Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

# HydroGEN: Low Temperature Electrolysis


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**National Renewable Energy Laboratory**


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DOE Hydrogen Program 2021 Annual Merit Review and Peer Evaluation Meeting

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# Overview - LTE Technology Relevance / Impact

**Proton exchange membrane (PEM)**

- Gas Crossover
- Membranes
- Catalyst Materials
- Catalyst Loading
- PTL Materials

**Anion exchange membrane (AEM)**

- Membranes
- Catalyst
- Ionomer
- Electrolyte feed
- BOP Materials

**Common Barriers**

- Material Integration
- Material Cost
- Understanding Interfaces and Interactions

**BOP – Balance of Plant**
**PTL – Porous Transport Layers**

# Approach: HydroGEN 2.0 Project Added to LTE Activities

## HydroGEN LTE Projects

- 8 FOA projects with 41 nodes
  - 3 currently supported (in Accomplishments)
  - 5 with closeout contributions (in Technical Backup)
- 2 Supernodes with 14 nodes
- LTE 2.0 with 4 nodes

**LTE Node Labs**

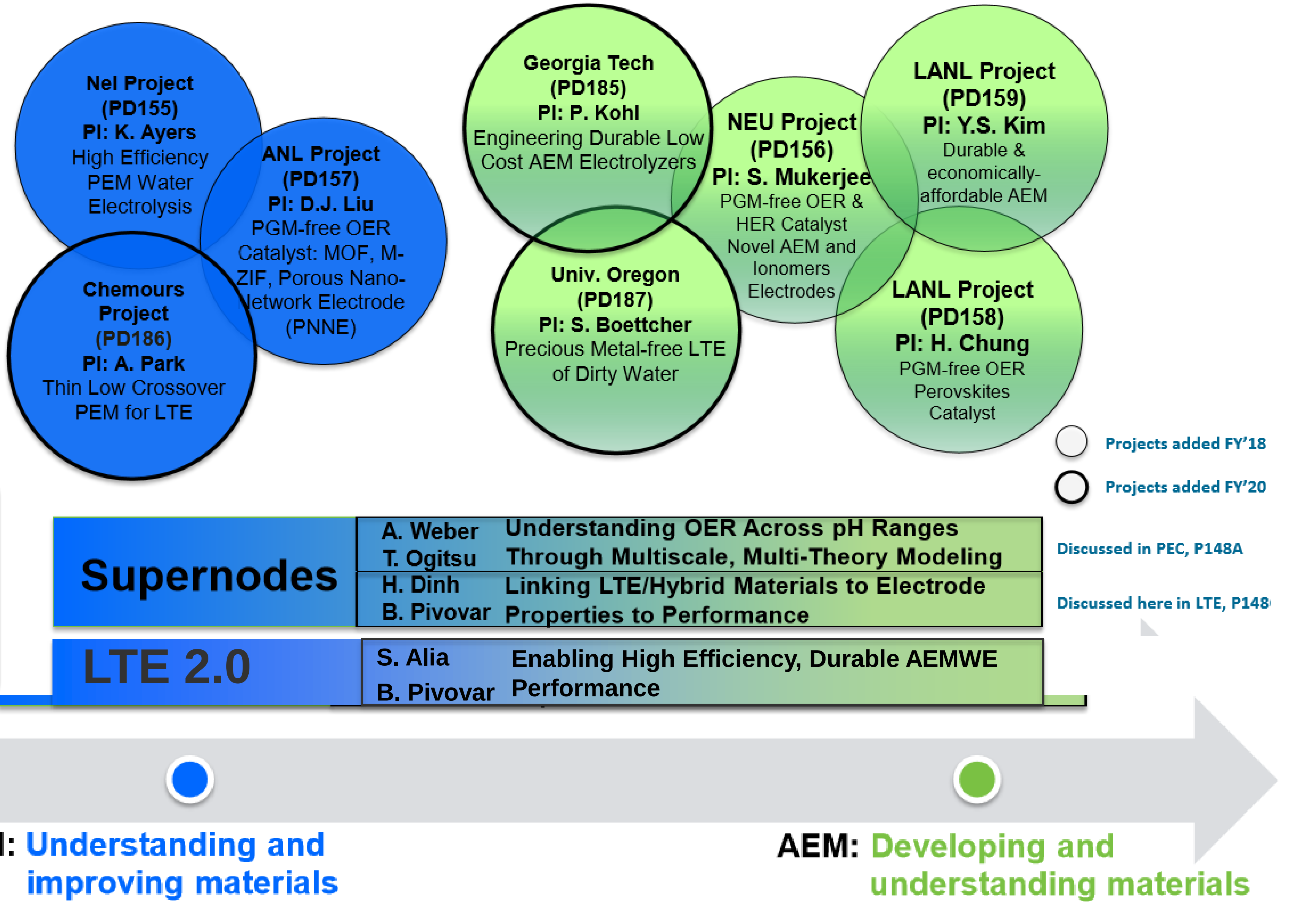
NREL
Berkeley Lab
Sandia National Laboratories
Lawrence Livermore National Laboratory

**Support through:**

Personnel
Equipment
Expertise
Capability
Materials
Data

**LTE FOA Projects**

nel
Argonne National Laboratory
Northeastern University
Los Alamos National Laboratory (2)
Georgia Institute of Technology
University of Oregon
Chemours



# Collaboration and Coordination - HydroGEN LTE Node Utilization

| Lab | Node | 2.0 | Super | Chemours | GT | Oregon | NEL | ANL | NEU | LANL1 | LANL2 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LLNL | Computational Materials Diagnostics and Optimization of PEC Devices | | | | | | | ✓ | | | | 1 |
| LBNL | DFT and Ab Initio Calculations | | | | | | | ✓ | | ✓ | | 2 |
| LBNL | Multiscale Modeling of Water-Splitting Devices | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | 7 |
| SNL | LAMMPS | | | | | | | | ✓ | | | 1 |
| NREL | Electronic-Structure Modeling for Atomistic Understanding of Catalytic Materials | ✓ | | | | | | | | | | 1 |
| NREL | Novel Membrane Fabrication | | ✓ | | | ✓ | ✓ | | ✓ | | | 4 |
| SNL | Separators for Hydrogen Production | | | | | ✓ | | | | ✓ | ✓ | 3 |
| NREL | Multi-Comp. Ink Development, High-Throughput Fabrication, & Scaling | | ✓ | | ✓ | | ✓ | ✓ | ✓ | | | 5 |
| SNL | Advanced Electron Microscopy | | | | | | | ✓ | | | | 1 |
| NREL | Catalyst Synthesis, Ex situ Characterization & Standardization | | ✓ | | | | ✓ | ✓ | | | | 3 |
| LBNL | Ionomer Characterization and Understanding | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | | ✓ | 7 |
| NREL | In Situ Testing Capabilities | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | 9 |
| LBNL | Understanding Inks and Ionomer Disp. | | ✓ | | | ✓ | | | | | | 2 |
| SNL | Near Ambient Pressure E-XPS | | | | | | | | | ✓ | | 1 |
| NREL | Surface Analysis Cluster Tool | | | | | | | ✓ | | ✓ | | 2 |
| LBNL | Probing and Mitigating Corrosion | | | | | | ✓ | | | | | 1 |
| LBNL | PEC In Situ Testing using X-Rays | | | | | | | | | ✓ | | 1 |
| LBNL | Water Splitting Device Testing | | | | | | | | | | ✓ | 1 |
| SRNL | Fabrication and Characterization of Components for $H_2$ Production | | ✓ | | | | | | | | | 1 |

**Nodes**

- Computation
- Materials Synthesis
- Processing and Scale Up
- Characterization

# LTE Supernode Approach:

## Linking LTE/Hybrid Materials to Electrode Properties to Performance

**Goals:** Create true understanding between *ex-situ* and *in-situ* performance. Identify how material properties are linked to electrode properties and how these are linked to electrolyzer performance.

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**8 Nodes**

Materials selection **PEM** **AEM**

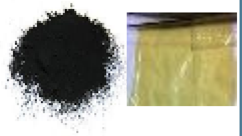
- Electrocatalyst ex-situ characterization **(NREL)**
- Ionomer thin films **(LBNL)**
- Modeling **(LBNL)**
- Polymers and Membranes **(NREL)**

- Catalyst-Ionomer-solvent Interactions: Ink properties **(NREL, LBNL)**
- Electrode Fabrication **(NREL)**
- Catalyst-Ionomer Interactions: Electrode properties **(NREL)**

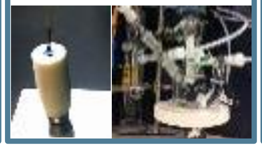
- In situ Cell testing **(NREL, SRNL)**
- Multiscale Electrolysis Model **(LBNL)**

**Materials** → **Devices**

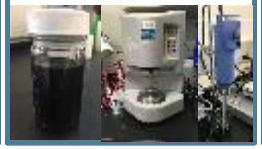
**Materials:** Catalyst, Ionomer & Membranes



**Electrochemical Characterization** Catalyst



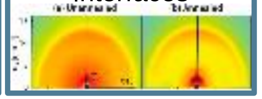
**Ink Composition** Catalyst, Ionomer & Solvents



**MEA Integration** Fabrication in Parameter Space

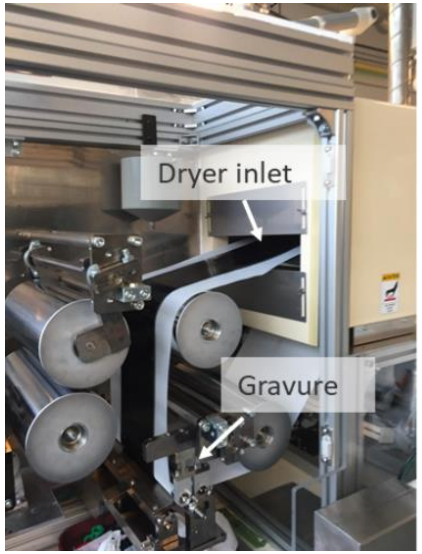
**Performance Evaluation** In-Situ PEM, AEM

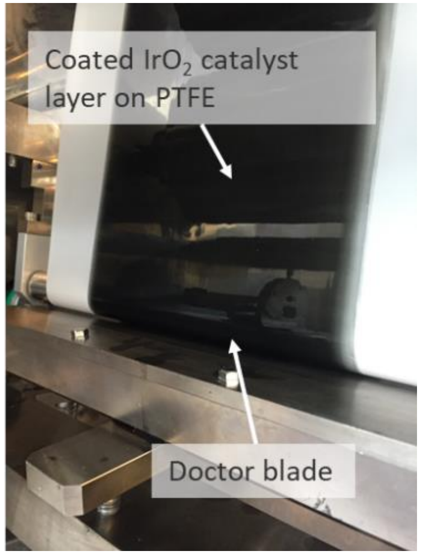
**Advanced Characterization** Morphology, Material Properties, Interfaces

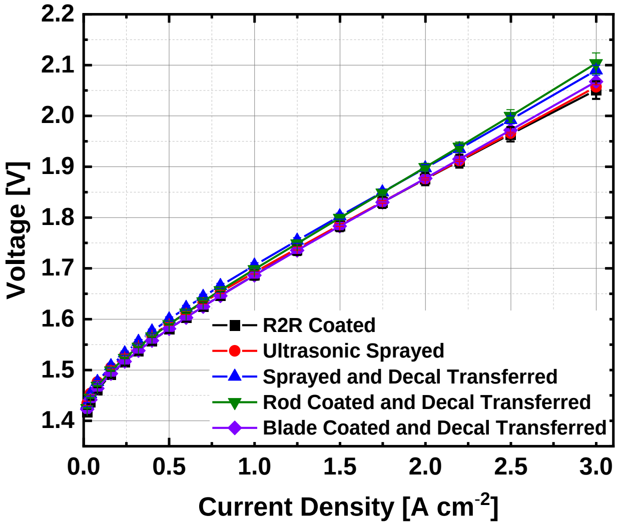


# LTE Supernode Accomplishments:

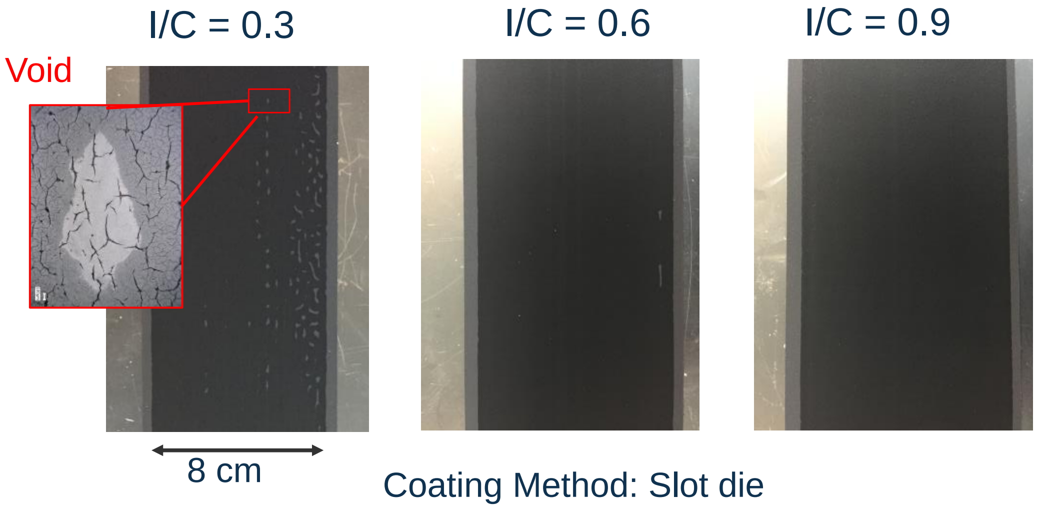
## Roll-to-roll Performance (R2R), Ionomer Impact on Coating Quality




- Demonstrated scalable electrode fabrication methods with similar performance to lab-scale methods
- R2R-coated anodes have high loading uniformity and are defect free




Coating Method: Slot die
Pt loading: 0.3 mg/cm$^2$
Substrate: SGL 29BC

| I/C | Notes |
|---|---|
| 0.3 | Numerous voids |
| 0.6 | Sporadic voids |
| 0.9 | Highly uniform |

Showed that increasing ionomer to carbon ratio (I/C) leads to improved coating quality, likely due to better dispersion of Pt/C

# LTE Supernode Accomplishments:
## Hybrid Cycle, Ionomer Impact on Performance

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$H_2SO_4 \rightarrow H_2O + SO_2 + 1/2\ O_2$

**Thermochemical: 800-900 °C**

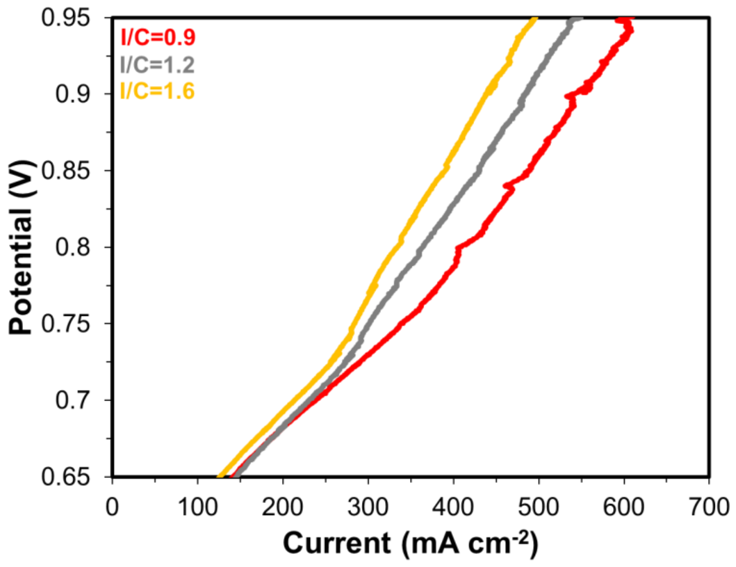
$SO_2 + 2\ H_2O \leftrightarrow H_2SO_4 + H_2$

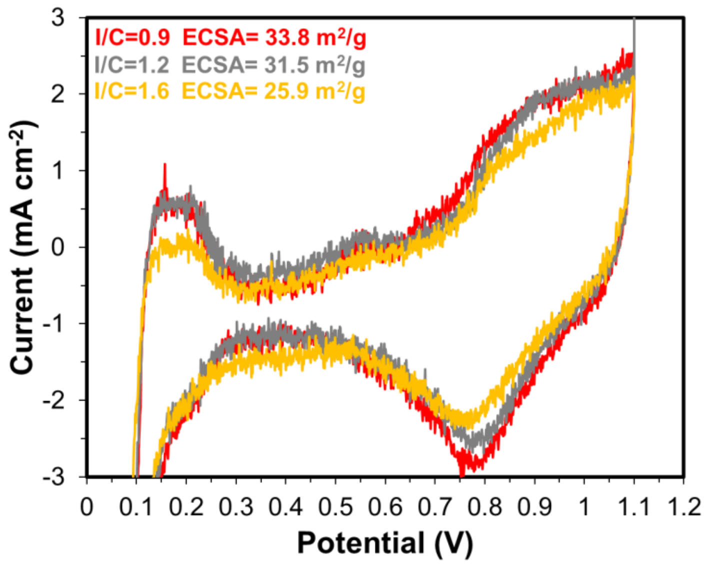
**Electrochemical: 80-140 °C**

**-0.172 V vs SHE (30 wt% & 20 °C)**

$H_2O \rightarrow H_2 + {}^1/_2\ O_2$

**Net Reaction**




- Optimization of ionomer content allows for improved electrode design
- Increasing the I:C ratio significantly impact the high current density region
- Decrease in performance can be partially attributed to lower available electrochemical surface area

# LTE 2.0 Approach:

## Enabling High Efficiency, Durable AEM Electrolysis Performance



Goals: Determine the role of the supporting electrolyte and the limiting factors behind water operation in AEM electrolysis.

- Evaluate AEM's ability to approach PEM performance/durability in water feeds, leveraging component development efforts in seedling projects
- Examine ionomer-electrolyte effects, how the ionomer's interaction with charged species enhances or diminishes catalytic activity
- Elucidate the role of conformational disorder and molecular motions to changes in catalyst activity via *ab initio* molecular dynamics simulations of the ionomer in contact with the catalyst surface.

| | |
|---|---|
| **State of the Art (Point A)** | Overvoltage for AEMWE operation with DI water is in excess of 100 mV of Nafion 112 at 2 A/cm$^2$. |
| **End of Project Milestone (Point B)** | Demonstrate overvoltage for AEMWE operation with deionized water that is within 50 mV of Nafion 112 at 2 A/cm$^2$. Demonstrate an overvoltage increase for AEMWE operation with deionized water that is within 0.15 mV/h during 500 h of operation at 1 A/cm$^2$. (NREL, LBNL) |

Point A: at the beginning of the project (October 2020)
Point B: at end of project (3 years)

# LTE 2.0 Approach:
## Linking Modeling, Characterization, and Performance

4 Nodes

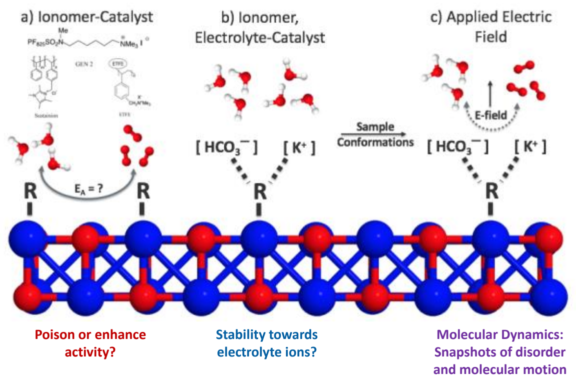
Materials Selection

- Electronic Structure Modeling **(NREL)**
- Ionomer Thin Films **(LBNL)**

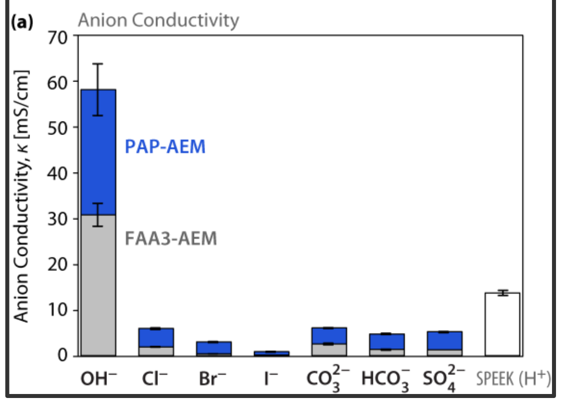
- In situ Cell Testing **(NREL)**
- Multiscale Model **(LBNL)**

**Materials** → **Devices**

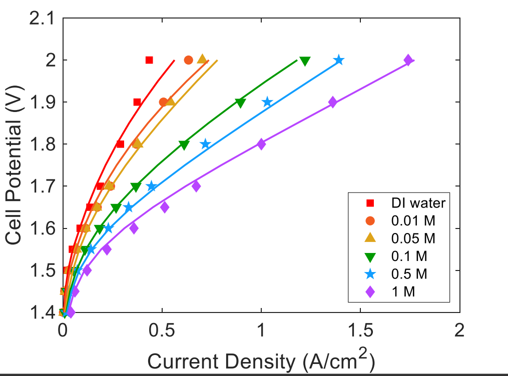
**Materials Properties:** Catalyst



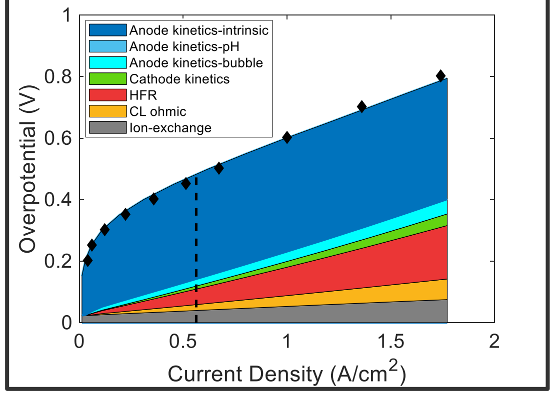

**Materials Properties:** Membrane




**Device:** Performance




**Device:** Analysis



# LTE 2.0 Accomplishments:

## Understanding Ionomer-Electrolyte Effects on Alkaline Oxygen Evolution

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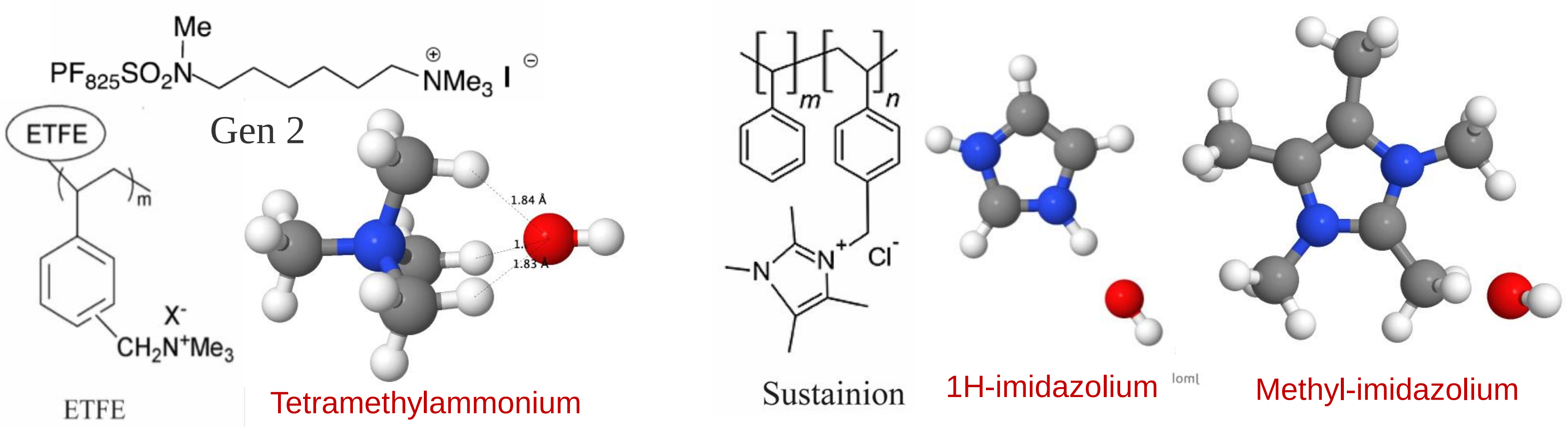
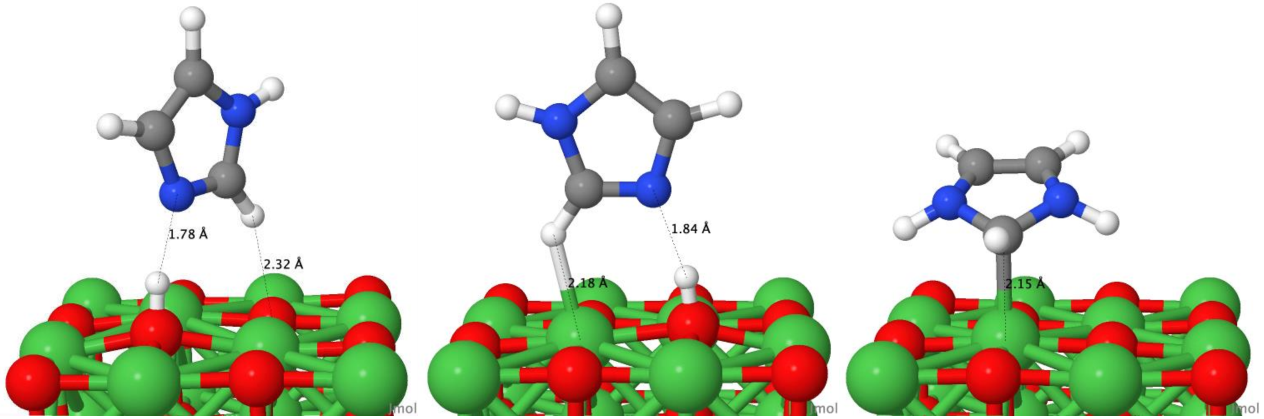
### Electronic-Structure Modeling

Approximate Ionomer with Smaller Organic Fragments: Gain insights into how $N^+R$ group may transport $OH^-$ to catalyst




Ionomer-Catalyst Interactions: $N^+R$ group can poison activity by blocking sites or influence catalysis by aiding $OH^-$ to catalyst

$E_{ads}$ (eV) = -1.27 | $E_{ads}$ (eV) = -1.23 | $E_{ads}$ (eV) = -1.22




**Preliminary calculations on (2x2) NiO (100) indicate:**

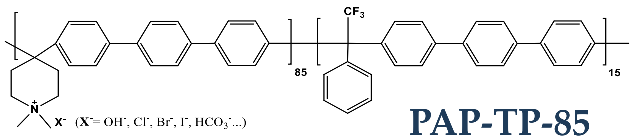
- Imidazolium *more weakly bound* than OH* ($E_{ads}$ = -2.12 eV)
- $N^+R$ group can *react with surface* via deprotonation, supply protons

# LTE 2.0 Accomplishments:

## Membrane Hydration, Structure, and Conductivity

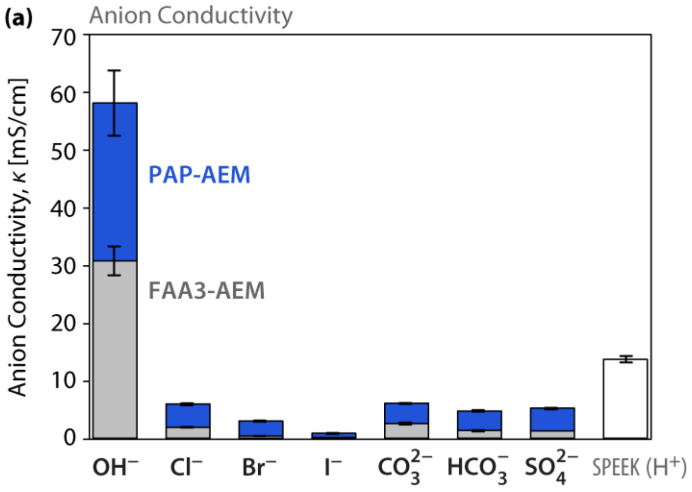
4 Nodes

- Anion form impacts hydration and conductivity

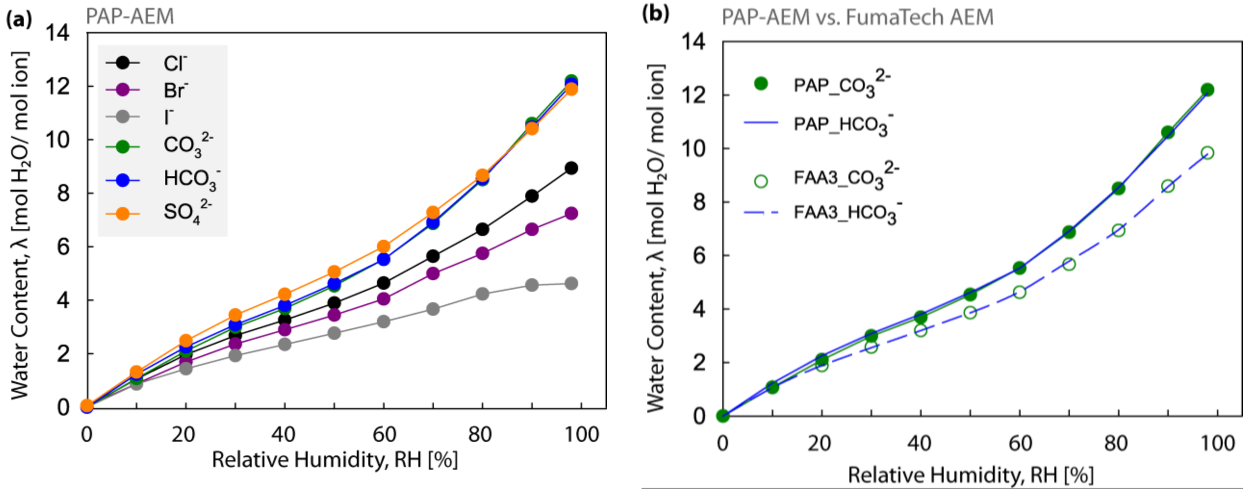


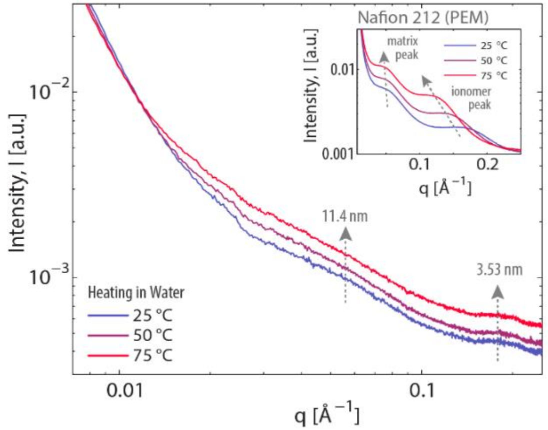

**PAP-TP-85**

  - PAP-AEM has higher conductivity than FAA3
  - Conductivity is strongly impacted by anion size
- The nano-morphology <u>does NOT</u> change with hydration, counter-ion, and temperature




Conductivity in water in various anion forms: Higher conductivity of PAP-AEM (in blue) compared to FAA3



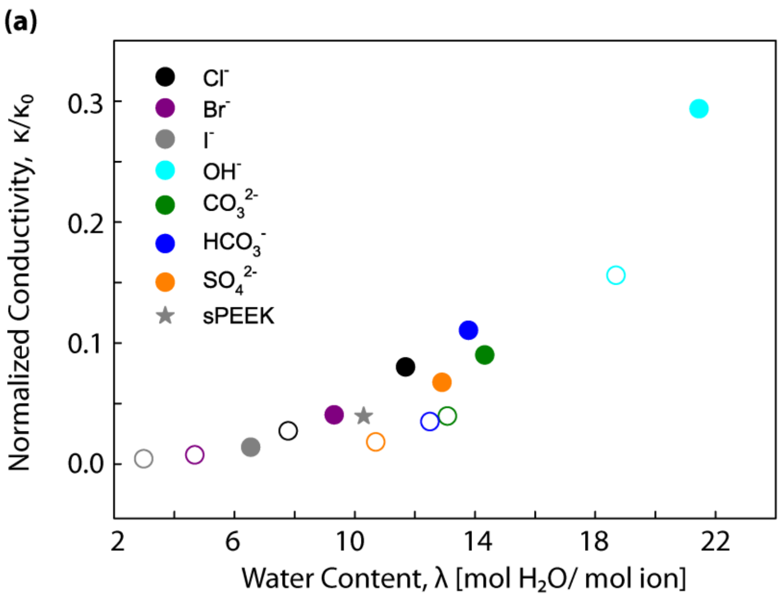



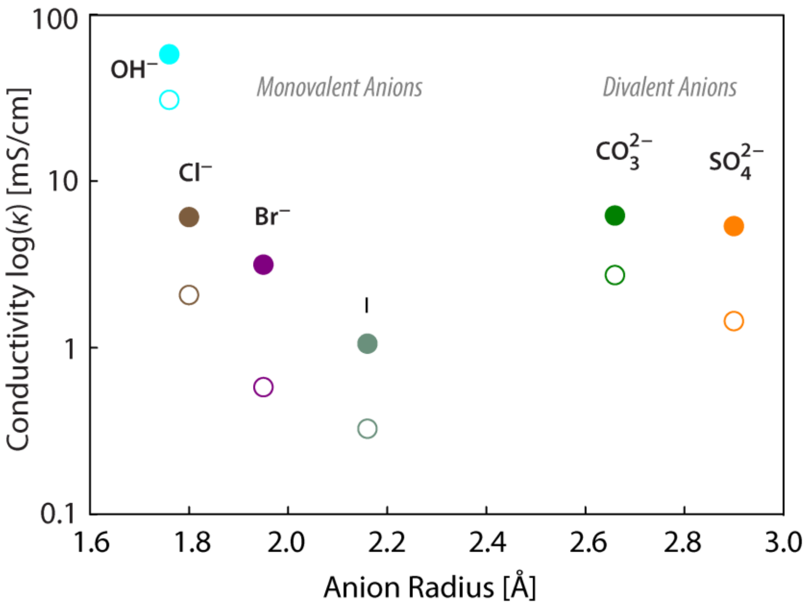

X. Luo, S. Rojas-Carbonell, Y. Yan, A. Kusoglu, *Structure-transport relationships of poly(aryl piperidinium) anion-exchange membranes: Effect of anions and hydration*, ***J. Membrane Science***, 598 (**2020**) 117680.

# LTE 2.0 Accomplishments:
## Membrane Hydration Governs Conductivity

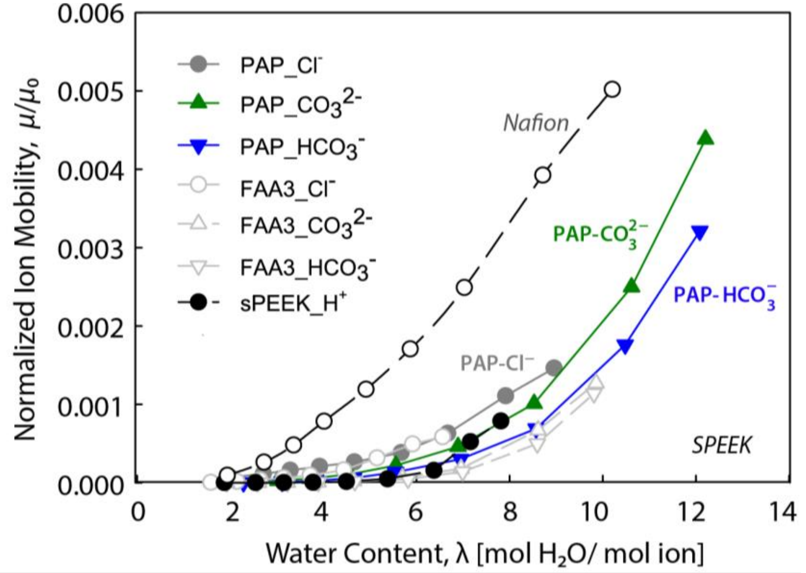


**Conductivity increases with hydration for all anion forms (PAP: closed symbols)**



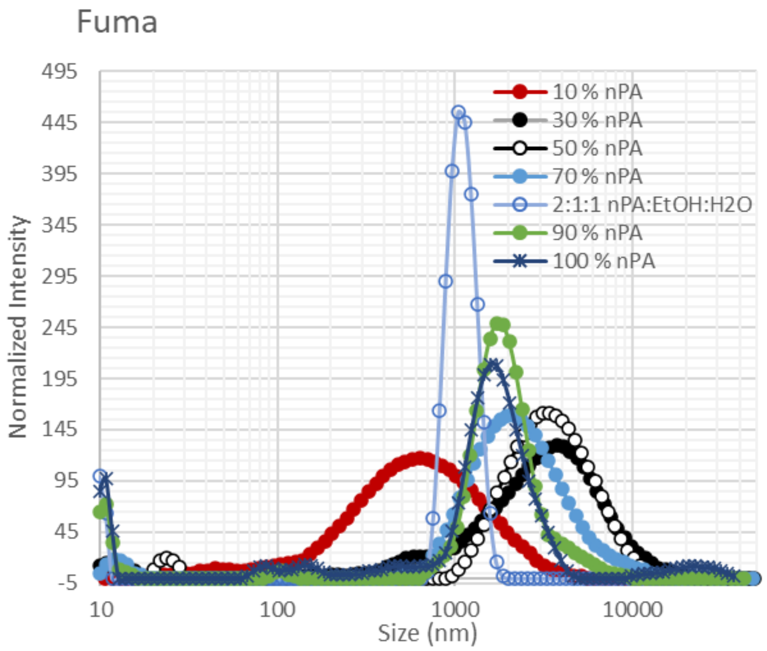

**Comparison of ion mobility for various AEMs and PEMs, effect of hydration**

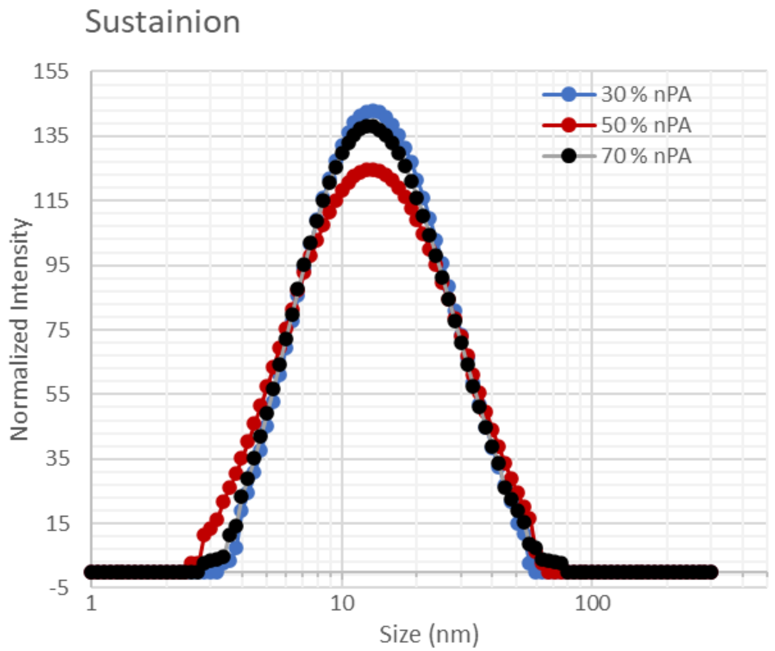


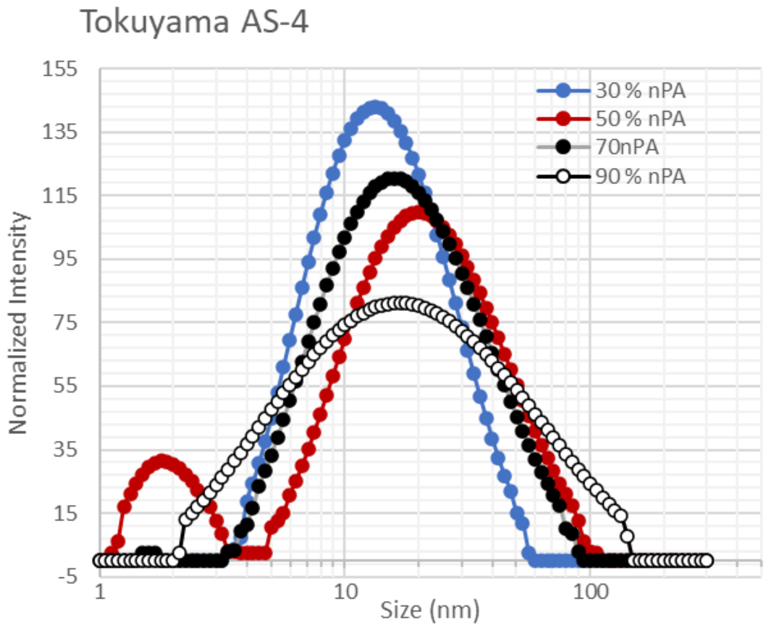

- Ion mobility plays a more important role than anion concentration and strongly dependent on hydration level (water content)
- Membrane conductivity: $CO_3^{2-} > HCO_3^-$

X. Luo, S. Rojas-Carbonell, Y. Yan, A. Kusoglu, *Structure-transport relationships of poly(aryl piperidinium) anion-exchange membranes: Effect of anions and hydration*, ***J. Membrane Science***, 598 (**2020**) 117680.

# LTE 2.0 Accomplishments:
## Impact of Ionomer Ink Composition



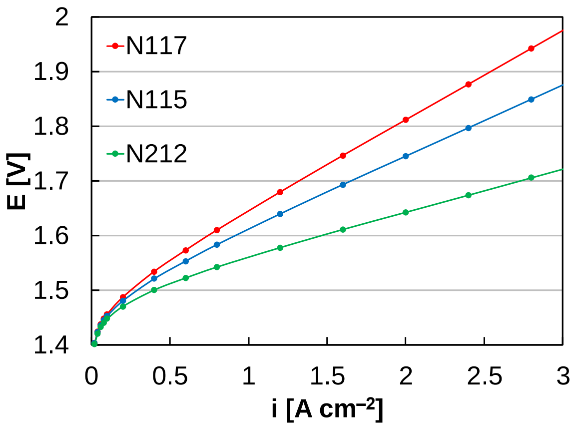




- Fumatech
  - FAA-3 shows much larger aggregates than Sustainion (XB-7) and Tokuyama (AS-4)
  - Shows broadening of distribution and increase in size for intermediate water content
  - Adding of 25 % ethanol narrows distribution
- Sustainion shows hardly any change with water content
- Tokuyama AS-4 shows broadening of distribution with decreasing water content

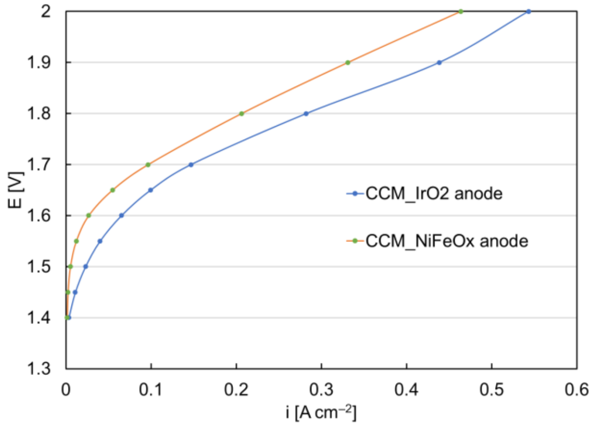
# LTE 2.0 Accomplishments:
## In-situ Electrolysis Performance

4 Nodes

### PEM Comparisons

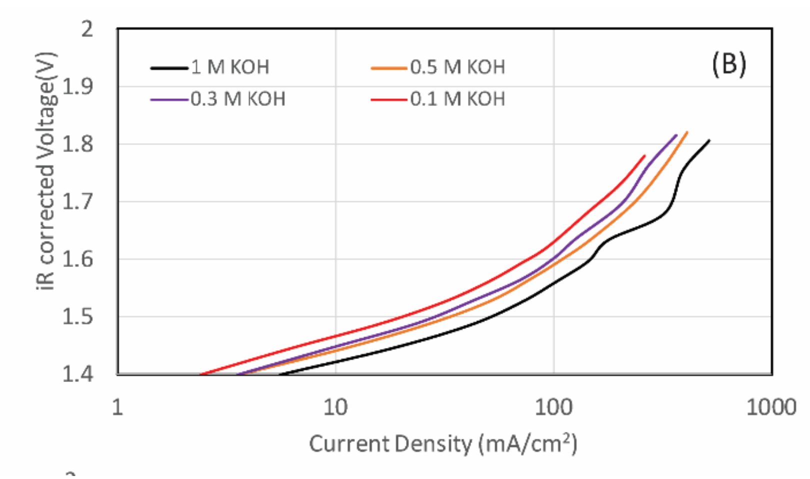


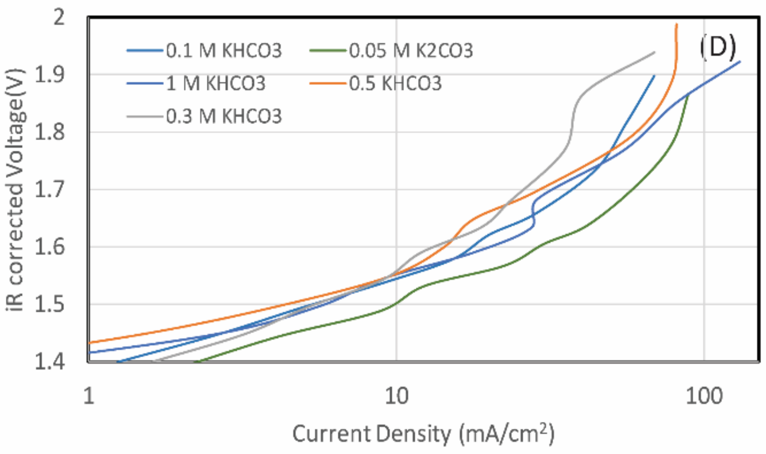

### Current AEM Status

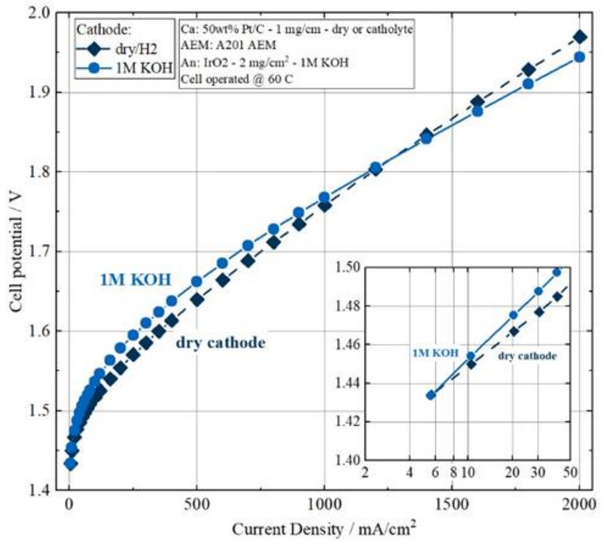



- Set AEM performance milestones based on PEM comparisons (membrane thickness normalized)
- AEM performance generally lower without supporting electrolyte, alkalinity and conductivity improve performance (alkalinity critical)
- Dry cathode generally results in lower performance (high current density), durability

### Role of Supporting Electrolyte



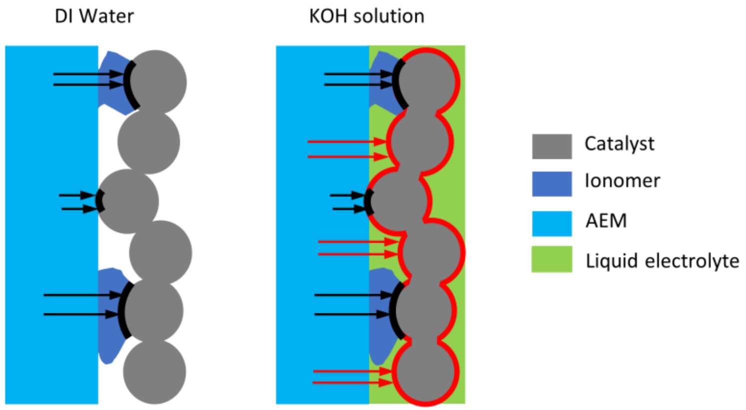



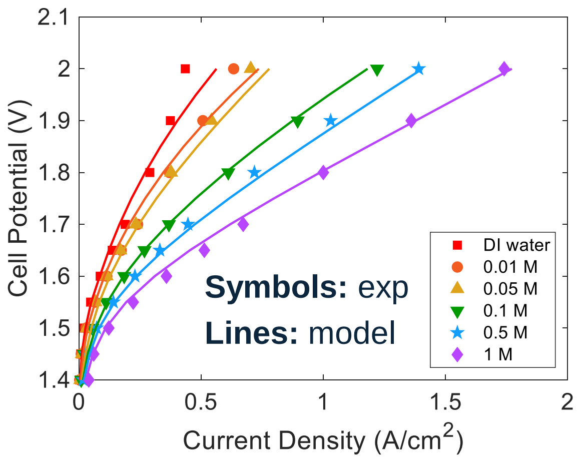
# LTE 2.0 Accomplishments:

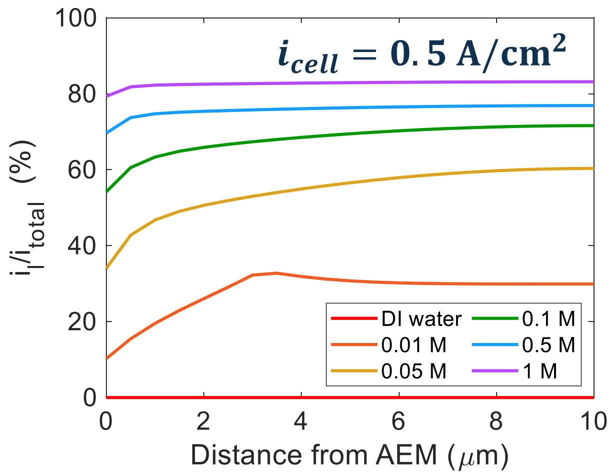
## Impact of External Electrolyte on Performance

4 Nodes

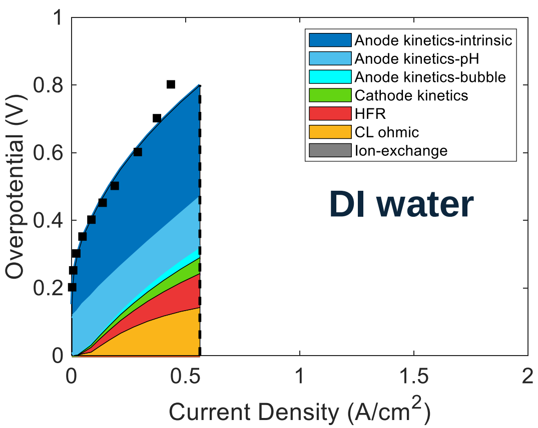


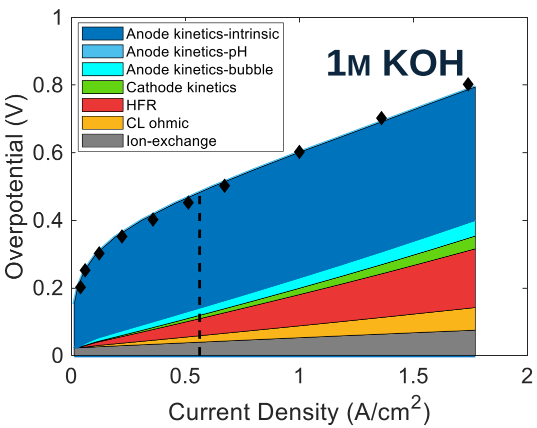

1. Catalyst/ionomer interface
2. Catalyst/liquid-electrolyte interface

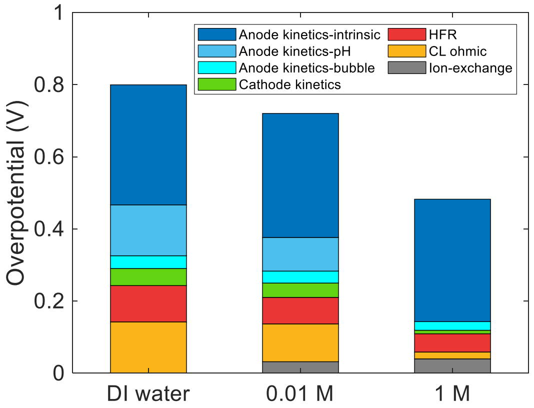



- Surface area increases with $c_{OH^-}$ by additional ion-transport pathways
- More uniform current distributions from catalyst/liquid-electrolyte interface at high $c_{OH^-}$




**Compositions at 0.56 A/cm²**

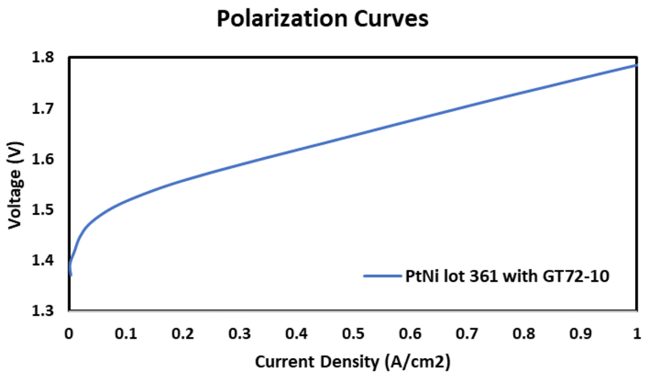
- Anode kinetics a significant factor in nonideal performance
- In unsupported electrolyte, increased overpotential largely due to a pH effect on anode kinetics and catalyst layer ohmic losses

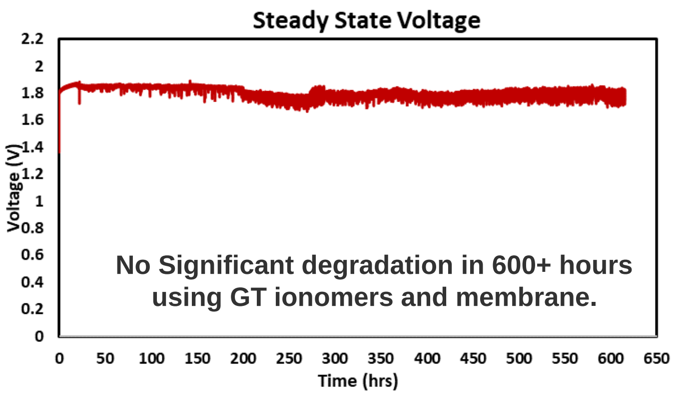
# P185 (P. Kohl): High-Performance AEM LTE with Advanced Membranes, Ionomers and PGM-Free Electrodes

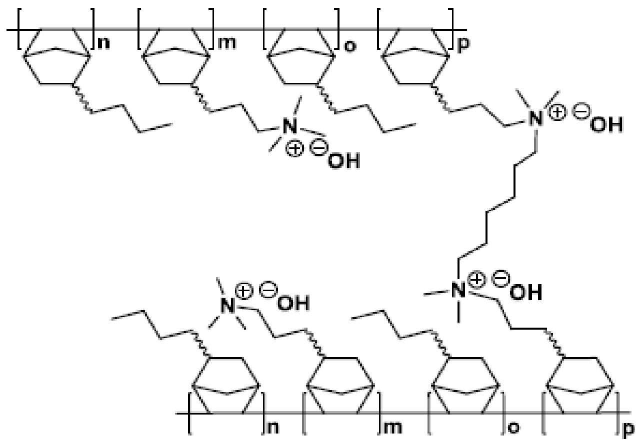
Georgia Institute of Technology | PAJARITO POWDER FUEL CELL CATALYSTS | UofSC South Carolina | nel

NREL Transforming ENERGY | BERKELEY LAB | 3 Nodes

Goals: To enhance and combine state-of-the-art alkaline polymer electrolyzer components into one optimized membrane electrode assembly (MEA) system to achieve the DOE targets for low temperature electrolysis (LTE)



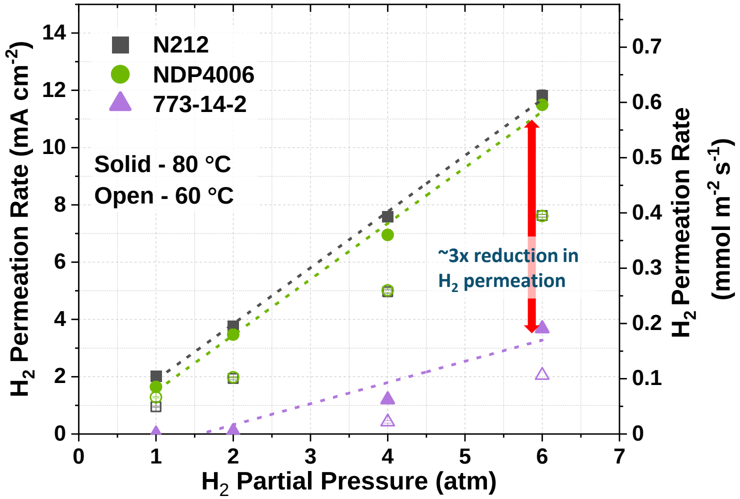

- Produced anion conducting polymer with conductivity >180 mS/cm (80°C) at the kg scale
- Developed OER and HER catalysts with high surface area (>30 $m^2/g$ unsupported, 400 $m^2/g$ supported)
- HER and OER ionomers for LTE MEAs stable at 500 $mA/cm^2$ and 1.75 V for >100 hour
- Achieved >600 h of durability with no losses using project-developed membranes, catalysts, and ionomers

# P186 (A. Park): Performance and Durability Investigation of Thin, Low Crossover Proton Exchange Membranes for Water Electrolyzers

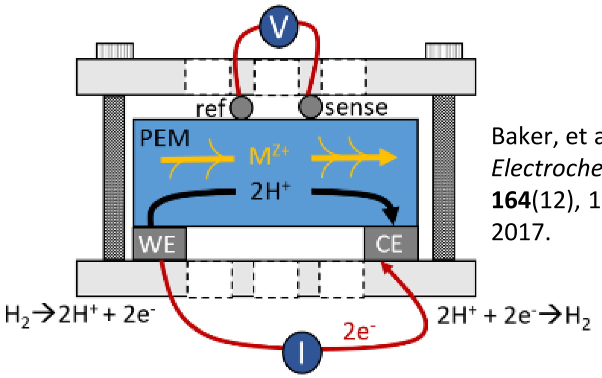
Chemours · Los Alamos National Laboratory EST. 1943

Goals: Develop thin, reinforced membrane with performance and durability additives that enables high current density and long lifetime in PEMWE systems.

NREL Transforming ENERGY · BERKELEY LAB · 3 Nodes

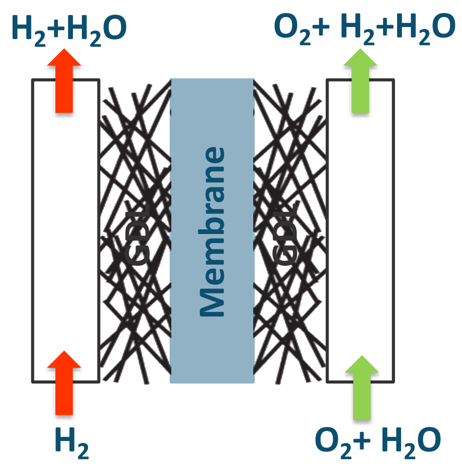


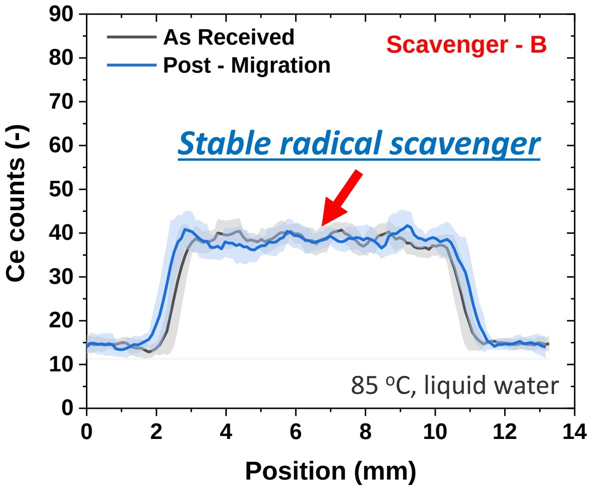

Active area: 50 cm$^2$, Cell temperature: 80 °C, $O_2$ partial pressure: 1 atm, titanium single serpentine flow field




Baker, et al., *J. Electrochem. Soc.*, **164**(12), 1272-1278, 2017.

Ex-situ $H_2$ Permeation Measurement




- $H_2$ crossover measurement in $H_2/O_2$ environment simulated with ex-situ cell
- Demonstrated 3x reduction in effective $H_2$ crossover with thin membranes (~50 µm with GRC, 1-6 atm $H_2$)

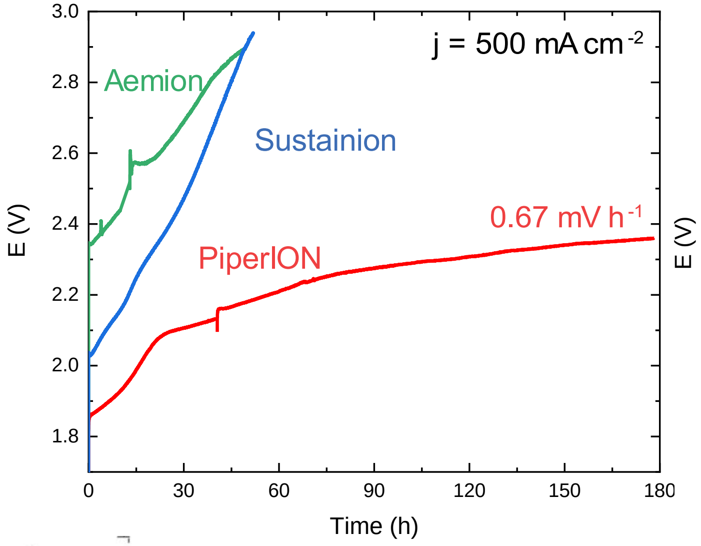
- Three candidate scavengers surveyed for retention in high temperature, water saturated PEMWE environment
- Scavenger morphology/composition has significant impact on mobility within PEMWE working environment

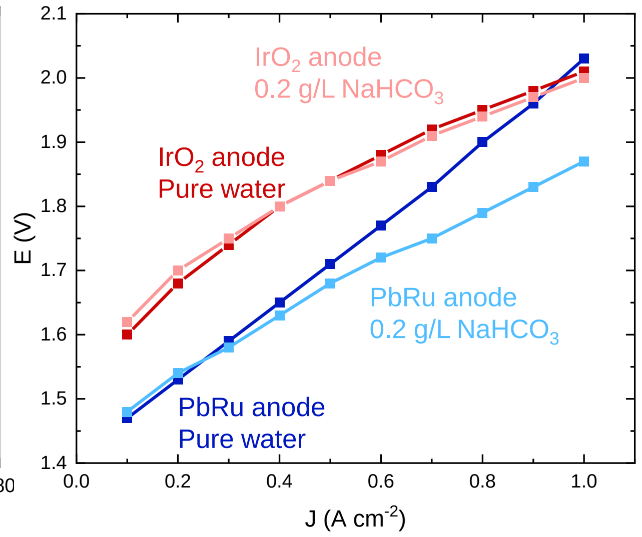
# **P187 (S. Boettcher):** Pure Hydrogen Production through Precious-Metal-Free Membrane Electrolysis of Dirty Water

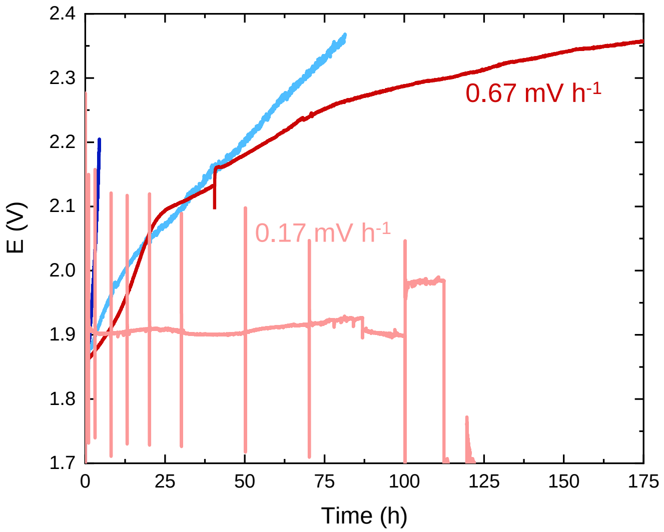
UNIVERSITY OF OREGON

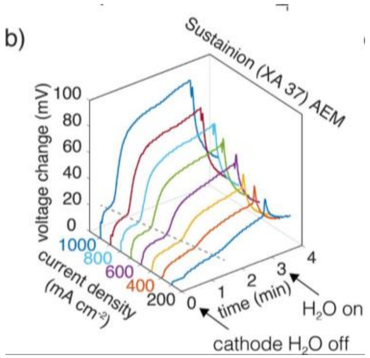
Sandia National Laboratories | NREL Transforming ENERGY | BERKELEY LAB | **6 Nodes**

Goals: Develop a technical understanding of performance degradation of alkaline and bipolar membrane electrolyzers in pure and dirty water and engineer impurity tolerant systems.




- Demonstrated significant improvements to AEM performance and durability
- Degradation rate below 5 mV $h^{-1}$ for over 100 h, below 1 mV $h^{-1}$ for the final 20 h
- $PbRuO_x$ catalyst has shown selectivity for OER over Cl reactivity. Stability of $IrO_x$ and $PbRuO_x$ catalysts were compared in water and carbonate solutions at relevant seawater concentration
- Reversible and irreversible degradation is observed in the absence of water flow to water-consuming electrode

# Summary of Accomplishments

- HydroGEN LTE supported 8 FOAs (41 nodes), 2 Supernodes (14 nodes), LTE 2.0 (4 nodes)
- **Separated the impacts of supporting electrolytes and built understanding for performance differences based on catalyst-ionomer interactions (LTE 2.0).** While supporting electrolytes improve performance by improving anode kinetics (alkalinity), materials have been developed to start bridging the gap between AEM/PEM performance.
- **Demonstrated that iridium oxide anodes fabricated by scalable coating methods (roll to roll) produce comparable PEM electrolysis performance to those fabricated by lab-scale methods (LTE Supernode).** This effort identified the potential to fabricate PEM electrolysis electrodes at much higher rates than current lab methods, contributing to per unit cost reductions.
- **Achieved AEM electrolysis durability of no performance loss for greater than 600 h (P185, P. Kohl).** Demonstrated at 1 $A/cm^2$ using project-developed catalysts (Pajarito Powder), membranes, and ionomers (Georgia Tech).
- **Demonstrated a three-fold reduction in the effective hydrogen crossover rate with thin membranes in PEM electrolysis (P186, A. Park).** Achievement enables high current density performance while improving upon lifetime.
- **Durability losses as low as 0.17 mV $h^{-1}$ achieved in electrolytes at seawater-relevant concentrations (P187, S. Boettcher).** Improved understanding of performance degradation enables the engineering of impurity tolerant systems.

# Collaboration, Effectiveness

- 3rd Annual Advanced Water Splitting Technology Pathways Benchmarking & Protocols workshop, March 1-3, 2021
- Interfacing between HydroGEN and IEA Annex 30 in benchmarking
- Contributions to the Meta Data development for the HydroGEN Data Center

| Seedling Leads | Seedling Teams | Supernode and 2.0 Teams |
|---|---|---|
| Kathy Ayers<br>Shannon Boettcher<br>Chris Capuano<br>Hoon Chung<br>Yu Seung Kim<br>Paul Kohl<br>Di-Jia Liu<br>Sanjeev Mukerjee<br>Andrew Park | Chemours<br>Pajarito Powder Fuel Cell Catalysts<br>Advent<br>nel<br>Argonne National Laboratory<br>Oak Ridge National Laboratory<br>Los Alamos National Laboratory Est. 1943<br>University of Oregon<br>UC Irvine<br>Georgia Institute of Technology<br>Rensselaer<br>Northeastern University<br>UofSC South Carolina<br>University at Buffalo The State University of New York<br>University of Delaware | NREL Transforming ENERGY: Shaun Alia, Guido Bender, Huyen Dinh, Mai-Anh Ha, Saad Intikhab, Allen Kang, Ross Larsen, Scott Mauger, Janghoon Park, Jason Pfeilsticker, Bryan Pivovar, Michael Ulsh, James Young<br>BERKELEY LAB Bringing Science Solutions to the World: Nemanja Danilovic, Julie Fornaciari, Ahmet Kusoglu, Jessica Luo, Adam Weber, Guosong Zeng, Jeremy Zhou<br>SRNL Savannah River National Laboratory, Operated by Savannah River Nuclear Solutions: Elise Fox, Héctor Colón-Mercado |

# Future Work

- LTE 2.0
  - Improve cell performance and durability through materials integration approaches, leveraging component development in the seedling projects
  - Improve our understanding of ionomer-electrolyte effects, through systematic studies, diagnostics, and simulations
- Leverage HydroGEN nodes to enable successful completion and continuation of the seedling projects, depending on which budget period they are in
- Any proposed future work is subject to change based on funding levels

# Technical Backup Slides

# Tech Transfer and Publications

- LTE HydroGEN supports numerous companies through FOA Projects
- Continual development of IP

<u>Publications</u>


- J.L. Young, Z. Kang, F. Ganci, S. Madachy, G. Bender, “PEM electrolyzer characterization with carbon-based hardware and material sets”, *Electrochem. Commun.*, 124 (2021) 106941.
- Z. Kang, M. Pak, G. Bender, “Introducing a novel technique for measuring hydrogen crossover in membrane-based electrochemical cells”, *Int. J. Hydrogen Energy*, 46 (2021) 15161-15167.
- J. Park, Z. Kang, G. Bender, M. Ulsh, S.A. Mauger, “ Roll-to-roll production of catalyst coated membranes for low-temperature electrolyzers”, *J. Power Sources*, 479 (2020) 228819.
- M.-A. Ha, R.E. Larsen, “ Multiple Reaction Pathways for the Oxygen Evolution Reaction May Contribute to $IrO_2$ (110)’s High Activity”, *J. Electrochem. Soc.*, 168 (2021) 024506.
- Z. Kang, S.M. Alia, M. Carmo, G. Bender, “In-situ and in-operando analysis of voltage losses using sense wires for proton exchange membrane water electrolyzers”, *J. Power Sources*, 481 (2021) 229012.
- S.M. Alia, K.S. Reeves, J.S. Baxter, D.A. Cullen, “The Impact of Ink and Spray Variables on Catalyst Layer Properties, Electrolyzer Performance, and Electrolyzer Durability”, *J. Electrochem. Soc*., 167 (2020) 144512.
- S.M. Alia, M.-A. Ha, C. Ngo, G.C. Anderson, S. Ghoshal, S. Pylypenko, “Platinum–Nickel Nanowires with Improved Hydrogen Evolution Performance in Anion Exchange Membrane-Based Electrolysis”, *ACS Catalysis*, 10 (2020) 9953-9966.
- S. Ghoshal, B.S. Pivovar, S.M. Alia, “Evaluating the effect of membrane-ionomer combinations and supporting electrolytes on the performance of cobalt nanoparticle anodes in anion exchange membrane electrolyzers”, *J. Power Sources*, 488 (2021) 229433.
- G.C. Anderson, B.S. Pivovar, S.M. Alia, “Establishing Performance Baselines for the Oxygen Evolution Reaction in Alkaline Electrolytes”, *J. Electrochem. Soc.*, 167 (2020) 044503.

# Tech Transfer and Publications

Publications (Continued)


- Z. Kang, S.M. Alia, J.L. Young, G. Bender, "Effects of various parameters of different porous transport layers in proton exchange membrane water electrolysis", *Electrochim. Acta*, 354 (2020) 136641.
- S. Zaccarine, S. Mauger, W. McNeary, A. Weimer, S.M. Alia, M. Shviro, M. Carmo, B.S. Pivovar, S. Pylypenko, "Microscopy-based Multi-technique, Multi-scale Characterization of Polymer Electrolyte Membrane Devices", *Microsc. Microanal.*, 26 (2020) 772-774.
- S.Z. Oener, L.P. Twight, G.A. Lindquist, S.W. Boettcher, "Thin Cation-Exchange Layers Enable High-Current-Density Bipolar Membrane Electrolyzers via Improved Water Transport", *ACS Energy Lett.*, 6, (2021) 1.
- Q. Xu, S.Z. Oener, G. Lindquist, H. Jiang, C. Li, S.W. Boettcher, "Integrated Reference Electrodes in Anion-Exchange-Membrane Electrolyzers: Impact of Stainless-Steel Gas-Diffusion Layers and Internal Mechanical Pressure", *ACS Energy. Lett.*, 6, (2021) 305.
- Z. Taie, X. Peng, D. Kulkarni, I.V. Zenyuk, A.Z. Weber, C. Hagen, N. Danilovic, "Pathway to Complete Energy Sector Decarbonization with Available Iridium Resources using Ultralow Loaded Water Electrolyzers", *ACS Appl. Mater. Interfaces*, 12, (2020) 52701.
- E. Leonard, A.D. Shum, N. Danilovic, C. Capuano, K.E. Ayers, L.M. Pant, A.Z. Weber, X. Xiao, D.Y. Parkinson, I.V. Zenyuk, "Interfacial analysis of a PEM electrolyzer using X-ray computed tomography", *Sustain. Energy Fuels*, 4, (2020) 921.
- P. Satjaritanun, M. O'Brien, D. Kulkarni, S. Shimpalee, C. Capuano, K.E. Ayers, N. Danilovic, D.Y. Parkinson, I.V. Zenyuk, "Observation of Preferential Pathways for Oxygen Removal through Porous Transport Layers of Polymer Electrolyte Water Electrolyzers", *iScience,* 23, (2020) 101783.
- J.C. Fornaciari, M.R. Gerhardt, J. Zhou, Y.N. Regmi, N. Danilovic, A.T. Bell, A.Z. Weber, "The Role of Water in Vapor-fed Proton-Exchange-Membrane Electrolysis," *J. Electrochem. Soc.*, 167, (2020) 104508.
- X. Luo, D.I. Kushner, J. Li, E.J. Park, Y.S. Kim, A. Kusoglu, Anion Exchange Ionomers: Impact of Chemistry on Thin-Film Properties, *Adv. Funct. Mat.*, (2021) 2008778.
- C. Arthurs, A. Kusoglu, Compressive Creep of Polymer Electrolyte Membranes: A Case Study for Electrolyzers, ACS Appl. Energy Mat., 4, (2021) 3249.

# Contribution to Achievement of DOE Targets or Milestones

- These projects will contribute to the achievement of the following DOE milestones from the Hydrogen Production section of the Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:
  - Hydrogen Levelized Cost (Production): $2/kg
  - Energy Efficiency: 43 kWh/kg

# Awards

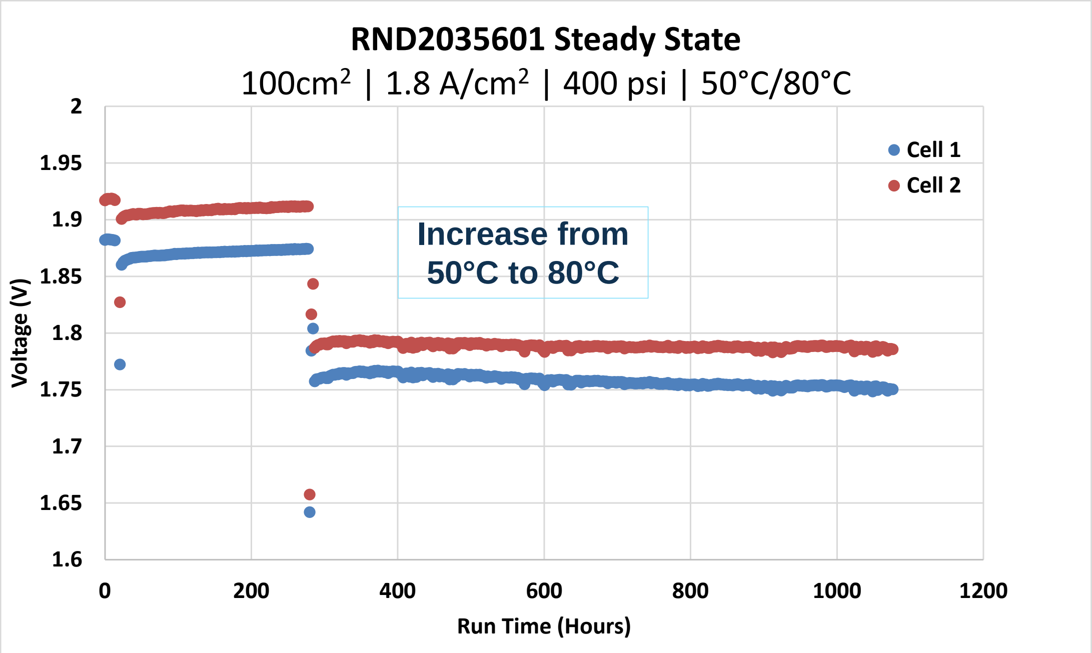
- Bryan Pivovar was awarded the 2021 Energy Technology Division Research Award of the Electrochemical Society and the 2021 US Department of Energy Secretary's Honor Award
- DOE Postdoc award: Eun Joo Park (LANL) seedling project

# **K. Ayers:** High Efficiency PEM Water Electrolysis

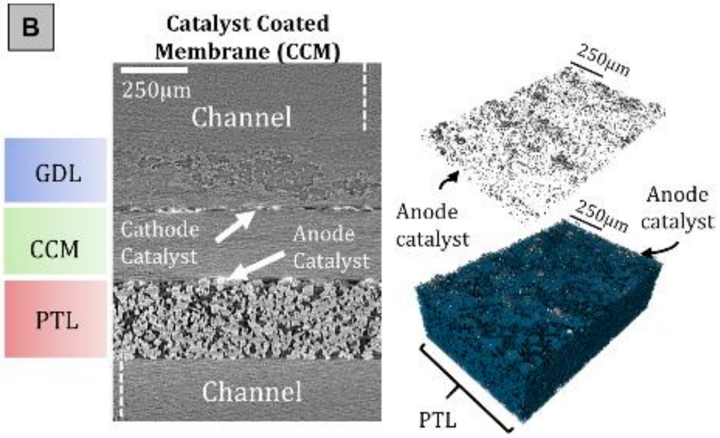
nel • UCIrvine • Oak Ridge National Laboratory

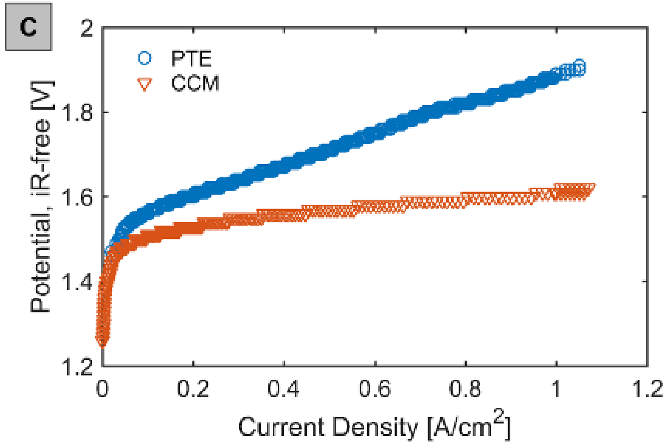
NREL Transforming ENERGY • Berkeley Lab — **7 Nodes**

Goals: To incorporate all elements of the advanced membrane, catalyst, electrode fabrication techniques, and cell modeling to realize a reliable MEA configuration with efficiency meeting the 43 kWh/kg targets




| Anode Loading | Cathode Loading |
|---|---|
| 0.6 mg/cm² IrOx | 0.1 mg/cm² Pt/C |




- Catalyst layer morphology is resolved, inhomogeneous distribution
- Better polarization for CCM (at 1 A/cm$^2$ 250 mV difference)
- Durability testing conducted over 1000 hours in 100 cm$^2$ stack
- Stable voltages achieved with high surface area $IrO_x$ showing a degradation rate of 0 µV/hr

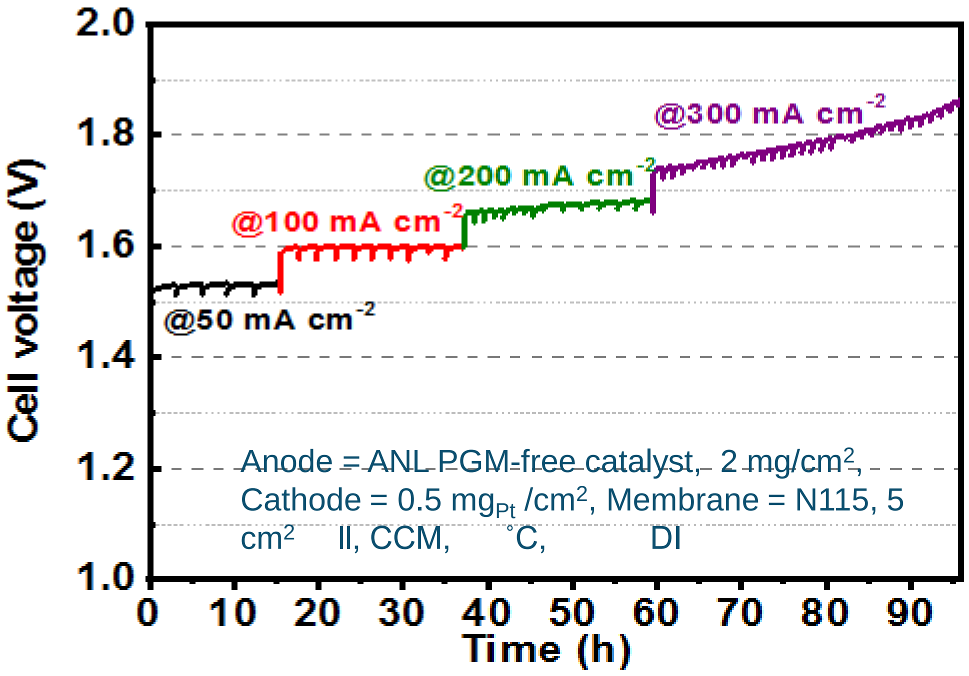
# D.-J. Liu: PGM-free OER Catalysts for PEM Electrolyzer

Argonne NATIONAL LABORATORY | University at Buffalo The State University of New York

Lawrence Livermore National Laboratory | Sandia National Laboratories | NREL Transforming ENERGY | BERKELEY LAB | **5 Nodes**

**Goals:** To develop platinum group metal-free oxygen evolution electrocatalysts as a viable replacement for iridium in proton exchange membrane water electrolyzers.

PEMWE cell voltage decay rates at 50, 100, and 200 mA/cm$^2$ meet the target of < 2mV/hr. At 300 mA/cm$^2$, the voltage increase exceeded the target value




| @ Current density (mA/cm$^2$) | Duration (hr) | Ave. Cell Voltage (V) | Decay rate (mV/hr) |
|---|---|---|---|
| 50 | 14.7 | 1.528 | 0.55 |
| 100 | 21.5 | 1.600 | 0.35 |
| 200 | 22.1 | 1.672 | 0.93 |
| 300 | 36.7 | 1.799 | 3.17 |

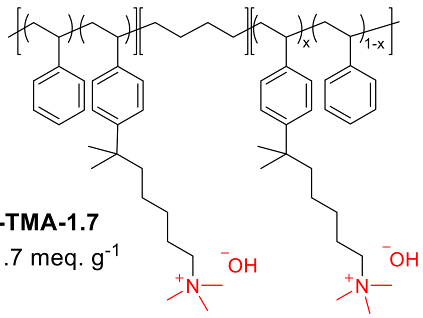
Progress demonstrates that PGM-free OER catalyst offers a promise as the replacement of Ir in PEMWE. Further development could lead to a major cost reduction in low-cost hydrogen production through low-temperature PEMWE electrolyzer

# Y. Kim: PGM-free OER Catalysts for PEM Electrolyzer

Los Alamos National Laboratory EST. 1943 | Rensselaer | nel

Sandia National Laboratories | NREL Transforming ENERGY | Berkeley Lab | 5 Nodes

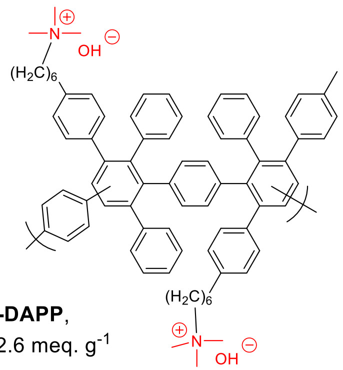
Goals: Prepare durable and economically-affordable alkaline hydroxide conducting SES materials and demonstrate high performance and durability in AEM-based water electrolysis.




**AEM**

**SES25-TMA-1.7**

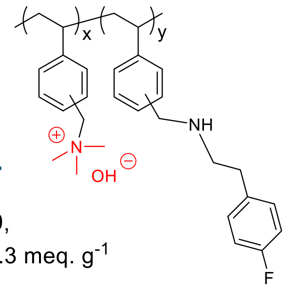
IEC = 1.7 meq. $g^{-1}$




**AEM**

**HTMA-DAPP**,

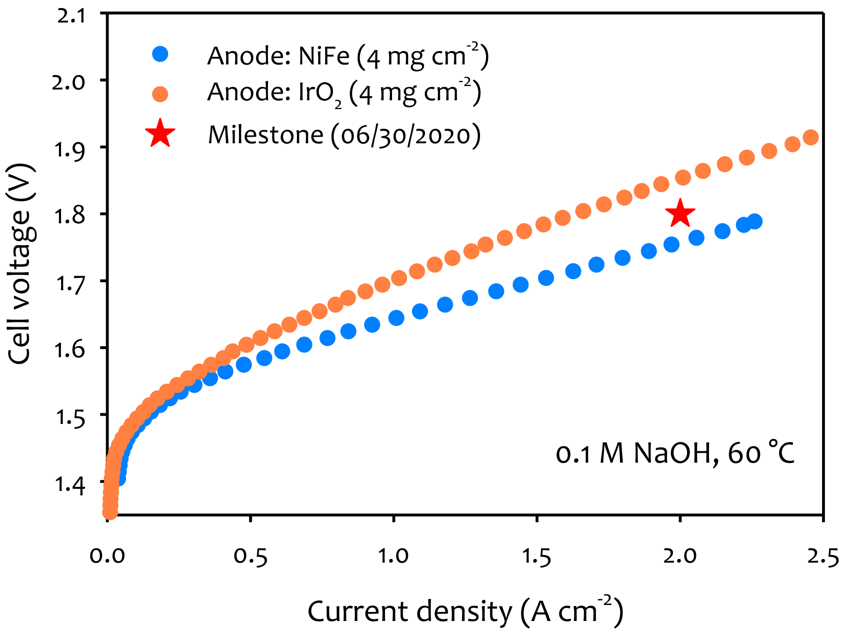
IEC = 2.6 meq. $g^{-1}$

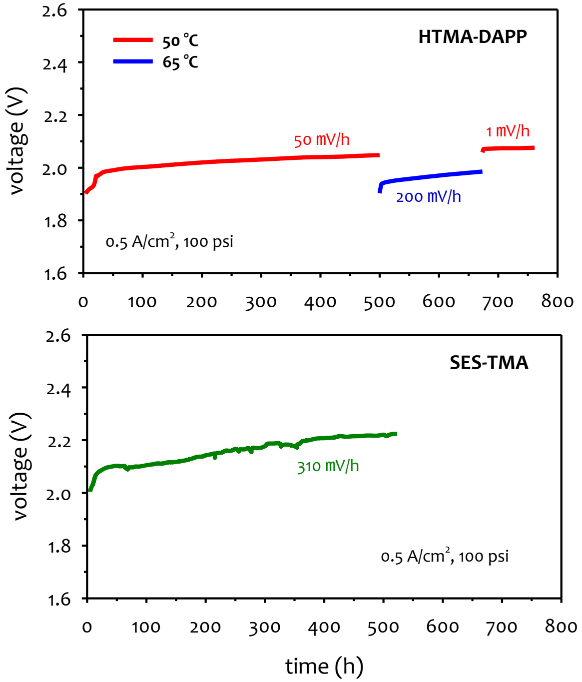



**Ionomer**

**TMA-70**,

IEC = 3.3 meq. $g^{-1}$



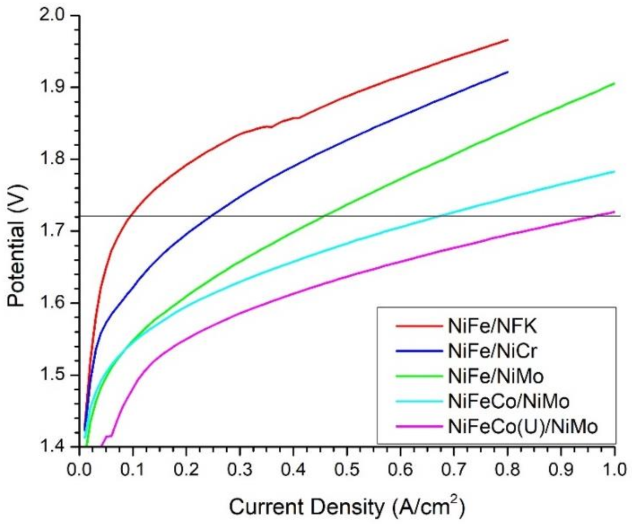

- Met the performance target using PGM-free anode
- AEM lifetime > 500 hours
- HTMA-DAPP AEM showed lower degradation rate (50 mV/h for HTMA-DAPP vs. 310 mV/h for SES-TMA)
- On track for AEM electrolyzer performance target, < 0.1 mV/h over 300 hours at 1 A/cm2 using PGM-free anode

# S. Mukerjee: Novel PGM-free Catalysts for Alkaline HER and OER

Northeastern University | University of Delaware | ADVENT

Sandia National Laboratories | NREL Transforming ENERGY | BERKELEY LAB | 3 Nodes

Goals: Decrease the cost of hydrogen production via water electrolysis using high-performing PGM-free catalysts and a novel, temperature-stable anion exchange membrane.




- A novel electrode architecture with Pt-free catalysts led to a performance of 1 A/cm$^2$ at 1.726 V.
- Performance decay of 0.02 mV/hr at 1 A/cm$^2$ for 30 hours.

| End of Project Targets | | |
|---|---|---|
| **Description** | **Milestone** | **Status** |
| HER catalyst | Overpotential below 150 mV at 500 mA/cm$^2$ in $H_2$ pump cell | 200 mV |
| OER catalyst | Overpotential below 100 mV @ 500 mA/cm$^2$ | 93 mV |
| AEM membrane and ionomer | Area specific resistance of 0.08 $\Omega \cdot cm^2$ | 0.08 $\Omega \cdot cm^2$ |
| | Less than 10% IEC after 1000 hr treatment in 90°C 1M KOH | 3.74% loss of IEC |
| Cell Performance | 1.72 V at 1 A/cm$^2$ | 1.726 V @ 1 A/cm$^2$ |
| | Less than 1 mV performance decay after 48hrs of sustained operation at 1 A/cm$^2$ | 0.02 mV/hr decay after 30 hours |