-P-1	Metrics, Units, Definitions	General	1
STCH-P-2	Ceria Standard and Material Specs	Materials	1
STCH-P-4	Detailed Thermodynamics Screen	Materials	2
STCH-P-8	Detailed Kinetics Screen	Materials	2
STCH-P-10	Durability Level 1 Screen	Materials	2

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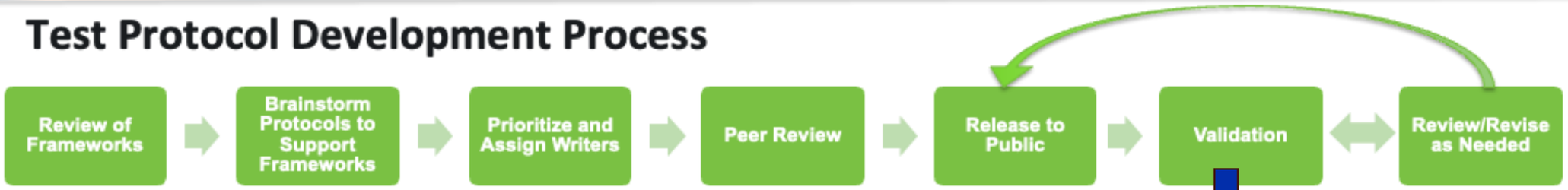
Accomplishments and Progress:
Protocol Validation Process

Test Protocol Development Process



Validation Process

Result
Final Validated Protocol

Example: Leverage HydroGEN Consortium Capabilities

HydroGEN
Advanced Water Splitting Materials

NREL, Berkeley LAB, SNL, INL, and LLNL

Combination of 63 different capabilities

Site Assessment Questionnaire

	Protocol Testing Priority: Protocol No. XXXXX Testing Center Ranking Matrix	1		
	Please Fill in Yellow and Green Spaces	RESULTS (0-100):	0	
No. of Factors		3. Sites:	Site 1	Sit
11	1. Factors	2. Weighting (1-10)	4. Score (1-10)	4. Scor
1	Expertise of Site PI in this particular measurement			
2	Number of skilled staff to perform measurements			
3	Staff workload width to enable Protocol Testing			
4	Funding width to enable Protocol Testing			
5	etc...			

Current LTE Validation Sites

-NREL
-LBNL
-Univ of Oregon

Validations in Progress

-LTE-P-7 AEM Ion Exchange Capacity
-LTE-P-22 Alkaline Stability

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Accomplishments and Progress:
New AWST Test Protocols Being Developed

The next level of Advanced Water Splitting Technologies Protocols are being written. Next Level Protocols: for materials, scaled-up components, and accelerated testing

LTE	*HTE*	*PEC*	*STCH*
Subscale Test Build Authors: NREL	**Cr Evaporation Test Authors: WVU**	**PEC diurnal cycle protocol Authors: Stanford, Caltech**	**Protocol and Authors Under Evaluation**
Short Circuit Resistance Authors: Nel Hydrogen, NREL	**Cell Preconditioning and Startup Authors: PNNL**	**Particle based PEC system protocol Authors: UC-Irvine, Yale**	**Protocol and Authors Under Evaluation**
Preliminary Test Cell Screen Authors: Nel Hydrogen, LBNL	**Lab Scale Steam Delivery Authors: PNNL, INL**	**Protocol and Authors Under Evaluation**	**Protocol and Authors Under Evaluation**
Hydrogen Permeation Authors: Hannover	**Test Termination and Disassembly Authors: PNNL**	**Protocol and Authors Under Evaluation**	**Protocol and Authors Under Evaluation**

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Accomplishments and Progress:
Held 5th Annual Benchmarking Meeting on September 20-22, 2023 at ASU

***6th Benchmarking Meeting** will be held at the ASU California Center in Los Angeles, June 10-12, 2024*

2023 Representative Outputs

- Plenary session covered overviews of:
  1) *International Benchmarking Activities*
  2) *The H2NEW consortium*
  3) *HydroGEN 2.0 projects*
  4) *The Regional Clean Hydrogen Hubs*
- Breakout sessions provided:

1) *Discussion of current Protocols updates/revisions*
   2) *Selection and author assignment of New Protocols*
   3) *Prioritization and destination for Protocol Validations*
   4) *Engagement of international community in the harmonization of protocols*

- Held Cross-Cutting sessions on:

1) *H2 Storage Benchmarking & Validation Experience*
   2) *HTE & STCH: Common Materials*
   3) *LTE & PEC: Common Materials*

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Accomplishments and Progress:
Responses to Previous Year Reviewers' Comments

- "The project has excellent coordination with DOE, national laboratories, academia, and industry. International coordination is unclear but appears to be happening also". "It will be hard to harmonize protocols across the world since each region will have its own sponsors and goals. Considering international input or validation would provide opportunities for harmonizing protocols."
  - 4 int. plenary speakers present annually updates on int. activities. Frontiers protocol issue has 4 EU co-editors. Protocol validation is organized worldwide, including int. sites; Participated in IAE meetings for coordination; reaching out to int. colleagues for sharing their protocols
- "It would be good to identify the sites to validate the protocols."
  - Validation sites have been identified in FY24
- "While it is early, including new and emerging solid oxide electrolyzer technologies must be considered."
  - PECEs are included and several protocols has been written
- "Engagement of external stakeholders (those not funded by this program), and fresh ideas from other informed added about how to maintain a process for future protocol/benchmark updates. The team could describe how stakeholders within DOE and academia is needed. Engagement of industrial stakeholders is low or missing".
  - Industry actively participates. Nel leads LTE. Industry participated in every Benchmarking annual meeting and in protocol writing.
- "More detail could be done to continue to have community engage with the protocol and benchmark process, even after award end date, especially if this program no longer funds the workshops. This may already be implied in the proposed future work."
  - This effort is ongoing. Workshops are now annual meetings. Team continues to present and advertise the Benchmarking effort at many national and intern. conferences. We are actively engaging junior staff to contribute.

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Collaboration and Coordination

Test Protocol Development Process

- Initially prioritized materials level test protocols
- Will include device level and accelerated testing

Thank you to our Protocol contributors!

Adam Weber	Charles Dismukes	Devan Solanki	Guiji Liu	Karen Heinselman	Michael Tucker	Ryan Ouimet	Todd Deutsch
Aldo Steinfeld	Chengxiang Xiang	Dong Ding	Guosong Zeng	Karl Gross	Miguel Miranda	Sami Sainio	Vijay Ramani
Alexey Serov	Chris Capuano	Ellen Stechel	Haoqing Su	Katherine Ayers	Myles Steiner	Santiago Rojas-Carbonell	Xiang Lyu
Andrea Ambrosini	Chris Muhich	Éowyn Lucas	Harry Atwater	Keda Hu	Nem Danilovic	Sarah Park	Xin Shen
Andrew Motz	Christopher Arges	Eric Coker	Hui Xu	Keenan Wyatt	Nemanja Danilovic	Sarah Shulda	Yeong-Shyung Chou
Ani Kulkarni	Chulsung Bae	Erin Brahm Creel	Ian Sullivan	Kelly Meeks	Nicholas Strange	Shannon Boettcher	Yifat Piekner
Anthony McDaniel	Daniel Grave	Eun Joo Park	James Young	Lan Wang	Olga Marina	Shaun Alia	Yu Seung Kim
Anyka Bergeson-Keller	Dave Ginley	Fengyu Shen	Jason Cooper	Lihao Han	Olivia Alley	Shu Hu	Yushan Yan
Avner Rothschild	Dave Palm	Francesca M. Toma	Jeff Stevenson	Lucy Metzroth	Patrick Schnell	Siddharth Komini Babu	Zetian Mi
Bob Bell	David Ellis	Geoff McCool	Jennifer Glenn	Marcelo Carmo	Rito Yanagi	Srinivas Vanka	Zhaohan Li
Brendan Bulfin	David Ginley	George Roberts	John Hardy	Martha Welander	Robert Bell	Subhayan Roychoudhury	Zhongyang Wang
Brian Setzler	David Larson	Grace Lindquist	Jonathan Scheffe	Matthew Ueckermann	Roel Van de Krol	Tobias Kistler	Seraphim Belko
Burt Simpson	David Prendergast	Guido Bender	Julie Mougin	Michael Sanders	Ryan O'Hayre	Tobias Schuler	Renaldo Springer

Plus expert reviews and workshop input from many national and international researchers

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Remaining Challenges and Barriers

- Ensuring wide-spread acceptance and utilization of the Protocols
- Involving international partners to promote adoption of a universally accepted series of Protocols and Benchmarking practices
- Validating and updating key Protocols at specific expert laboratories
- Establishing key materials and component standards to test the accuracy of lab equipment and procedures
- Identifying curators of material and component standards
- Securing appropriate financial support to cover the costs and labor of curators and validation centers

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Proposed Future Work

- Coordinate regular (e.g., annual) updates on high priority research areas
- Continue engaging technology experts to create new high-priority protocols
- Coordinate methods of making the next generation of protocols publicly available through the DOE DataHub and publications (including a follow-on volume in *Frontiers Special Issue*)
- Engage the community in identifying advanced testing protocols for bench-scale, sub-scale and higher levels
- Coordinate with the existing expert sites within DOE and international programs in validation testing, evaluation, and improvements of high-priority protocols (1st step, 2 protocols per technology)
- Provide re-evaluation of alignment of Lab nodes current technical capabilities to help support program projects needs
- Identify community accepted standards for round-robin/validation testing and potentially a curator for these standards
- Continue Annual Benchmarking Meetings to engage the DOE, protocol developers, international community, and industry in the advancement of these AWST Benchmarking Best Practices

***** Any proposed future work is subject to change based on funding levels***

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Summary

Experience has demonstrated:

That accurately quantifying progress against target goals requires consistent measurement methods and benchmarking standards. Without this, RD&D efforts can easily become mired in dead-end pathways and/or wasted or duplicative efforts. For this reason this project was created by the DOE to establish key components of a universal system for benchmarking within the AWST community.

Currently this project has:

- *Completed 59 test protocols across the four AWS technologies involving more than 100 authors and other experts*
- *Published a first set of 20 protocols in an open access journal receiving over 10,000 downloads and 55,000 views*
- *Held 5 annual Benchmarking meetings with international participation leading to benchmarking collaborations and cross-cutting information sharing between the four very diverse AWST*

Looking forward we have begun:

- *Prioritizing these protocols for validation testing and improvement, with first validations underway*
- *Developing universal materials and component testing standards for the AWST community*
- *Planning the next level of scale up RD&D protocols, benchmarks, and road maps*

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Technology Transfer Activities

- Frequent discussions and information exchange with experts and industry could be considered as technology transfer
- Open and accessible presentations and publications
- Lessons learned sharing
- Annual expert meetings with invited international speakers

Special Recognition and Awards

2021 DOE Hydrogen Program R&D Award

For exceptional teamwork and leadership on the development of benchmarks and test protocols for advanced water splitting technologies

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Publications & Presentations - 1

“Advanced water splitting technologies development: Best practices and protocols”; Frontiers in Energy Research on-line publication: Hydrogen Storage and Production

1. *Editorial*: “Advanced water splitting technologies development: Best practices and protocols”; Brendan Bulfin, Marcelo Carmo, Roel Van de Krol, Julie Mougin, Kathy Ayers, Karl J. Gross, Olga A. Marina, George M. Roberts, Ellen B. Stechel and Chengxiang Xiang.
2. “*Performance Indicators for Benchmarking Solar Thermochemical Fuel Processes and Reactors*”; Brendan Bulfin, Miguel Miranda and Aldo Steinfeld.
3. “*Considerations for the Accurate Measurement of Incident Photon to Current Efficiency in Photoelectrochemical Cells*”; David S. Ellis, Yifat Piekner, Daniel A. Grave, Patrick Schnell and Avner Rothschild.
4. “*Comprehensive Evaluation for Protective Coatings: Optical, Electrical, Photoelectrochemical, and Spectroscopic Characterizations*”; Xin Shen, Rito Yanagi, Devan Solanki, Haoqing Su, Zhaohan Li, Cheng-Xiang Xiang and Shu Hu.
5. “*Assessing the Oxidative Stability of Anion Exchange Membranes in Oxygen Saturated Aqueous Alkaline Solutions*”; Christopher G. Arges, Vijay Ramani, Zhongyang Wang and Ryan J. Ouimet.
6. “*A Thermogravimetric Temperature-Programmed Thermal Redox Protocol for Rapid Screening of Metal Oxides for Solar Thermochemical Hydrogen Production*”; Michael D. Sanders, Anyka M. Bergeson-Keller, Eric N. Coker and Ryan P. O’Hayre.
7. “*Metal-Supported Solid Oxide Electrolysis Cell Test Standard Operating Procedure*”; Fengyu Shen, Martha M. Welander and Michael C. Tucker.
8. “*Standard Operating Protocol for Ion-Exchange Capacity of Anion Exchange Membranes*”; Lan Wang, Santiago Rojas-Carbonell, Keda Hu, Brian P. Setzler, Andrew R. Motz, Matthew E. Ueckermann and Yushan Yan.
9. “*Long-Term Stability Metrics of Photoelectrochemical Water Splitting*”; Srinivas Vanka, Guosong Zeng, Todd G. Deutsch, Francesca Maria Toma and Zetian Mi.
10. “*Protocol for Screening Water Oxidation or Reduction Electrocatalyst Activity in a Three-Electrode Cell for Alkaline Exchange Membrane Electrolysis*”; Erin Brahm Creel, Xiang Lyu, Geoff McCool, Ryan J. Ouimet and Alexey Serov.
11. “*Measurement of Resistance, Porosity, and Water Contact Angle of Porous Transport Layers for Low-Temperature Electrolysis Technologies*”; Ryan J. Ouimet, James L. Young, Tobias Schuler, Guido Bender, George M. Roberts and Katherine E. Ayers.
12. “*Conductivity and Transference Number Determination Protocols for Solid Oxide Cell Materials*”; John S. Hardy, Aniruddha P. Kulkarni, Jeffry W. Stevenson and Olga A. Marina.
13. “*Gas Permeability Test Protocol for Ion-Exchange Membranes*”; Eun Joo Park, Siddharth Komini Babu and Yu Seung Kim.
14. “*Standard operating procedure for post-operation component disassembly and observation of benchtop water electrolyzer testing*”; Jennifer R. Glenn, Grace A. Lindquist, George M. Roberts, Shannon W. Boettcher and Katherine E. Ayers.
15. “*Evaluation of steam supply performance: Steamer vs. bubbler*”; Yongliang Zhang, Nansheng Xu, Qiming Tang, William Gibbons and Kevin Huang.

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Publications & Presentations - 2

16. “*Rotating Disk Electrode Standardization and Best Practices in Acidic Oxygen Evolution for Low-Temperature Electrolysis*”; Shaun M. Alia and Nemanja Danilovic.
17. “*Measurement of ion transport properties in ion exchange membranes for photoelectrochemical water splitting*”; Éowyn Lucas, Lihao Han, Ian Sullivan, Harry A. Atwater and Chengxiang Xiang.
18. “*Best Practices in PEC Water Splitting: How to Reliably Measure Solar-to-Hydrogen Efficiency of Photoelectrodes*”; Olivia J. Alley, Keenan Wyatt, Myles A. Steiner, Guiji Liu, Tobias Kistler, Guosong Zeng, David M. Larson, Jason K. Cooper, James L. Young, Todd G. Deutsch and Francesca M. Toma.
19. “*Synchrotron-based techniques for characterizing STCH water-splitting materials*”; Sarah Shulda, Robert T. Bell, Nicholas A. Strange, Lucy Metzroth, Karen N. Heinselman, Sami Sainio, Subhayan Roychoudhury, David Prendergast, Anthony H. McDaniel and David S. Ginley.
20. “*Leak test for solid oxide fuel cells and solid oxide electrolysis Cells*”; Yeong-Shyung Chou, John Hardy and Olga A. Marina.

Presentations:

21. K Ayers, (Invited) Hydrogen Benchmarking Project: Progress and Future Opportunities, 244th ECS meeting, Gothenburg, Sweden, October 10, 2023
22. M Carmo, (Invited) K Ayers, G Bender, B Bensmann, A Gago, T Gottschalk, K Gross, R Hanke-Rauschenbach, JO Jensen, MR Kraglund, O Marina, G Roberts, S Metz, T Smolinka, EB Stechel, T Turek, C Xiang, Advancing hydrogen generation technologies assisted by a solid international benchmarking effort, 243rd ECS Meeting, 28 May, 2023, Boston MA.
23. K Ayers, *Challenges and Opportunities for Large Scale PEM Electrolysis*, Invited, *The H2 Economy Program*, University of Houston, March 8, 2023.
24. OA Marina, High Temperature Electrolyzers for Hydrogen and Chemicals Production, Invited, The H2 Economy Program, University of Houston, March 8, 2023.
23. K Ayers, *Challenges and Opportunities for Large Scale PEM Electrolysis*, Invited, *The H2 Economy Program*, University of Houston, September 9, 2023.
24. OA Marina, High Temperature Electrolyzers for Hydrogen and Chemicals Production, Invited, The H2 Economy Program, University of Houston, September 9, 2023.
23. K Ayers, *Challenges and Opportunities for Large Scale PEM Electrolysis*, Invited, *The H2 Economy Program*, University of Houston, March 11, 2024.
24. OA Marina, High Temperature Electrolyzers for Hydrogen and Chemicals Production, Invited, The H2 Economy Program, University of Houston, March 11, 2024.
25. 23. OA Marina, (Invited) *High Temperature Electrolysis: Challenges and Opportunities of H_2 Production*, Workshop: Where Is Energy Storage Headed? Challenges of Degradation in Long-term Operation, Boston University, February 11, 2022.

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