Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

Benchmarking Advanced Water Splitting Technologies

Dr. Katherine Ayers
Proton OnSite
June 13, 2018

Project ID # PD170

NREL National Renewable Energy Laboratory · 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

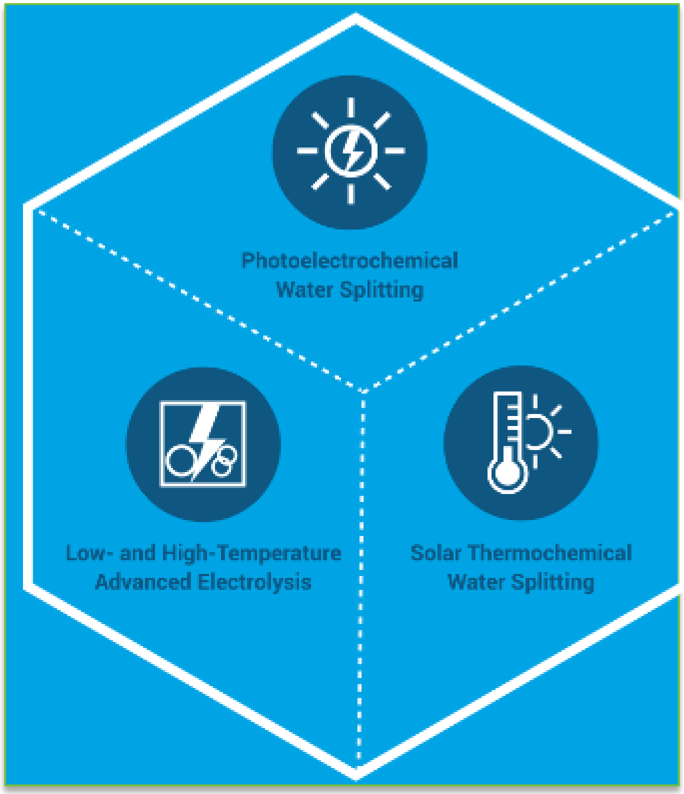
Award #	EE0008092
Start/End Date	09/01/2017 – 02/28/2019
Total Project Value Funds Received to Date	$2.2 M $0.99 M

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 history

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

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)
2. Capabilities Assessment	Nov ‘17 – Jul ‘18	Assess existing capabilities within the EMN across all water splitting pathways
3. Protocol Definition	Jun ’18 – Feb ‘19	Develop bench scale testing protocols for each water splitting pathway as output of Year 1 project meeting
4. Protocol Verification	Nov ’18 – Feb ‘19	Verify procedures and configurations have been sufficiently defined for reproducible results
5. Program Management	Nov ‘17 – Feb ‘19	Ensure protocols and Best Practices are developed in accordance with broader EMN guidelines

Relevance & Impact

- Development of standardized test methods and benchmarks
  - 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
  - Applicable across the broader HydroGEN Consortium
  - 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 commercializing of water splitting technologies

Accomplishments: Budget Period 1 Milestones

Milestone #	Project Milestones	Task Completion Date (Project Quarter)				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
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		40%	Preliminary meeting plans, presentations at conferences
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			20%	Initial feedback solicited. Sending to broader community
3.1.1	Project meeting results and outcome report compiled and published.	12/31/2018			0%	Not started.

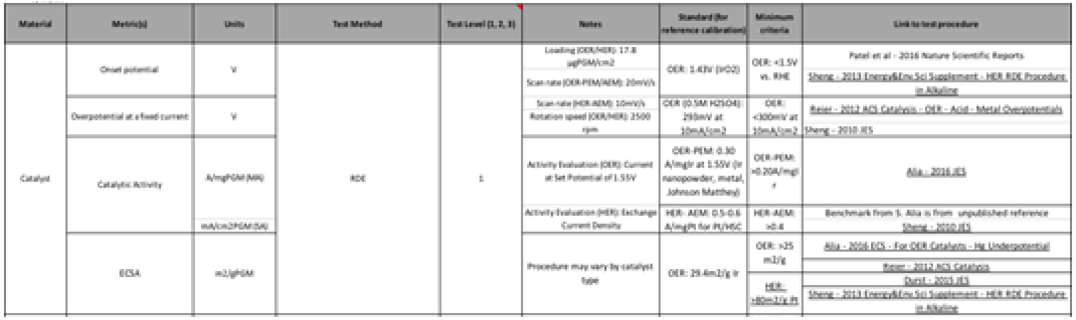
Accomplishments: Test Frameworks & Questionnaire

- A draft framework and questionnaire was developed for each water splitting technology in the HydroGEN consortium and categorized into:
  - Material Level Properties
  - Component Level Properties
  - Device Level Properties
- Feedback was solicited from nodes and the broader water splitting community
- Periodic newsletter established to update HydroGEN consortium on strategy and progress

Accomplishments: Test Frameworks: LTE (Low Temperature Electrolysis)

- Intent: Screening of new materials to determine if in-situ testing is warranted
- Established standards and minimum criteria (where available/applicable)
- Test methods based on published procedures

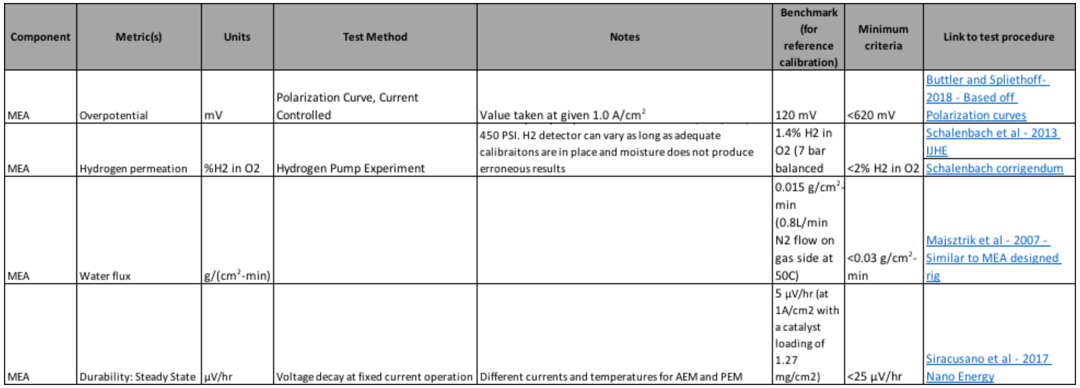
LTE: Ex-Situ Material Testing



Material	Metric(s)	Units	Test Method	Test Level (1, 2, 3)	Notes	Standard (for reference calibration)	Minimum criteria	Link to test procedure
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	Patel et al - 2016 Nature Scientific Reports Sheng - 2013 Energy&Env Sci Supplement - HER RDE Procedure in Alkaline
	Overpotential at a fixed current	V			Scan rate (HER-AEM): 10mV/s Rotation speed (OER/HER): 2500 rpm	OER (0.5M H2SO4): 293mV at 10mA/cm2	OER: <300mV at 10mA/cm2	Reier - 2012 ACS Catalysis - OER - Acid - Metal Overpotentials Sheng - 2010 JES
	Catalytic Activity	A/mgPGM (MA)			Activity Evaluation (OER): Current at Set Potential of 1.55V	OER-PEM: 0.30 A/mgIr at 1.55V (Ir nanopowder, metal, Johnson Matthey)	OER-PEM: >0.20A/mgIr	Alia - 2016 JES
		mA/cm2PGM (SA)			Activity Evaluation (HER): Exchange Current Density	HER: AEM: 0.5-0.6 A/mgPt for Pt/HSC	HER-AEM: >0.4	Benchmark from S. Alia is from unpublished reference Sheng - 2010 JES
	ECSA	m2/gPGM			Procedure may vary by catalyst type	OER: 29.4m2/g Ir	OER: >25 m2/g HER: >80m2/g Pt	Alia - 2016 ECS - For OER Catalysts - Hg Underpotential Reier - 2012 ACS Catalysis Durst - 2015 JES Sheng - 2013 Energy&Env Sci Supplement - HER RDE Procedure in Alkaline

- Intent: Test at simulated conditions for short duration in standardized sub-scale cell hardware
- Identified non-proprietary hardware and test methods

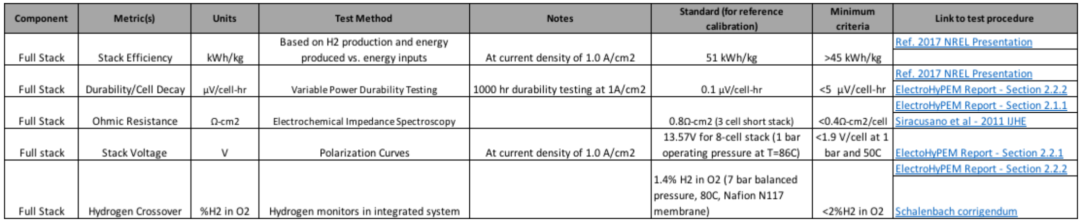
LTE: In-Situ Testing at Simulated Conditions



Component	Metric(s)	Units	Test Method	Notes	Benchmark (for reference calibration)	Minimum criteria	Link to test procedure
MEA	Overpotential	mV	Polarization Curve, Current Controlled	Value taken at given 1.0 A/cm^2	120 mV	<620 mV	Buttler and Spliethoff-2018 - Based off Polarization curves
MEA	Hydrogen permeation	%H2 in O2	Hydrogen Pump Experiment	450 PSI. H2 detector can vary as long as adequate calibraitons are in place and moisture does not produce erroneous results	1.4% H2 in O2 (7 bar balanced	<2% H2 in O2	Schalenbach et al - 2013 IJHE Schalenbach corrigendum
MEA	Water flux	g/(cm^2-min)			0.015 g/cm^2-min (0.8L/min N2 flow on gas side at 50C)	<0.03 g/cm^2-min	Majsztrik et al - 2007 - Similar to MEA designed rig
MEA	Durability: Steady State	µV/hr	Voltage decay at fixed current operation	Different currents and temperatures for AEM and PEM	5 µV/hr (at 1A/cm2 with a catalyst loading of 1.27 mg/cm2)	<25 µV/hr	Siracusano et al - 2017 Nano Energy

- Intent: Test at realistic operating conditions for extended duration in OEM cell stack hardware
- Established test methods and criteria for evaluation

LTE: In-Situ Testing at Operating Conditions



Component	Metric(s)	Units	Test Method	Notes	Standard (for reference calibration)	Minimum criteria	Link to test procedure
Full Stack	Stack Efficiency	kWh/kg	Based on H2 production and energy produced vs. energy inputs	At current density of 1.0 A/cm2	51 kWh/kg	>45 kWh/kg	Ref. 2017 NREL Presentation
Full Stack	Durability/Cell Decay	µV/cell-hr	Variable Power Durability Testing	1000 hr durability testing at 1A/cm2	0.1 µV/cell-hr	<5 µV/cell-hr	Ref. 2017 NREL Presentation ElectroHyPEM Report - Section 2.2.2
Full Stack	Ohmic Resistance	Ω-cm2	Electrochemical Impedance Spectroscopy		0.8Ω-cm2 (3 cell short stack)	<0.4Ω-cm2/cell	ElectroHyPEM Report - Section 2.1.1 Siracusano et al - 2011 IJHE
Full stack	Stack Voltage	V	Polarization Curves	At current density of 1.0 A/cm2	13.57V for 8-cell stack (1 bar operating pressure at T=86C)	<1.9 V/cell at 1 bar and 50C	ElectoHyPEM Report - Section 2.2.1 ElectroHyPEM Report - Section 2.2.2
Full Stack	Hydrogen Crossover	%H2 in O2	Hydrogen monitors in integrated system		1.4% H2 in O2 (7 bar balanced pressure, 80C, Nafion N117 membrane)	<2%H2 in O2	Schalenbach corrigendum

*Tables truncated for clarity

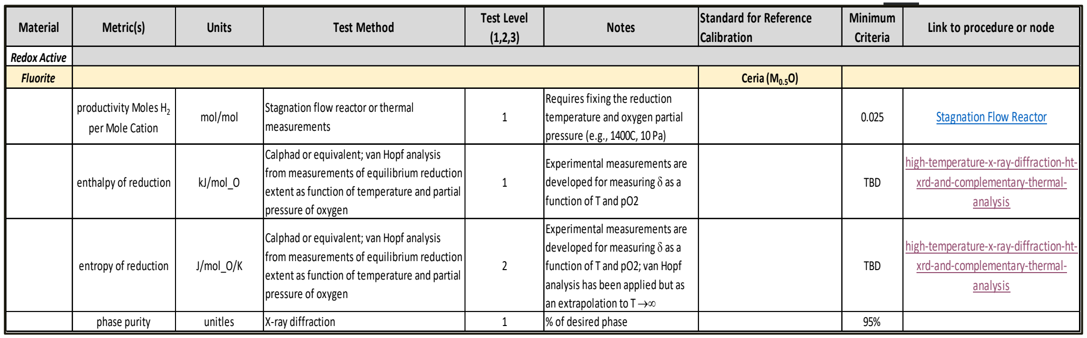
Accomplishments: Test Frameworks: STCH (Solar ThermoChemical H_2)

- Intent: Screening of new materials to determine if further testing is warranted
- Established standards for each materials class
- Establish normalization of formula unit; for example on one metal cation or one oxygen
- Test methods build on literature results and node capabilities

- At least three and perhaps more materials classes, with standards for each class of the fundamental functional material: the redox active metal oxides
- Fluorites ½ AO_2, Perovskites $^1/_3$ ABO_3, Spinels, Normal and Inverse ¼ AB_2O_4, and others, e.g. Pyrochlores $^1/_7$ ($A_2B_2O_7$)

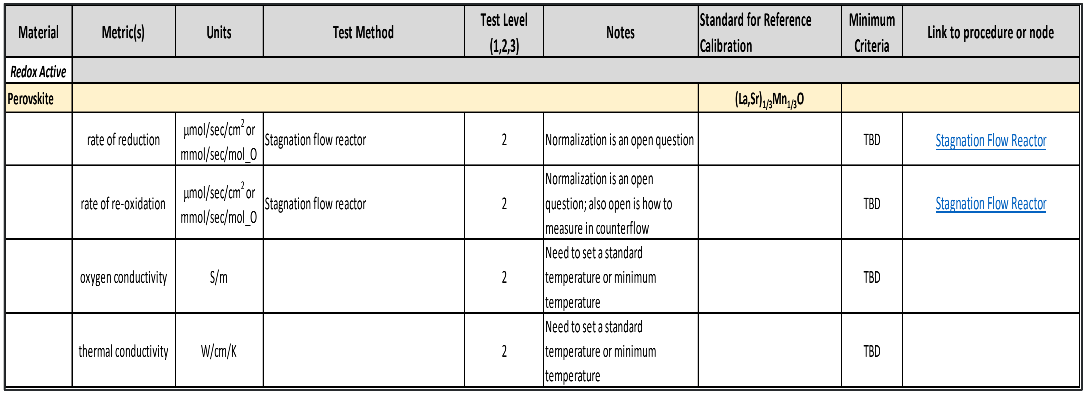
- Intent: Take into account actual operating conditions and/or operating cycle for extended duration as feasible
- Established sets of standardized operating conditions

STCH: Ex-Situ Material Testing: Fluorites, e.g. $Ce_{1/2}O$



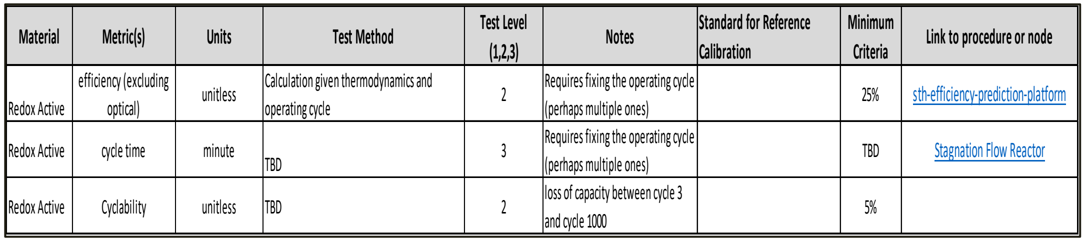
Material	Metric(s)	Units	Test Method	Test Level (1,2,3)	Notes	Standard for Reference Calibration	Minimum Criteria	Link to procedure or node
Redox Active								
Fluorite						Ceria ($M_{0.5}O$)		
	productivity Moles H_2 per Mole Cation	mol/mol	Stagnation flow reactor or thermal measurements	1	Requires 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		95%	

STCH: Ex-Situ Material Testing: Perovskites, e.g. $(La,Sr)_{1/3}Mn_{1/3}O$



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								
Perovskite						$(La,Sr)_{1/3}Mn_{1/3}O$		
	rate of reduction	μmol/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	μmol/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	

STCH: In-Situ Testing at Operating Conditions



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	efficiency (excluding optical)	unitless	Calculation given thermodynamics and operating cycle	2	Requires fixing the operating cycle (perhaps multiple ones)		25%	sth-efficiency-prediction-platform
Redox Active	cycle time	minute	TBD	3	Requires fixing the operating cycle (perhaps multiple ones)		TBD	Stagnation Flow Reactor
Redox Active	Cyclability	unitless	TBD	2	loss of capacity between cycle 3 and cycle 1000		5%	

Accomplishments: Test Frameworks: HTE (High Temperature Electrolysis)

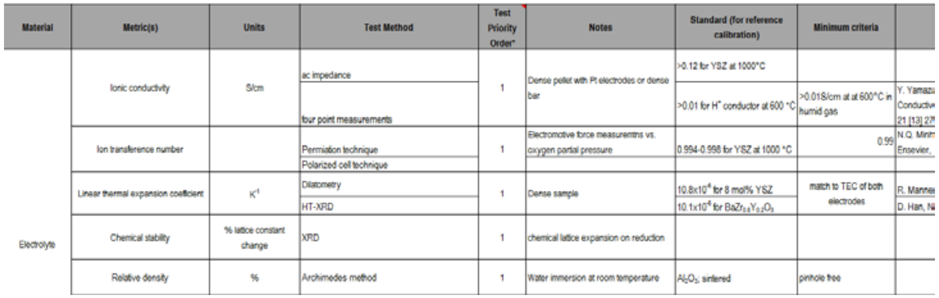
Test Framework

- Ex-situ Material and Component Characterization: identify standards, reference materials, test techniques, experimental conditions, and comparison criteria
- In-situ *S*ingle Cell Test: compare protocols, operating conditions, safety aspects, and lessons learned for effective lab scale testing
- In-situ *S*tack Testing: protocol search, identify critical parameters, review and employ best practices and appropriate emergency measures. Validate protocols with industry

HTE Questionnaire

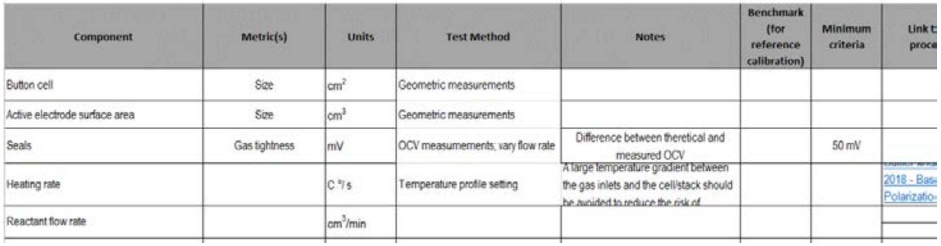
- Assemble multiple choice survey questions on standard materials, single cell choice and standard operating conditions for benchmarking HTE materials and devices
- Seek solicited collaborative efforts with lab nodes

HTE: Ex-Situ Materials Characterization



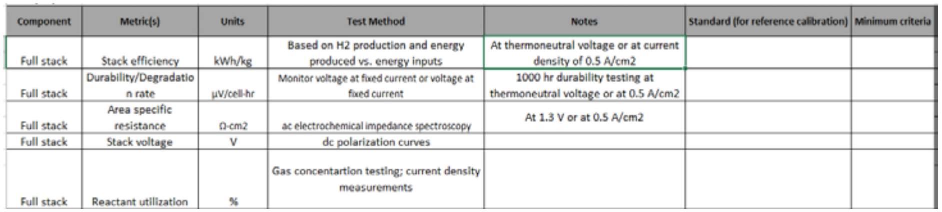
Material	Metric(s)	Units	Test Method	Test Priority Order*	Notes	Standard (for reference calibration)	Minimum criteria	
Electrolyte	Ionic conductivity	S/cm	ac impedance four point measurements	1	Dense pellet with Pt electrodes or dense bar	>0.12 for YSZ at 1000°C >0.01 for H^+ conductor at 600 °C	>0.01S/cm at at 600°C in humid gas	Y. Yamaz Conductiv 21 [13] 27
	Ion transference number		Permiation technique Polarized cell technique	1	Electromotive force measurenmtns vs. oxygen partial pressure	0.994-0.998 for YSZ at 1000 °C	0.99	N.Q. Mini Ensevier,
	Linear thermal expansion coefficient	K^{-1}	Dilatometry HT-XRD	1	Dense sample	$10.8x10^{-6}$ for 8 mol% YSZ $10.1x10^{-6}$ for $BaZr_{0.8}Y_{0.2}O_3$	match to TEC of both electrodes	R. Manne D. Han, N
	Chemical stability	% lattice constant change	XRD	1	chemical lattice expansion on reduction			
	Relative density	%	Archimedes method	1	Water immersion at room temperature	Al_2O_3; sintered	pinhole free	

HTE: In-Situ Testing Under Simulated Conditions



Component	Metric(s)	Units	Test Method	Notes	Benchmark (for reference calibration)	Minimum criteria	Link t proce
Button cell	Size	cm^2	Geometric measurements				
Active electrode surface area	Size	cm^3	Geometric measurements				
Seals	Gas tightness	mV	OCV measumements; vary flow rate	Difference between theretical and measured OCV		50 mV	
Heating rate		C °/ s	Temperature profile setting	A large temperature gradient between the gas inlets and the cell/stack should be avoided to reduce the risk of			2018 - Bas Polarizatio
Reactant flow rate		cm^3/min					

HTE: In-Situ Stack Testing



Component	Metric(s)	Units	Test Method	Notes	Standard (for reference calibration)	Minimum criteria
Full stack	Stack efficiency	kWh/kg	Based on H2 production and energy produced vs. energy inputs	At thermoneutral voltage or at current density of 0.5 A/cm2		
Full stack	Durability/Degradation rate	µV/cell-hr	Monitor voltage at fixed current or voltage at fixed current	1000 hr durability testing at thermoneutral voltage or at 0.5 A/cm2		
Full stack	Area specific resistance	Ω-cm2	ac electrochemical impedance spectroscopy	At 1.3 V or at 0.5 A/cm2		
Full stack	Stack voltage	V	dc polarization curves			
Full stack	Reactant utilization	%	Gas concentartion testing; current density measurements			

Accomplishments: Test Frameworks: PEC (Photo Electrochemical Electrolysis)

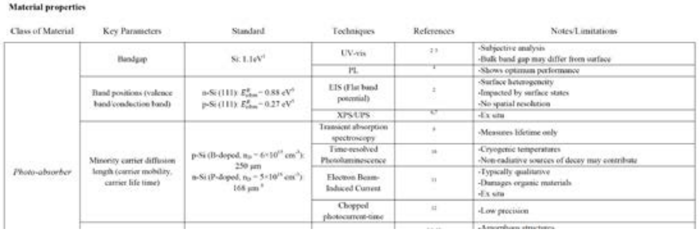
PEC questionnaire

- Included three theme questions that help inform new guidelines for benchmarking PEC materials and devices and enable effective comparisons across research community.
- Included open questions that address the pressing needs for PEC water-splitting and solicited collaborative efforts with lab nodes.

PEC Test Framework

- Test framework was categorized into Materials level, Component level and Device level testing and benchmarking.
  - Materials level included photo-absorbers, catalysts, protective layers, electrolytes (liquid or polymer).
  - Component level included photoelectrodes, transport component and auxiliary component.
  - Device level included key performance parameters at various operating conditions.
- Characterization techniques, literature standards and notes/limitations were also included in the test framework.

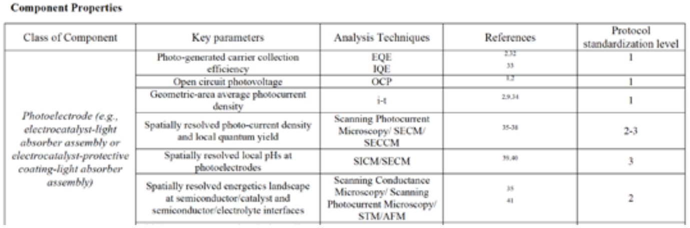
PEC-materials level



Material properties

Class of Material	Key Parameters	Standard	Techniques	References	Notes/Limitations
Photo-absorber	Bandgap	Si: 1.1eV[1]	UV-vis	2,3	-Subjective analysis -Bulk band gap may differ from surface
			PL	4	-Shows optimum performance
	Band positions (valence band/conduction band)	n-Si (111): E^{g}_{vbm} ~ 0.88 eV[5] p-Si (111): E^{g}_{vbm} ~ 0.27 eV[5]	EIS (Flat band potential)	2	-Surface heterogeneity -Impacted by surface states -No spatial resolution
			XPS/UPS	6,7	-Ex situ
	Minority carrier diffusion length (carrier mobility, carrier life time)	p-Si (B-doped, n_D ~ 6×10^{15} cm^{-3}): 250 μm n-Si (P-doped, n_D ~ 5×10^{15} cm^{-3}): 168 μm[9]	Transient absorption spectroscopy	8	-Measures lifetime only
			Time-resolved Photoluminescence	10	-Cryogenic temperatures -Non-radiative sources of decay may contribute
			Electron Beam-Induced Current	11	-Typically qualitative -Damages organic materials -Ex situ
			Chopped photocurrent-time	12	-Low precision

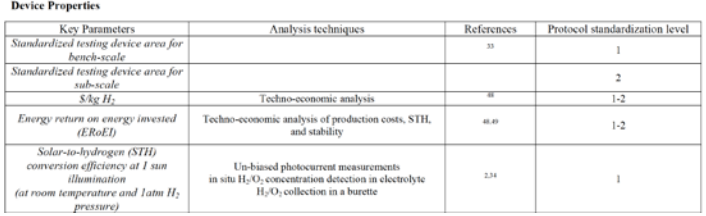
PEC-component level



Component Properties

Class of Component	Key parameters	Analysis Techniques	References	Protocol standardization level
Photoelectrode (e.g., electrocatalyst-light absorber assembly or electrocatalyst-protective coating-light absorber assembly)	Photo-generated carrier collection efficiency	EQE IQE	2,32 33	1
	Open circuit photovoltage	OCP	1,2	1
	Geometric-area average photocurrent density	i-t	2,9,34	1
	Spatially resolved photo-current density and local quantum yield	Scanning Photocurrent Microscopy/ SECM/ SECCM	35-38	2-3
	Spatially resolved local pHs at photoelectrodes	SICM/SECM	39,40	3
	Spatially resolved energetics landscape at semiconductor/catalyst and semiconductor/electrolyte interfaces	Scanning Conductance Microscopy/ Scanning Photocurrent Microscopy/ STM/AFM	35 41	2

PEC-device level



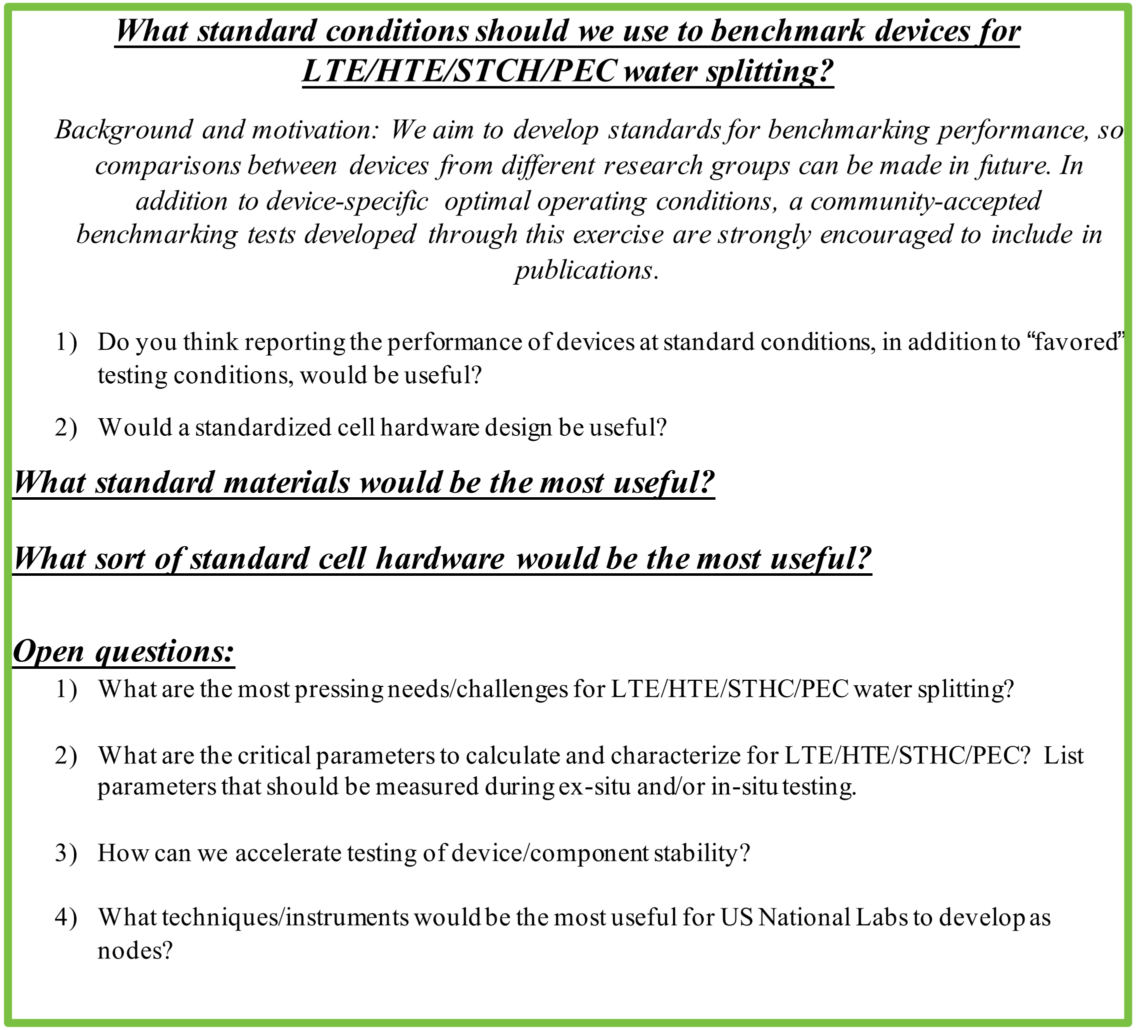
Device Properties

Key Parameters	Analysis techniques	References	Protocol standardization level
Standardized testing device area for bench-scale		33	1
Standardized testing device area for sub-scale			2
$/kg H_2	Techno-economic analysis	48	1-2
Energy return on energy invested (ERoEI)	Techno-economic analysis of production costs, STH, and stability	48,49	1-2
Solar-to-hydrogen (STH) conversion efficiency at 1 sun illumination (at room temperature and 1atm H_2 pressure)	Un-biased photocurrent measurements in situ H_2/O_2 concentration detection in electrolyte H_2/O_2 collection in a burette	2,34	1

Accomplishments: Questionnaires

- A questionnaire was developed for each water splitting technology
- Specific choices were provided for standards:
  - Materials
  - Test hardware
- Feedback will be reviewed to reach a common set of standards

Excerpt from Questionnaire



<u>What standard conditions should we use to benchmark devices for LTE/HTE/STCH/PEC water splitting?</u>

Background and motivation: We aim to develop standards for benchmarking performance, so comparisons between devices from different research groups can be made in future. In addition to device-specific optimal operating conditions, a community-accepted benchmarking tests developed through this exercise are strongly encouraged to include in publications.

1) Do you think reporting the performance of devices at standard conditions, in addition to “favored” testing conditions, would be useful?
2) Would a standardized cell hardware design be useful?

<u>What standard materials would be the most useful?</u>

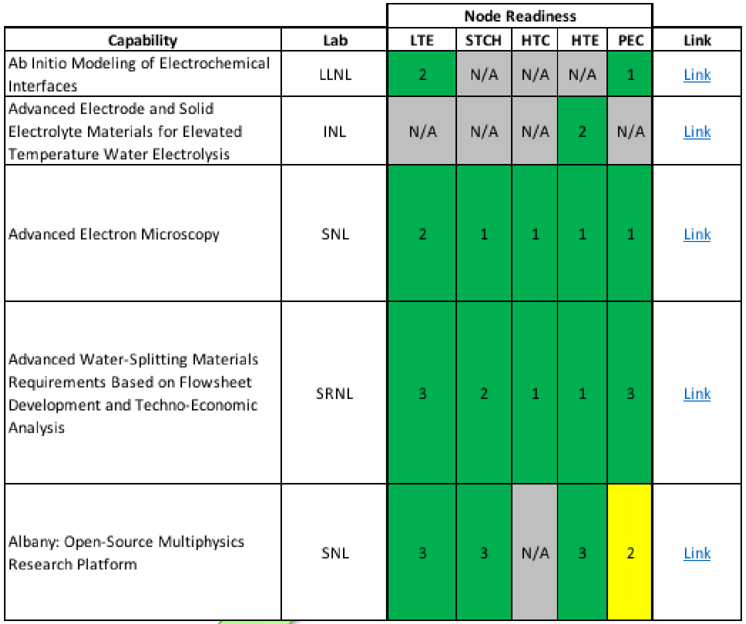
<u>What sort of standard cell hardware would be the most useful?</u>

<u>Open questions:</u>

1) What are the most pressing needs/challenges for LTE/HTE/STHC/PEC water splitting?
2) What are the critical parameters to calculate and characterize for LTE/HTE/STHC/PEC? List parameters that should be measured during ex-situ and/or in-situ testing.
3) How can we accelerate testing of device/component stability?
4) What techniques/instruments would be the most useful for US National Labs to develop as nodes?

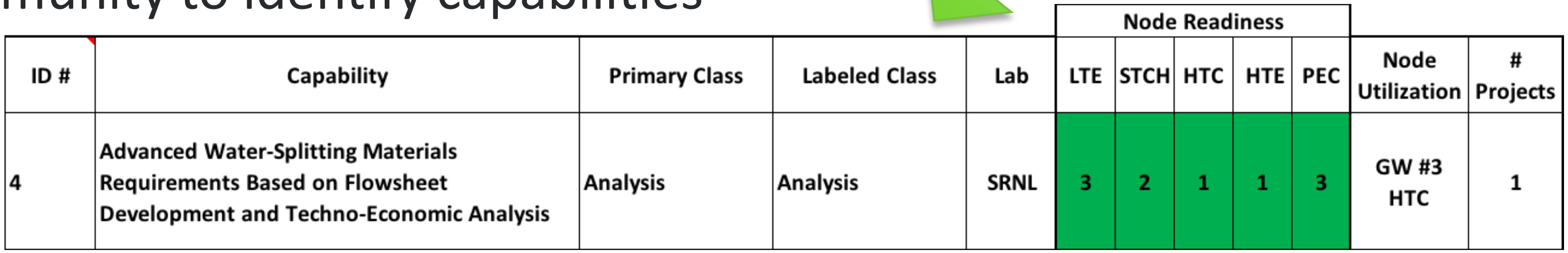
Accomplishments: Capabilities Assessment

- All HydroGEN Node capabilities were assessed for applicability and readiness level for each AWS technology
- Coordination with node leads to clarify and re-assess readiness as needed
- Reviewed with HydroGEN Steering Committee to ensure H2AWSM website updates are implemented
- A consolidated table was created to serve as a resource for the broad water splitting community to identify capabilities



Capability	Lab	Node Readiness LTE	STCH	HTC	HTE	PEC	Link
Ab Initio Modeling of Electrochemical Interfaces	LLNL	2	N/A	N/A	N/A	1	Link
Advanced Electrode and Solid Electrolyte Materials for Elevated Temperature Water Electrolysis	INL	N/A	N/A	N/A	2	N/A	Link
Advanced Electron Microscopy	SNL	2	1	1	1	1	Link
Advanced Water-Splitting Materials Requirements Based on Flowsheet Development and Techno-Economic Analysis	SRNL	3	2	1	1	3	Link
Albany: Open-Source Multiphysics Research Platform	SNL	3	3	N/A	3	2	Link

*Truncated list



ID #	Capability	Primary Class	Labeled Class	Lab	Node Readiness LTE	STCH	HTC	HTE	PEC	Node Utilization	# Projects
4	Advanced Water-Splitting Materials Requirements Based on Flowsheet Development and Techno-Economic Analysis	Analysis	Analysis	SRNL	3	2	1	1	3	GW #3 HTC	1

Budget Period 1 Outlook

- Project is on track to meet BP 1 milestones
- Remaining tasks
  - Task 1: Incorporate feedback from broad water splitting research community, finalize test frameworks
  - Task 2: Finalize assessment of EMN Node capabilities, update H2AWS website
  - Task 3: Using input from Task 1, begin development of test protocols. Hold project meeting to report results, solicit additional inputs
- Impact on water splitting research community
  - Identification of capabilities within nodes
  - Provide outline of test methods and criteria for characterizing and benchmarking new materials

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
  - Recommend standards, protocols, and priorities
  - Assemble themes into cohesive strategy
  - 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
- Total Budget: $2.2 million (over 3 years, including Lab funding)

Milestone #	Project Milestones	Completion Date
3.1	Assessment of relevant operational conditions for field use completed.	6/30/2019
3.2	Recommended accelerated testing protocol including defining how the protocols address known degradation mechanisms.	3/31/2020
3.3.1	Gap assessment on capabilities within EMN / R&D community for field simulations and long term reliability testing completed.	12/31/2019
3.3.2	Field test sites and requirements for subscale testing within EMN and expert sites established/recommended.	6/30/2020

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
- Accomplishments:
  - Draft framework and questionnaire was developed in collaboration with lab node experts and experts for each water splitting technology in the HydroGEN consortium
  - All HydroGEN capabilities were assessed for applicability and readiness level
- Future work:
  - Protocol validation, accelerated test development, and capabilities gap assessment