Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

Benchmarking Advanced Water Splitting Technologies:
Best Practices in Materials Characterization

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Proton OnSite

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Project ID # p170

NREL · Berkeley Lab · Sandia National Laboratories · INL Idaho National Laboratory · Lawrence Livermore National Laboratory · SRNL

Project Overview

Benchmarking Advanced Water Splitting Technologies

PI: Kathy Ayers, Proton OnSite
Co-PIs: Ellen B. Stechel, ASU; Olga Marina, PNNL; CX Xiang, Caltech
Consultant: Karl Gross

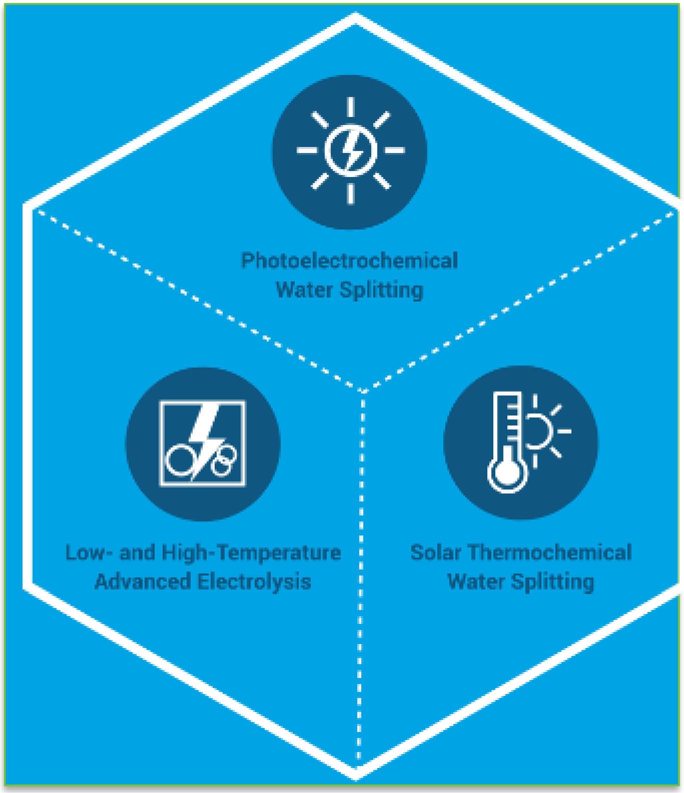
Award #	EE0008092
Start/End Date	09/01/2017 – 09/30/2019
Total Project Value Funds Received to Date	$2.2 M $1.97 M

Project Vision

A cohesive R&D community working together; interacting with the EMN to define targets, best practices, gaps, and priorities; aggregating and disseminating knowledge; accelerated innovation and deployment of advanced water splitting technologies.

Project Impact

Development of a community-based living roadmap across technologies to assist in maintaining a balanced DOE portfolio.



Approach- Summary

Project Motivation

Team of subject matter experts assembled for each sub-area to engage with each sub-community

Consultant from a similar effort in hydrogen storage added to convey lessons learned

Proposed targets

Metric	State of the Art	Proposed
Survey for priorities	*N/A*	*High % response and opportunity for dialogue*
Metrics	*$/kW, $/kg*	*Component level parameters; system considerations*
Node assessment	*N/A*	*Identification of gaps and strengths*

Barriers

Lack of consensus regarding testing protocol/standards

Large diversity of information to compile and develop recommendations from

Different TRLs for different technologies

Partnerships

LTE (PEM/AEM): Proton OnSite

HTE (SOEC): PNNL

STCH: ASU

PEC: Caltech

Consultant: Karl Gross

Approach- Innovation

- 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

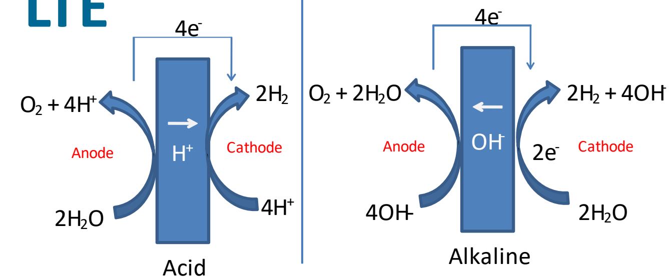
Approach- Budget Period 1 Project Tasks

Task	Timing	Goal
1. Framework Set-up	Sep ‘17 – Aug ’18	Develop a searchable library of screening tools, materials, and state of the art technology (with HydroGEN)
3. Protocol Definition	Jun ’18 – Mar ‘19	Develop bench scale testing protocols for each water splitting pathway as output of Year 1 project meeting
4. Protocol Verification & Revision	Nov ’18 – Mar ‘19	Verify procedures and configurations have been sufficiently defined for reproducible results
5. Program Management	Nov ‘17 – Mar ‘19	Ensure protocols and Best Practices are developed in accordance with broader EMN guidelines

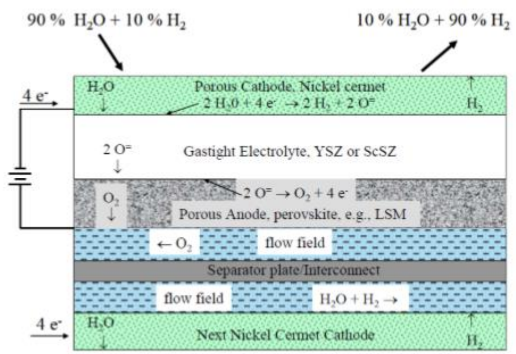
Relevance & Impact

- Development of standardized test methods and benchmarks
  - Community wide workshop held to review and provide feedback on draft frameworks
  - Test protocols identified and are being drafted
  - Leverage EMN node capabilities
  - Decrease development cycle times through common comparison
  - Support DOE Hydrogen and Fuel Cells Program goals to sustainably produce hydrogen for <$2/kg
  - Allow for direct comparisons of materials and water splitting technologies
- Supports the HydroGEN Consortium R&D model by bringing together and partnering with National Labs, Academia and Industry to:
  - Develop and implement test methods and evaluation criteria
  - Facilitate R&D and commercialization of water splitting technologies
  - Develop roadmaps for each water splitting technology to align future development projects

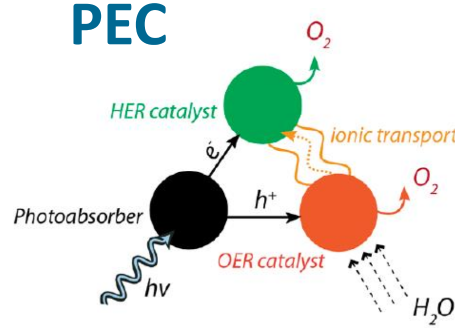
LTE



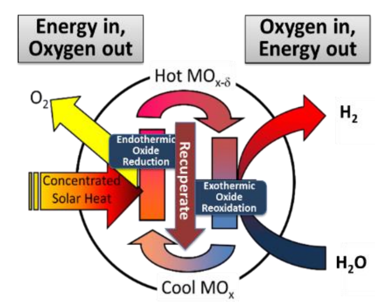
HTE



PEC



STCH

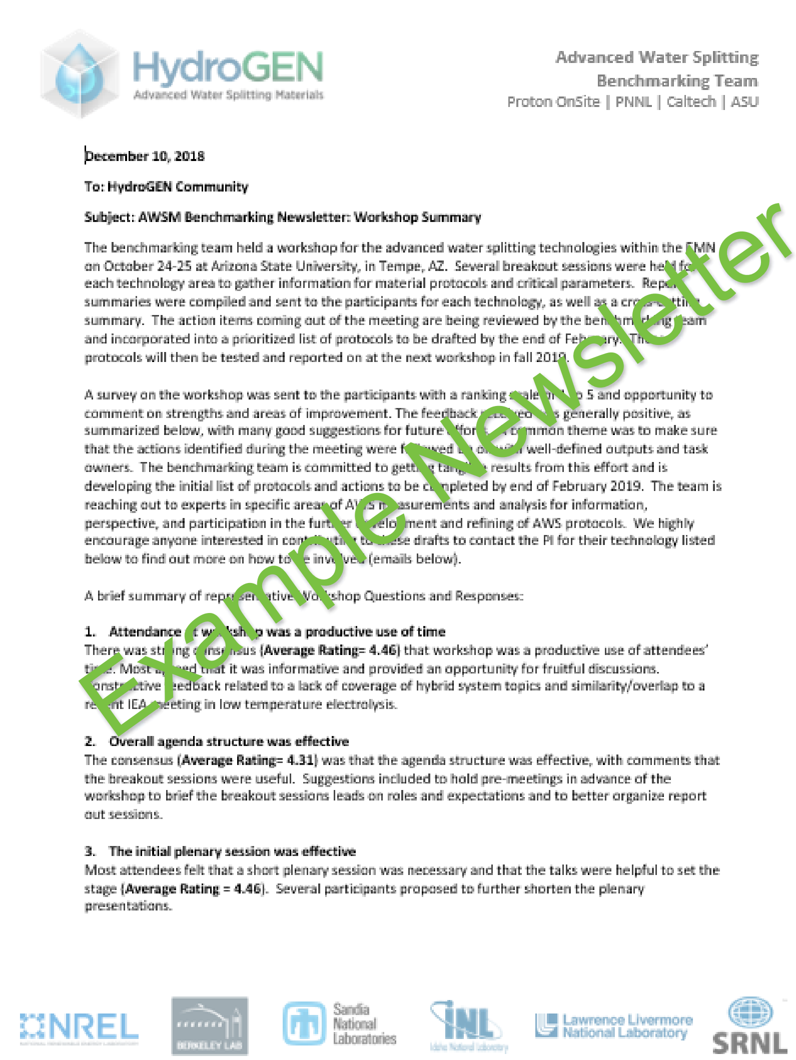


Accomplishments- Budget Period 1 Milestones

Milestone #	Project Milestones	Task Completion Date (Project Quarter) Original Planned	Revised Planned	Actual	Percent Complete	Progress Notes
1.1	Year 1 project meeting to present output of capabilities and gap assessment, and solicited input to define details of bench scale protocol development based on an initial framework.	9/30/2018	10/30/2018	10/30/2018	100%	Workshop was held on Oct 24-25, 2018. Test frameworks were reviewed, and updates will be made based on breakout session feedback.
1.1.1	Important questions and parameters for each technology area and surveys ready for dissemination.	12/31/2017	1/31/2018	3/31/2018	100%	Framework and questionnaire developed for each technology.
2.1.1	Capabilities assessment including surveys of each Node with 80% response rate completed and synthesized.	3/31/2018		3/31/2018	100%	Table developed to summarize capabilities and readiness. Feedback received from node owners.
2.2.1	Gap assessment including questionnaires with a goal of 50% response rate completed and synthesized.	6/30/2018		6/30/2018	100%	Questionnaire responses received. Node gap analysis completed.
3.1.1	Workshop results and outcome report compiled and published.	12/31/2018		12/31/2018	100%	Workshop breakout session summaries and attendee surveys compiled and distributed.
G/NG 1	Draft bench scale protocols published, definitions and notations agreed on, and metrics recommended. Draft Roadmap framework for each technology area completed	2/28/2019	4/15/2019		60%	In Progress

Accomplishments

- Framework and questionnaire developed with input from node experts at National Labs for each technology in a common format
- Questionnaire for each technology distributed to broad community for input and responses collected
- Framework reviewed by questionnaire respondents that “opted in” to provide feedback
- Completed assessment of node capabilities and summarized capabilities and readiness
- Quarterly Newsletters sent out to the advanced Water Splitting Technologies community
- Fall Community Wide Meeting held at Arizona State University on October 24 - 25, 2018
- Preliminary roadmaps developed for each technology



Advanced Water Splitting Benchmarking Team
Proton OnSite | PNNL | Caltech | ASU

December 10, 2018

To: HydroGEN Community

Subject: AWSM Benchmarking Newsletter: Workshop Summary

The benchmarking team held a workshop for the advanced water splitting technologies within the EMN on October 24-25 at Arizona State University, in Tempe, AZ. Several breakout sessions were held for each technology area to gather information for material protocols and critical parameters. Report summaries were compiled and sent to the participants for each technology, as well as a cross-cutting summary. The action items coming out of the meeting are being reviewed by the benchmarking team and incorporated into a prioritized list of protocols to be drafted by the end of February. These protocols will then be tested and reported on at the next workshop in fall 2019.

A survey on the workshop was sent to the participants with a ranking scale of 1 to 5 and opportunity to comment on strengths and areas of improvement. The feedback received was generally positive, as summarized below, with many good suggestions for future efforts. A common theme was to make sure that the actions identified during the meeting were followed up on with well-defined outputs and task owners. The benchmarking team is committed to getting tangible results from this effort and is developing the initial list of protocols and actions to be completed by end of February 2019. The team is reaching out to experts in specific areas of AWS measurements and analysis for information, perspective, and participation in the further development and refining of AWS protocols. We highly encourage anyone interested in contributing to these drafts to contact the PI for their technology listed below to find out more on how to be involved (emails below).

A brief summary of representative Workshop Questions and Responses:

1. **Attendance at workshop was a productive use of time**

There was strong consensus (**Average Rating= 4.46**) that workshop was a productive use of attendees' time. Most agreed that it was informative and provided an opportunity for fruitful discussions. Constructive feedback related to a lack of coverage of hybrid system topics and similarity/overlap to a recent IEA meeting in low temperature electrolysis.

2. **Overall agenda structure was effective**

The consensus (**Average Rating= 4.31**) was that the agenda structure was effective, with comments that the breakout sessions were useful. Suggestions included to hold pre-meetings in advance of the workshop to brief the breakout sessions leads on roles and expectations and to better organize report out sessions.

3. **The initial plenary session was effective**

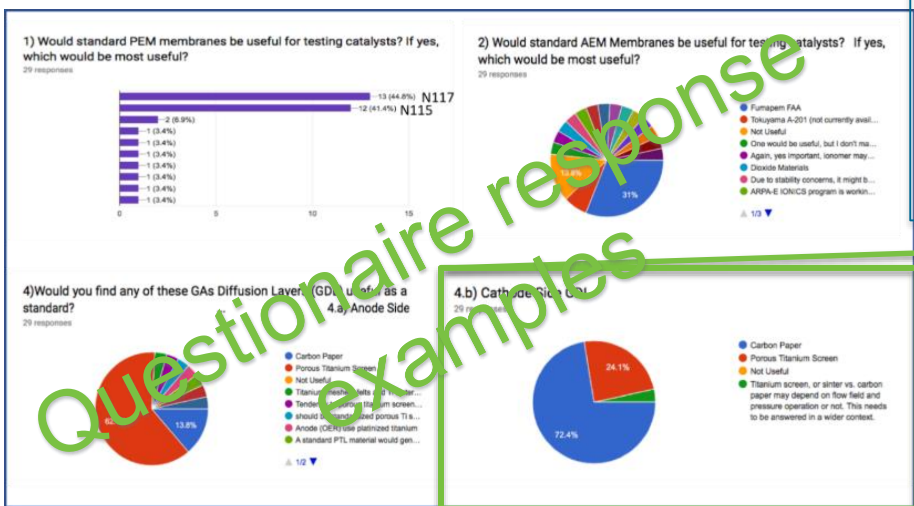
Most attendees felt that a short plenary session was necessary and that the talks were helpful to set the stage (**Average Rating = 4.46**). Several participants proposed to further shorten the plenary presentations.

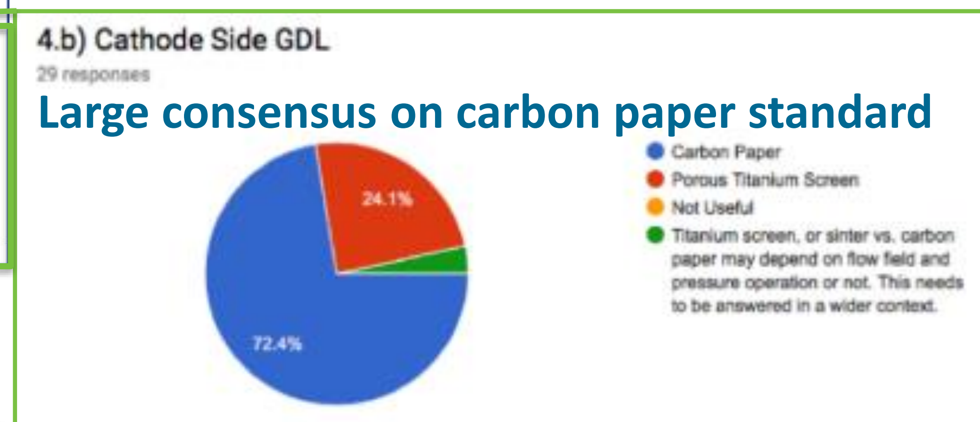
Accomplishments- Questionnaires

- A questionnaire was created and distributed for each water splitting pathway.
  - Collected broad feedback across the community
  - Target of obtaining >/= 50% response rate from EMN Level 1 Node Leads and Project PI's.

Response Rate

Affiliation	Sent	Response Rec'd	% Response Rate
EMN	21	17	81%
Domestic (Non EMN)	33	9	27%
International	16	11	69%
Total	70	37	53%





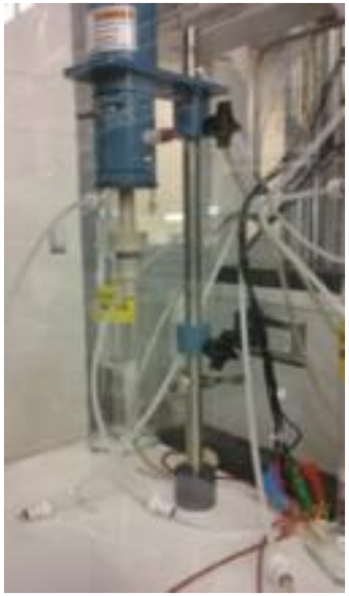
Complete results can be found on the data hub: https://datahub.h2awsm.org/project/about/benchmarking

Accomplishments- Test Frameworks

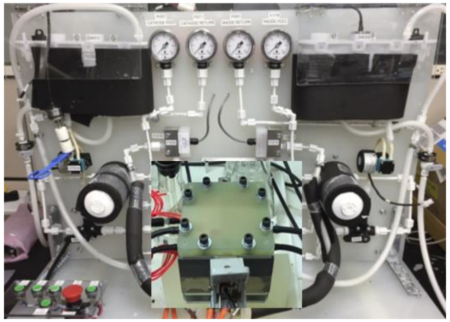
- A standardized framework was developed
  - Applicable across all water splitting pathways
  - Comprehensive best practices of benchmarking methods
  - Primary categories: Ex-situ materials testing and in-situ testing

- Standards for calibrating test equipment and test methods identified based on inputs from subject matter experts and literature
  - Includes minimum performance criteria for comparison
  - Continue to review and solicit feedback from subject matter experts

- Individual frameworks have been developed for each technology
  - Continue to refine based on feedback from the questionnaire and workshop breakout sessions.



Ex situ example: catalyst activity via rotating disk electrode



In situ example: electrolysis test cell for components

Accomplishments- Test Frameworks

Specific Parameters Defined By Component

LTE

Material	Metric(s)	Units	Test Method	Test Level (1, 2, 3)	Notes	Standard (for reference calibration)	Minimum criteria	Reference
Catalyst	Onset potential	V	RDE	1	Loading (OER/HER): 17.8 μgPGM/cm2 Scan rate (OER-PEM/AEM): 20mV/s	OER: 1.43V (IrO2)	OER: <1.5V vs. RHE	Alia - 2016 JES
	Overpotential at a fixed current	V			Scan rate (HER-AEM): Rotation speed (OER/HER): 2500 rpm	[illegible] 10mA/cm2	OER: <300mV at 10mA/cm2	Re[illegible] - 2012 ACS Catalysis - OER - Acid Met[illegible] Overpotentials
	Catalytic Activity	A/mgPGM (MA) mA/cm2PGM			Activity Evaluation (OER): Current at Set Potential of 1.55[illegible] Activity Eval[illegible] Exchange Cur[illegible]	OER-PEM: 0.30 A/mgIr at 1.55V (Ir nanopowder, metal, Johnson	OER-PEM: >0.20A/mgIr	Alia - 2016 JES
	ECSA	m2/gPGM			Procedure m[illegible] catalyst[illegible]			
Catalyst	Dissolution of catalyst components	%	ICP	2	Performed as[illegible] proc[illegible]			
Catalyst	Particle Size	nm	TEM, SEM,XRD	1	XRD: Can[illegible] crystallinity a[illegible] data when c[illegible] JCPDS st[illegible] HRTEM: Pa[illegible] analysis, i[illegible] struct[illegible]			
Catalyst	Surface area	m2/g	BET	1	Typical cata[illegible] 100m[illegible]			

HTE

Material	Metric(s)	Units	Test Method
Electrolyte	Ionic conductivity	S/cm	ac impedance
			four point measurements
	Ion transference number		Permiation technique
			Polarized cell technique
	Linear thermal expansion coefficient	K^{-1}	Dilatometry
			HT-XRD
	Chemical stability	mg	Thermal gravimetric analysis
		% lattice constant change	SEM/EDS, XRD, TEM
	Relative density	%	Dilatometry
			Archimedes method
	Bend strength	MPa	Flexural test
	Fracture toughness	MN $m^{-3/2}$	
	Creep rate	MPa	Strain testing

Material	Metric(s)	Units
Electrolyte	Ionic conductivity	S/cm
	Ion transference number	
	Linear thermal expansion coefficient	K^{-1}
	Chemical stability	mg
		% lattice constant change

Accomplishments- Test Frameworks

PEC

Material	Metric(s)	Test Method	Limitations	Standard (for reference calibration)	Minimum criteria	References
Photoabsorber	Bandgap	UV-vis Photoluminescence	-Subjective analysis -Bulk band gap may differ from surface -Shows optimum performance	Si (111)	1.1 eV	2 3 4
	Band positions	EIS (Flat band potential) XPS/UPS	-Surface heterogeneity -Impacted by surface states -No spatial resolution -Ex situ	n-Si (111) p-Si (111)	E_{vbm}= 0.88 eV E_{vbm}= 0.27 eV	2 6,7
	Minority carrier diffusion length (carrier mobility, carrier life time)	Transient absorption spectroscopy Time-resolved Photoluminescence Electron Beam-Induced Current Chopped photocurrent-time	-Measures lifetime only -Cryogenic temperatures -Non-radiative sources of decay may contribute -Typically qualitative -Damages organic materials -Ex situ -Low precision	n-Si (P-doped, nD = 5×10^{16} cm^{-3}) p-Si (B-doped, nD = 6×10^{15} cm^{-3})	168 μm 250 μm	9 10 11 12
	Doping types and doping concentrations	EIS (Mott-Schottky) Hall measurements	-Amorphous structures -Surface states -Low mobility -High polycrystallinity -Multiple carrier species	n-Si: P, 5×10^{16} cm^{-3} p-Si: B, 6×10^{15} cm^{-3}	P, 5×10^{16} cm^{-3} B, 6×10^{15} cm^{-3}	2,9 13
	Photo-generated carrier collection efficiency	External Quantum Efficiency Internal Quantum Efficiency	-Sensitive to lamp calibration -Determination of absorbed photons difficult	Si (111)	33 mA/cm^2	2,9,14,15

STCH

Material	Metric(s)	Units	Test Method	Test Level (1,2,3)	Notes	Standard for Reference Calibration	Minimum Criteria	Link to procedure or node
Redox Active								
Fluorite						**Ceria ($M_{0.5}O$)**		
	productivity Moles H_2 per Mole Cation	mol/mol	Stagnation flow reactor or thermal measurements	1	Requires fixing the reduction temperature and oxygen partial pressure (e.g., 1400C, 10 Pa)		0.025	Stagnation Flow Reactor
	enthalpy of reduction	kJ/mol_O	Calphad or equivalent; van Hopf analysis from measurements of equilibrium reduction extent as function of temperature and partial pressure of oxygen	1	Experimental measurements are developed for measuring δ as a function of T and pO2		TBD	high-temperature-x-ray-diffraction-ht-xrd-and-complementary-thermal-analysis
	entropy of reduction	J/mol_O/K	Calphad or equivalent; van Hopf analysis from measurements of equilibrium reduction extent as function of temperature and partial pressure of oxygen	2	Experimental measurements are developed for measuring δ as a function of T and pO2; van Hopf analysis has been applied but as an extrapolation to T →∞		TBD	high-temperature-x-ray-diffraction-ht-xrd-and-complementary-thermal-analysis
	phase purity	unitles	X-ray diffraction	1	% of desired phase		99%	
	rate of reduction	$\mu mol/sec/cm^2$ or mmol/sec/mol_O	Stagnation flow reactor	2	Normalization is an open question		TBD	Stagnation Flow Reactor
	rate of re-oxidation	$\mu mol/sec/cm^2$ or mmol/sec/mol_O	Stagnation flow reactor	2	Normalization is an open question; also open is how to measure in counterflow		TBD	Stagnation Flow Reactor
	oxygen conductivity	S/m		2	Need to set a standard temperature or minimum temperature		TBD	
	thermal conductivity	W/cm/K		2	Need to set a standard temperature or minimum temperature		TBD	
	Melting point	K	Thermal measurements	2			2000 K	
	Heat capacity as function of reduction extent	J/mol_M/K	Thermal measurements	3			no minimum	

Similar Frameworks Defined for All Technologies

Accomplishments- Node Gap Analysis

- Areas for expanded EMN node capabilities identified and reviewed with DOE

	Material/Component	Test Method Gaps
Low Temperature Electrolysis (LTE)	Membrane	Water content/uptake 3-D dimensional change H2 cross-over/permeation Mechanical Testing
	Bipolar Plate	Contact Resistance Area specific resistance Flexural strength Forming Elongation H2 uptake
	Carbon GDL	Porosity Tensile Strength Flexural Strength
	MEA	Hydrogen permeation Water flux Durability: Cycling
	Full Stack	Durability/Cell Decay Ohmic Resistance Stack Voltage Stack Efficiency Hydrogen Crossover

	Material/Component	Test Method Gaps
[illegible] Electrochemical (PEC)	Materials Level	Photoabsorber doping types and concentrations Photoabsorber minority carrier diffusion length (carrier mobility, carrier lifetime) Electrolyte optical and polarization properties
	Component Level	Spatially resolved local pHs at photoelectrodes Spatially resolved energetic landscape at semiconductor/catalyst and semiconductor/electrolyte interfaces Membrane/electrolyte interface energetics Bubble management
	Device Level	Solar-to-Hydrogen (STH) conversion efficiency at concentrated illumination (e.g. 10x) (at elevated temperature and elevated H2 pressure) Average STH conversion efficiency during diurnal cycles (at varying temperature and elevated H2 pressure)

	Material/Component	Test Method Gaps
High Temperature Electrolysis (HTE)	Solid electrolyte	Conductivity measurements Transference numbers
	Electrodes	High-throughput screening of electrodes to determine polarization losses I-Vs Porosity of electrodes High pressure electrode kinetics Impurities tolerance
	Seals	Long term stability
	Cell	In operando characterization techniques Electrochemical impedance spectroscopy Durability Accelerated aging protocol Life time predictions Bench scale high pressure cell testing platform Cell fabrication assistance Hydrogen production control Robust humidity sensors
	Stack	Test protocols Stack evaluation Stability/Degradation Efficiency Maintenance Start-up cycling

Identified Needs for Node Expansion in Each Technology

	Material/Component	Test Method Gaps
Solar Thermochemcial (STCH)	Redox Active	Phase Purity Rate of Reduction Rate of Re-oxidation Oxygen conductivity Thermal conductivity Melting point Vapor pressure Heat capacity as function of reduction extent

STCH example

Accomplishments- Annual Project Meeting

- A community wide workshop was held on October 24 - 25, 2018 at Arizona State University, Tempe campus.

- Workshop Objectives:
  - Understand needs of the community for effective comparison of results
  - Review/refine draft frameworks for standardized testing by component/ configuration;
  - Hold face-to-face discussions about protocol development in breakout sessions;
  - Refine methods based on community engagement;
  - Leverage international efforts to increase harmony across the field;
  - Realize increased usage of DOE database capabilities for community benefit.

Representative Outputs:
- Protocols Version 1.0;
- Documentation on needs/gaps in protocols and benchmarking;
- Perspective paper to be written on crosscutting and/or overall advanced water-splitting technology pathways.

Accomplishments- Annual Project Meeting

Breakout Sessions

Parallel Sessions
Color Coded by Water Splitting Technology

2018 HydroGEN Advanced Water Splitting Technology Pathways Benchmarking and Protocols Workshop - Breakout Sessions

Breakout Session #	Session ID	Technology	Topic	Room ID	Lead
1	C1-A	PEC/LTE	Membrane operating at different regimes	Yavapai	Cy Fujimoto
1	C1-B	LTE, PEC	Theory on catalytic reactions with metal oxides and other materials	Yuma	Tadashi Ogitsu & Hector Colon-Mercado
1	C1-C	PEC, LTE, HTE, STCH	Standards development and crosscutting measurement issues	Graham	Karl Gro[illegible]
1	S1-A	STCH	Performance Metrics - units, system boundaries	Pinel	Jim [illegible]
2	H2-A	HTE	Electrolyte: oxygen and proton conductors	Yavapai	[illegible]ker
2	L2-A	LTE	PEM: Membrane Physical Requirements/Tests	Yuma	[illegible] Pivovar
2	L2-B	LTE	Non PGM Catalyst: OER Stability & Activity	Graduate Plenary	Alexey Serov
2	P2-A	PEC	Protocol development in a half cell vs. a full cell	Pinel	Todd Deutsch
2	P2-B	PEC	In situ/operando methods for PEC interfaces and devices	Graduate Location #2	Shu Hu & Walter Drisdell
2	S2-A	STCH	Standard materials and form factors	Santa Cruz	Dave Ginley
2	S2-B	STCH	Detailed thermodynamics - operating conditions and methodology	Graduate Location #3	Jim Miller
3	H3-A	HTE	Electrode Activity & Stability	Graduate Plenary	Joseph Barton
3	L3-A	LTE	AEM: Membrane Physical Requirements/Tests	Yavapai	Yu Sueng Kim
3	L3-B	LTE	PGM Catalyst: OER Stability & Activity	Yuma	Nemanja Danilovic
3	P3-A	PEC	Protocols for PEC stability testing	Pinel	Kimberly Papadantonakis
3	P3-B	PEC	PEC electrolytes	Graham	Adam Weber
3	S3-A	STCH	"Quick and dirty" thermodynamic screen[illegible]	Santa Cruz	Andrea Ambrosini
3	S3-B	STCH	Extracting thermodynamic variables from theory and experiment[illegible]	Graduate Location #2	Ellen Stechel
4	H4-A	HTE	Cell test protocols	Yavapai	Mark Williams
4	L4-A	LTE	[illegible]: Characteristics & Characterization Tools	Graduate Plenary	Adam Weber
4	L4-B	LTE	[illegible] Device Level Protocols: Criteria/Tests	Yuma	Guido Bender
4	P4-A	PEC	[illegible]ototype formats and key metrics for benchmarking	Graduate Location #2	James Young
4	P4-B	PEC	Protocol development on OER/HER activity benchmarking at intermediate/dynamic current density	Graham	Nemanja Danilovic
4	S4-A	STCH	Detailed kinetic screening	Pinel	Tony McDaniel
4	S4-B	STCH	Systems analysis and TEA	Santa Cruz	Ivan Ermanoski
5	H5-A	HTE	In situ methods for degradation studies	Graduate Plenary	Xingbo Liu
5	L5-A	LTE	Carbon GDL: Physical Requirements/Tests	Copper	Chris Capuano
5	L5-B	LTE	Full Stack Level Protocols: Criteria/Tests	Graduate Location #2	Corky Mittelsteadt
5	P5-A	PEC	PEC Nodes capabilities and gaps assessment.	Crisola	Tadashi Ogitsu
5	S5-A	STCH	"Quick and dirty" kinetics screening	Plata	Tony McDaniel
5	S5-[illegible]	STCH	Durability protocols	Yavapai	Ivan Ermanoski
6	H6-A	HTE	Full stack test protocols	Graduate Plenary	James O'Brien
6	C6-A	PEC/STCH, LTE/HTE	Comparative analysis on key cross cutting metrics (definition and discussion of device efficiency, cost of hydrogen, etc)	Copper	Huyen Dinh
6	L6-A	LTE	HOLD FOR AD-HOC SESSIONS	Crisola	TBD
[illegible]	P6-A	PEC	HOLD FOR AD-HOC SESSIONS	Graduate Location #2	TBD
6	S6-A	STCH	HOLD FOR AD-HOC SESSIONS	Plata	TBD

Session IDs

L	LTE
H	HTE
P	PEC
S	STCH
C	Cross-Cutting

Example Session Output: Quad Chart for Each Breakout

P3-B | **PEC electrolytes** | **Adam Weber**

Summary of Discussion

- Should we standardize the electrolyte for PEC testing?
  - Suggest 3 electrolytes:
    - 0.5 M H_2SO_4
    - Phosphate vs. borate buffer
    - 1M KOH
  - Is it a system?
- What characterization should we use benchmark electrolyte?
- Discussed solid electrolytes as well

Consensus or Dissenting Opinions

- Need to worry foremost about safety and cost
- Ensure that electrolyte is not sacrificial
- Transport properties beyond conductivity could be important
  - Water transport, bubble management, gas solubility/permeation

Key Take-Aways

- Electrolyte choice should not be restrictive
- There could be effects due to spectator counterion
- Note that pH should be measured
- Local conditions are critical so stability by soaking is not enough, need to test in operating cell where pH gradients can form

Action items

- *Suggest* possible acid, neutral and alkaline electrolytes to use
  - Includes purity assessment
  - Understand interactions with light
  - Interaction with other components including both chassis and photoelectrodes

HydroGEN: Advanced Water Splitting Materials 7

Accomplishments- Test Protocols

- A first round of test protocols were defined and written in a standardized format prior to to the close of Year 1.

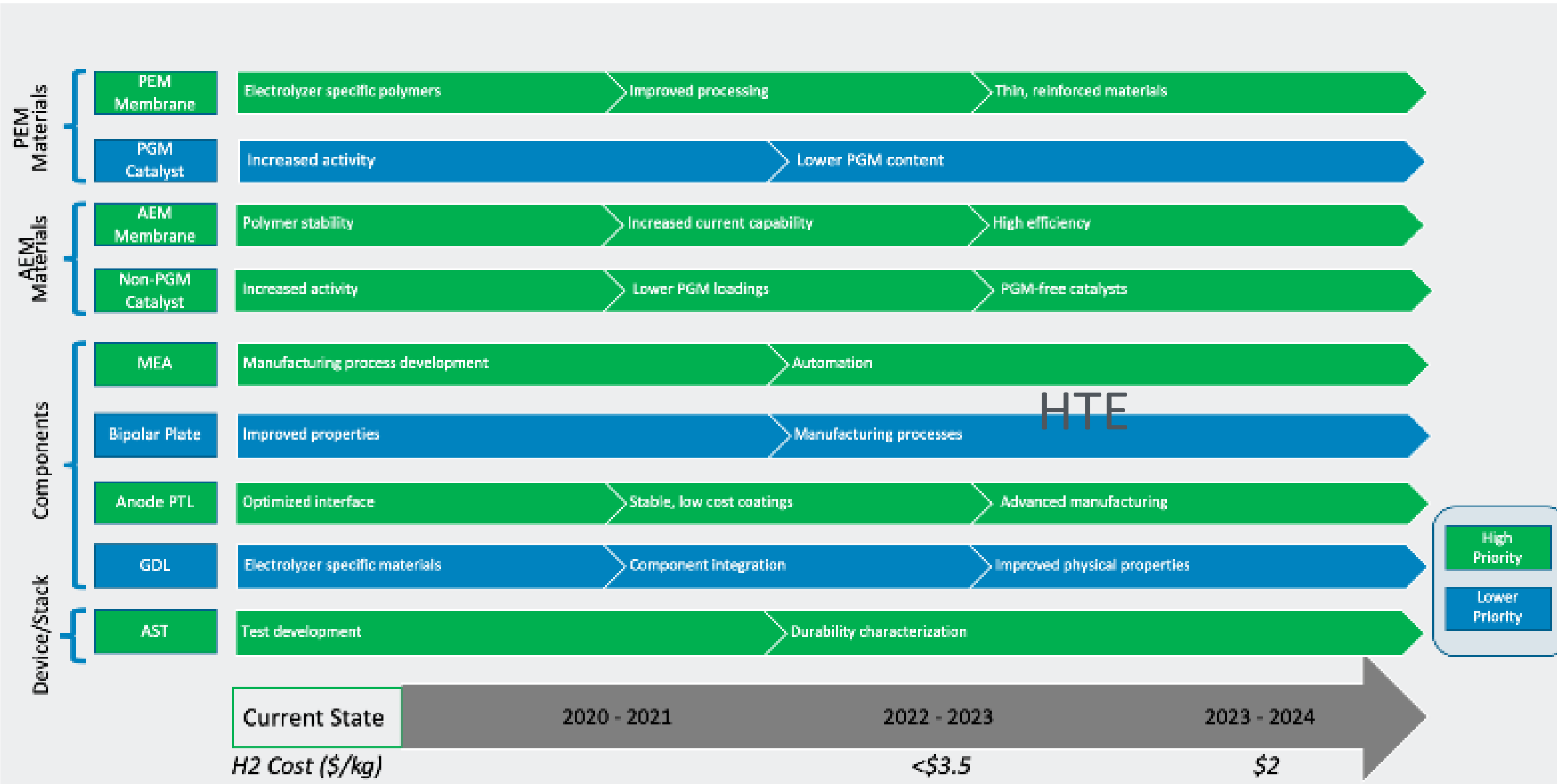
AWS Technology	Protocol	Component
LTE	Compressibility	GDL
LTE	Strength	GDL
LTE	Ion Exchange Capacity	PEM
LTE	Chemical Stability	PEM
LTE	Thermal Stability	PEM
LTE	Conductivity	AEM
LTE	Ion Exchange Capacity	AEM
LTE	Gas Permeability	AEM
LTE	Chemical Stability	AEM
LTE	RDE	PGM
LTE	ECS	PGM
LTE	Surface Area (BET)	PGM
LTE	Define necessary tests and protocols	Non-PGM
LTE	Electroconductivity	Non-PGM
LTE	Corrosion/degradation protocols	PTL
LTE	Mechanical testing protocols	PTL
LTE	Resistance measurements and water properties	PTL
LTE	Material characterization protocols	PTL
HTE	Conductivity	Electrolyte
HTE	Mechanical Strength	Electrolyte
HTE	Mixed Ion Conductivity/Transference Numbers	Electrolyte
HTE	Density Measurements	Electrolyte
HTE	Thermal Expansion Coefficient	Electrolyte
HTE	Thermal Stability	Electrolyte
HTE	Leak Tests	Electrolyte
HTE	Cell Condition Protocols	Electrolyte
HTE	Performance Steady State Tests	Electrolyte
HTE	Polarization Resistance Tests	Electrode
HTE	Impedance Spectroscopy Tests	Electrode

AWS Technology	Protocol
PEC	Standard protocols for photoelectrodes preparation
PEC	Standard protocols for illumination calibrations
PEC	Tandem light absorber IPCE measurements
PEC	Measurements and reporting of STHs
PEC	Measurements of product crossovers
PEC	Standard protocols for stability measurements of protective layers
PEC	Standard protocols for measurements and characterization of interfacial band energetics
PEC	Standard protocols for conductivity and permeability measurements on membrane separators
STCH	Metrics, Units, Definitions
STCH	Ceria Standard and Material Specs
STCH	ABO3 Standard and Material Specs
STCH	Detailed Thermodynamic Screen
STCH	"Quick and Dirty" Thermodynamic Screen
STCH	Extracting the Thermodynamics Measurables from the Measurements
STCH	Surrogate Measure for "Quick and Dirty" Screen
STCH	Detailed Kinetic Screen
STCH	"Quick and Dirty" Kinetic Screen
STCH	Durability Level 1 Screen
STCH	Durability Level 2 Screen
STCH	Durability Level 3 Screen
STCH	Computational Materials
STCH	Systems Performance Model
STCH	Techno-economic Model

Accomplishments- Roadmaps

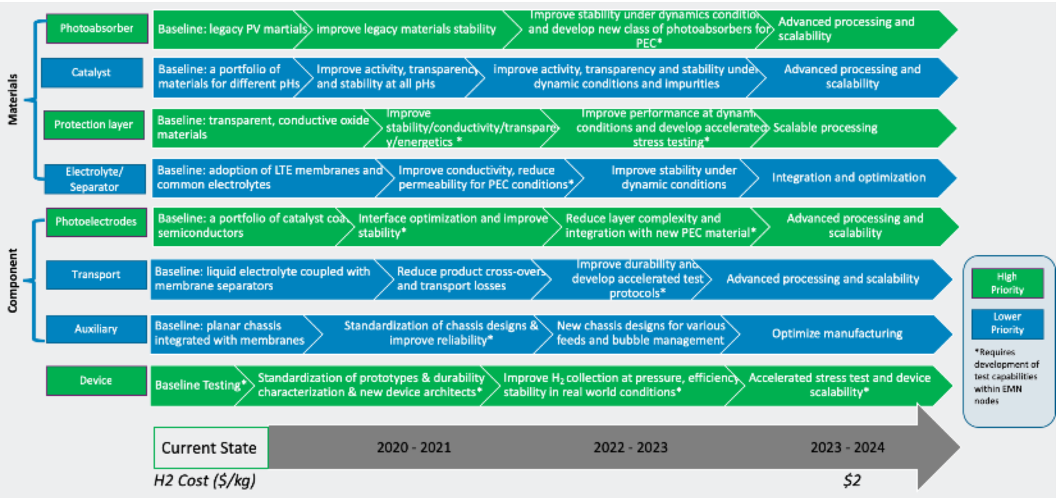
- Preliminary roadmaps have been developed for each water splitting technology
- Detailed tasks and timing currently under review; will be presented before the next annual workshop

LTE Example

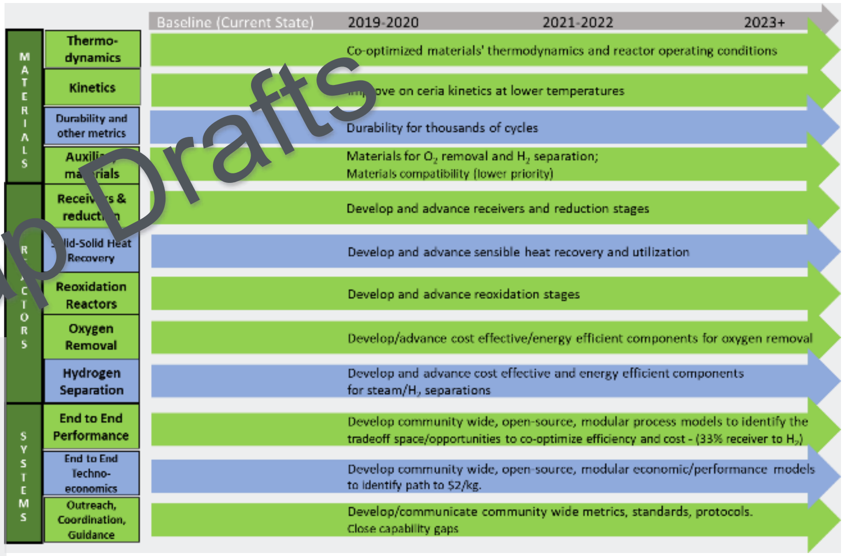


Accomplishments- Roadmaps

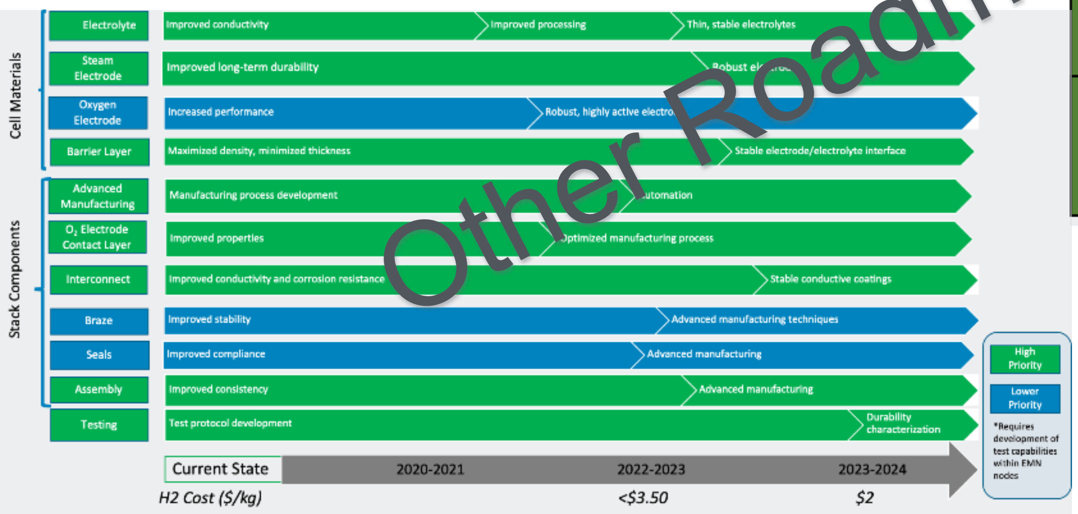
PEC



STCH



HTE



Other Roadmap Drafts

Responses to Previous Year Reviewer's Comments Slide

- Project was not reviewed last year

Collaboration- Effectiveness

- Wide-ranging and collaborative effort within and beyond the HydroGEN consortium
  - LTE, HTE, STCH, and PEC technologies
- Goal: develop a roadmap across technologies to assist in maintaining balanced DOE portfolio
  - Protocol and benchmarking development
  - Specific needs for each technology
  - Cooperative coordination effort across technologies
- Approach: Engage subject matter experts, Steering Committee, FCTO staff, and community in dialogue for each pathway
  - Gather input through surveys and questionnaires
  - Assess capabilities and gaps, including EMN Lab nodes
  - Engage broad community in development of standards, protocols, and priorities through annual workshop and regular communication
  - Encourage collaborative best practices development efforts

Proposed Future Work

- Any proposed future work is subject to change based on funding levels
- Budget period 2 will focus on Bench Scale Protocol Validation & Sub-Scale Development

Milestone #	Project Milestones	Completion Date
3.1	Assessment of relevant operational conditions for field use completed.	6/30/2019
3.3.1	Gap assessment on capabilities within EMN / R&D community for field simulations and long term reliability testing completed.	12/31/2019

Remaining Challenges and Barriers

- Timely engagement of broad community in contributing to and/or drafting protocols.
- Increased bandwidth and resources at Labs
- Path to reach consensus on standards and protocols.
- Improved set of common definitions to establish context for common standards and definitions (tie to real world conditions).

Budget Period Status & Outlook

- Project is on track to meet BP 1 milestones (no cost extension granted to push go/no go 6 weeks)
- Upcoming BP 2 Milestones
  - Task 3: Protocol Definition- Finalize draft protocols
  - Task 4: Protocol Verification and Revision- Exercise protocols and update as necessary
- Impact on water splitting research community
  - Identification of capabilities within nodes
  - Provide outline of test methods and criteria for characterizing and benchmarking new materials

Project Summary

- Objectives:
  - Define targets, testing protocols, validation standards, best practices, gaps, and priorities
  - Aggregate and disseminate knowledge
  - Accelerate innovation and deployment of advanced water splitting technologies
- Relevance & Impact:
  - Development of a community-based living roadmap across technologies to assist in maintaining a balanced DOE portfolio
- Collaboration Effectiveness:
  - Engagement of node subject matter experts, HydroGEN Steering Committee and broad water splitting community at annual workshop and through regular communication
- Accomplishments:
  - Areas for expanded EMN node capabilities were identified and reviewed with DOE
  - A community wide workshop was held to review, develop and update standards and test frameworks
  - Draft test protocols were developed
  - Preliminary roadmaps have been developed for each water splitting technology
- Future work:
  - Continue protocol development, protocol validation and accelerated test development