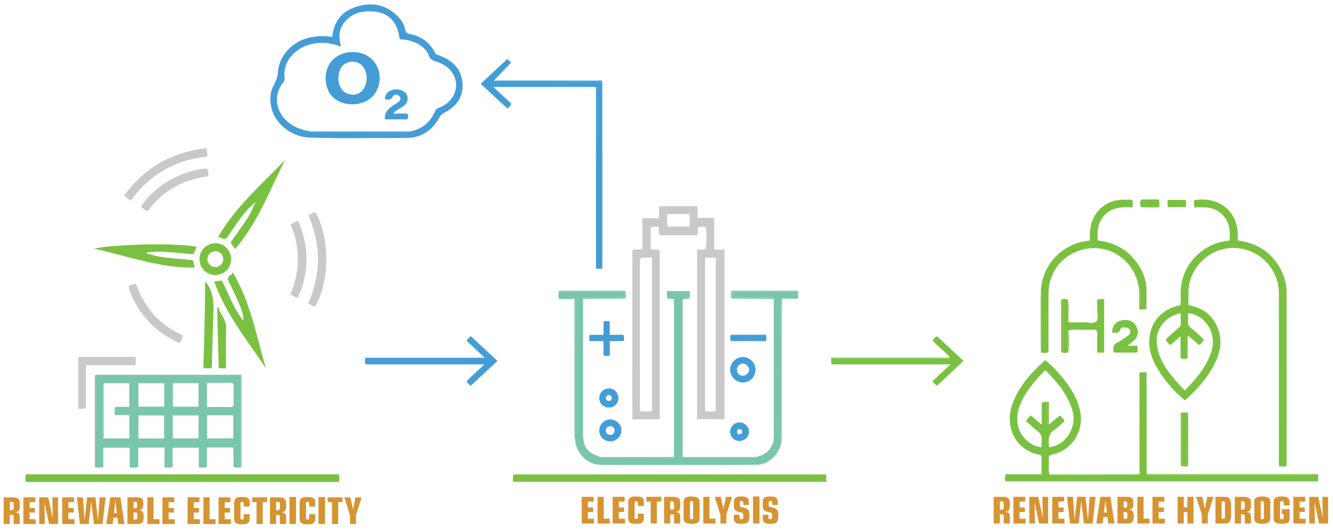
ICE 2021

3rd International Conference on Electrolysis

June 20 – 23, 2022
Golden, Colorado USA



Contents

Welcome to the 3rd International Conference on Electrolysis (ICE 2021)

Building on the success of the first two International Conference on Electrolysis (ICE 2017 in Copenhagen, Denmark and ICE 2019 in Loen, Norway), we welcome you to Golden, Colorado USA for the 3rd International Conference on Electrolysis. The "COVID" years have been challenging for many, and we have chosen to brand this event ICE 2021 even though we have had to delay until 2022. It can hardly be a more important time for hydrogen and electrolysis, as growth and deployment has been growing exponentially in this area. In 2019, the prominence of electrolysis was growing quickly, but the pace that it has advanced at is far beyond what most of us had hoped for, but still perhaps slower than is necessary. Our community bears a heavy weight in this responsibility, and I truly believe that the 2020's will be looked back on as the decade of hydrogen.

The fact that electrolysis is so important and that time is so short to make the impact only increases the need for events like ICE 2021. It has been too long since we have been able to come together as a community and collectively help accelerate the field of electrolysis. This year's event includes approximately 120 abstract submissions that cover the topics of polymer electrolyte membrane (PEM), alkaline/alkaline membrane (AEL), and solid oxide (SOEC) electrolysis. Now that we are finally gathered here in person at the ICE 2021, we will do our utmost to host you all. But only you – the participants – can ensure the quality and success of the conference.

On behalf of the scientific and organizing committees,

Welcome to ICE 2021 in Golden, Colorado, USA!

Bryan Pivovar
Chair of ICE 2021

Committees

International Advisory Committee

Dmitri Bessarabov, HySA Infrastructure at North-West University (South Africa)

Marcelo Carmo, NEL Hydrogen (Germany)

EunAe Cho, Korea Advanced Institute of Science and Technology (Republic of Korea)

John T. S. Irvine, University of St. Andrews (United Kingdom)

Olga Marina, Pacific Northwest National Laboratory (United States)

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The ICE 2021 Conference is being administered by Continuing and Professional Education Services at Colorado School of Mines.

Web: learn.mines.edu
Email: learn@mines.edu

Conference website: learn.mines.edu/ice2021

Session Chairs

Plenary Session 1

Bryan Pivovar, National Renewable Energy Laboratory

Plenary Session 2

Bryan Pivovar, National Renewable Energy Laboratory

Polymer Electrolyte Membrane Electrolysis 1

Magnus Thomassen, HyStar

Alkaline Electrolysis 1

Jens Oluf Jensen, DTU Energy

Solid Oxide Electrolysis 1

Neal Sullivan, Colorado School of Mines

Polymer Electrolyte Membrane Electrolysis 2

Pierre Millet, Université Paris Sud

Alkaline Electrolysis 2

Dmitri Bessarabov, HySA Infrastructure at North-West University

Solid Oxide Electrolysis 2

John T. S. Irvine, University of St. Andrews

Polymer Electrolyte Membrane Electrolysis 3

Svitlana Pylypenko, Colorado School of Mines

Alkaline Electrolysis 3

EunAe Cho, Korea Advanced Institute of Science and Technology

Polymer Electrolyte Membrane Electrolysis 4

Tom Smolinka, Fraunhofer ISE

Solid Oxide Electrolysis 3

Olga Marina, Pacific Northwest National Laboratory

Conference Dinner

The Conference Dinner takes place on Wednesday, June 22, from 6:30 PM (18:30) until 10:00 PM (22:00) at The Fort Restaurant, located in Morrison, Colorado at 19192 Colorado Highway 8. Transportation from the Mines campus to The Fort and return via chartered bus is provided. Buses will leave the Mines campus at 6:00 PM (18:00) and will leave The Fort at 9:30 PM (21:30) for the return to the campus. Buses will leave from and return to the campus outside of Green Center near the intersection of 16th and Arapahoe Streets.

The meal at The Fort is a buffet that includes appetizers, salad, choice of three entrées, multiple sides, bread, and several dessert offerings. Each guest is provided with one alcoholic beverage at the dinner. Any drinks after that will be a cash bar. The Conference Dinner is included in all full registrations for ICE2021.

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The Colorado Fuel Cell Center is a Colorado School of Mines partner with federal agencies and industrial developers to advance technology in high-efficiency electricity generation and green fuels synthesis for energy storage. The Center is grid connected to 18 kWe, with pressurized SOFC stack testing to 30 kWe. The team advances new materials from the button cell to the stack, develops electrochemical theory and system-level models, targets economic applications for effective deployment, while training the scientists and engineers of tomorrow.

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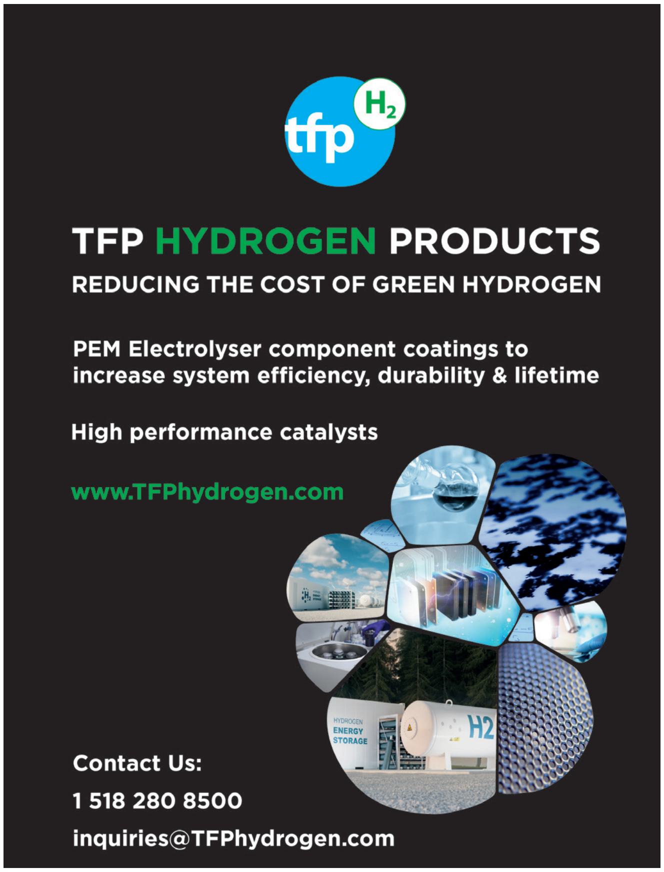


Welcoming Reception

All Conference attendees are invited to the Welcoming Reception taking place in the Green Center Lobby from 18:00 (6:00 PM) until 20:00 (8:00 PM) on Sunday, June 19, 2022.

NREL Tour

NREL has one of the premier hydrogen research facilities in the world. The tour will focus on the Energy System Integration Facility (ESIF) - the 2014 R&D Magazine Lab of the Year. The tour will include 6 separate labs/areas that involve fabrication of electrodes, testing in fuel cells and electrolysis systems, manufacturing considerations, megawatt scale electrolysis, and hydrogen infrastructure and distribution. Information about travel to NREL will be provided before the date/time of the tour.

Afternoon Networking Activities

To participate in the organized Afternoon Networking Activities on Wednesday, June 22, please sign up by Monday, June 20 at the Registration Desk. Options include white water rafting, tours, and “on your own”.

Conference at a Glance

Monday • June 20

07:30	Check-In • Green Center Lobby
08:00	Welcome and Plenary Session 1 Metals Hall
09:45	Break • Refreshments are available
10:15	Plenary Session 2 Metals Hall
12:15	Lunch
13:30	Polymer Electrolyte Membrane Electrolysis 1 Metals Hall
15:10	Break • Refreshments are available
15:40	Alkaline Electrolysis 1 Metals Hall
17:30 20:00	Poster Session 1 Green Center Lobby

Tuesday • June 21

07:30	Check-In • Green Center Lobby
08:00	Solid Oxide Electrolysis 1 Metals Hall
10:00	Break • Refreshments are available
10:30	Polymer Electrolyte Membrane Electrolysis 2 Metals Hall
12:20	Lunch • Friedhoff Hall
13:30	Alkaline Electrolysis 2 Metals Hall
15:40	Break • Refreshments are available
16:00	Solid Oxide Electrolysis 2 Metals Hall
17:30 20:00	Poster Session 2 Green Center Lobby

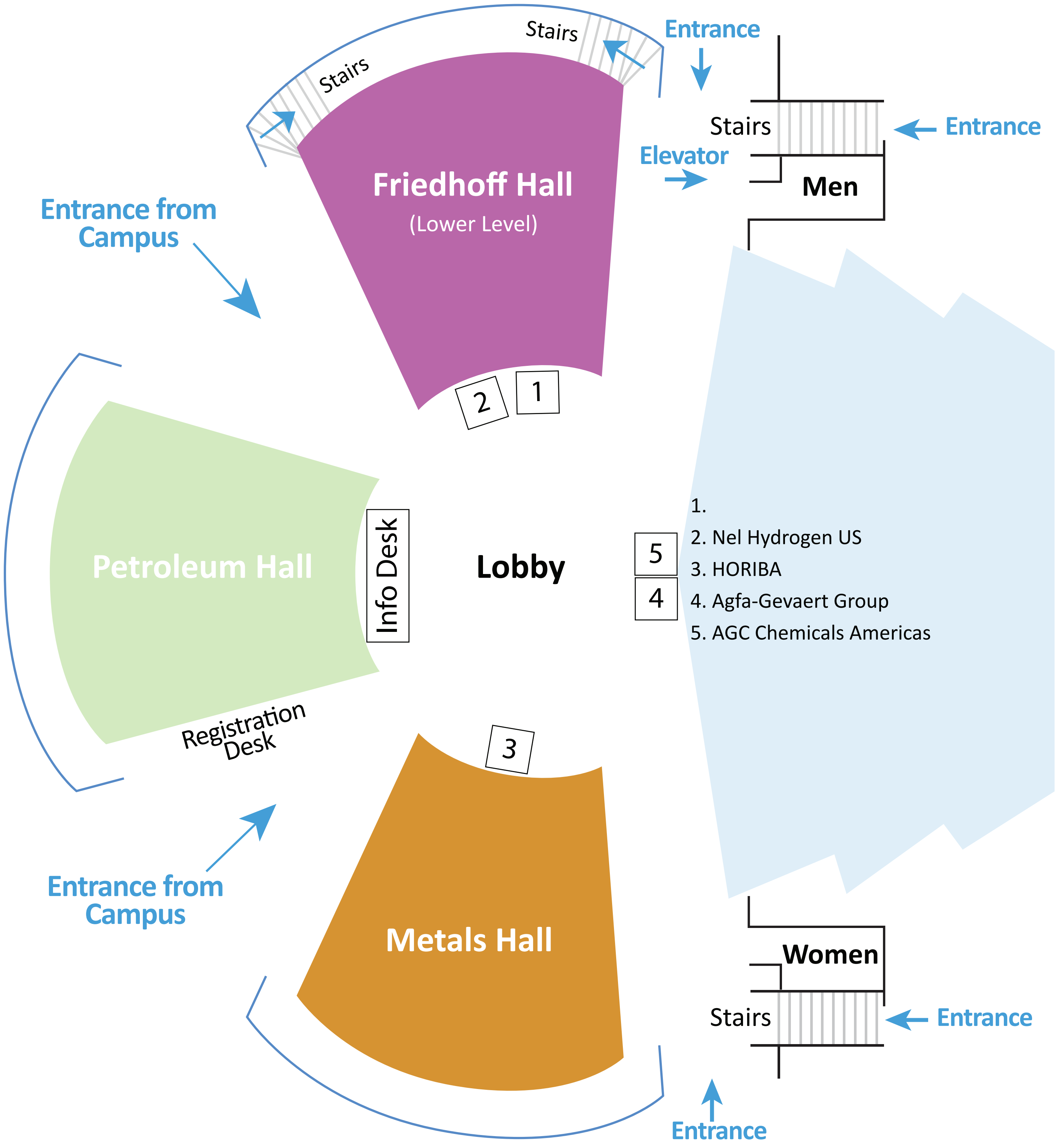
Wednesday • June 22

07:30	Check-In • Green Center Lobby
08:00	Polymer Electrolyte Membrane Electrolysis 3 Metals Hall
10:00	Break • Refreshments are available
10:30	Alkaline Electrolysis 3 Metals Hall
12:20	Bag Lunch
12:30	Afternoon Networking Activities
18:00 22:00	Conference Dinner The Fort Restaurant

Thursday • June 23

07:30	Check-In • Green Center Lobby
08:00	Polymer Electrolyte Membrane Electrolysis 4 Metals Hall
10:00	Break • Refreshments are available
10:30	Solid Oxide Electrolysis 3 Metals Hall
11:50	Closing Session Metals Hall
12:20	Bag Lunch
13:00	Tour of NREL H_2/Electrolysis Facility

Conference Venue - Green Center • Colorado School of Mines



1.
2. Nel Hydrogen US
3. HORIBA
4. Agfa-Gevaert Group
5. AGC Chemicals Americas

Conference Venue and Emergency Information

The Conference venue is: **Green Center**
924 16th Street
Golden, Colorado 80401 USA

For questions or assistance, contact:
Continuing and Professional Education Services
at 303.384.2690

Emergency Information

Fire

In case of a fire, do the following:

- Activate the nearest fire alarm and/or call 911 on any wired or wireless telephone. If you are in danger, leave the telephone “off hook” and evacuate.
- Evacuate the area; take your valuables with you.
- Do not use elevators.
- If it is safe to do so, assist others in evacuating the area.

Medical Emergency

In case of a medical emergency, do the following:

- Call 911 on any wired or wireless telephone.
- Render first aid if trained to do so.
- Stay with the injured/ill person until help arrives.
- Try to gather as much information about the emergency to pass on to responders

Active Shooter or Armed Intruder

In case of an active shooter or an armed intruder, do the following:

- Run - Evacuate or flee if possible and safe. Distance yourself from the shooter/intruder.
- Hide - If flight is not possible, shelter in place. Get out of sight.
- Block entry points or lock doors. Put something solid between yourself and the shooter/intruder.
- Be prepared to wait; elapsed time is a good sign.
- Wait for instructions from law enforcement.
- Fight - As a last resort, take action, and only if your life is in imminent danger. Attempt to disrupt and/or incapacitate the shooter/intruder. Act with aggression.

Photography, Video, and Audio Recording

No photography or recording of video or audio is allowed in the technical sessions at any time.

Mobile Telephones

Please have your mobile phone on silence during the Conference

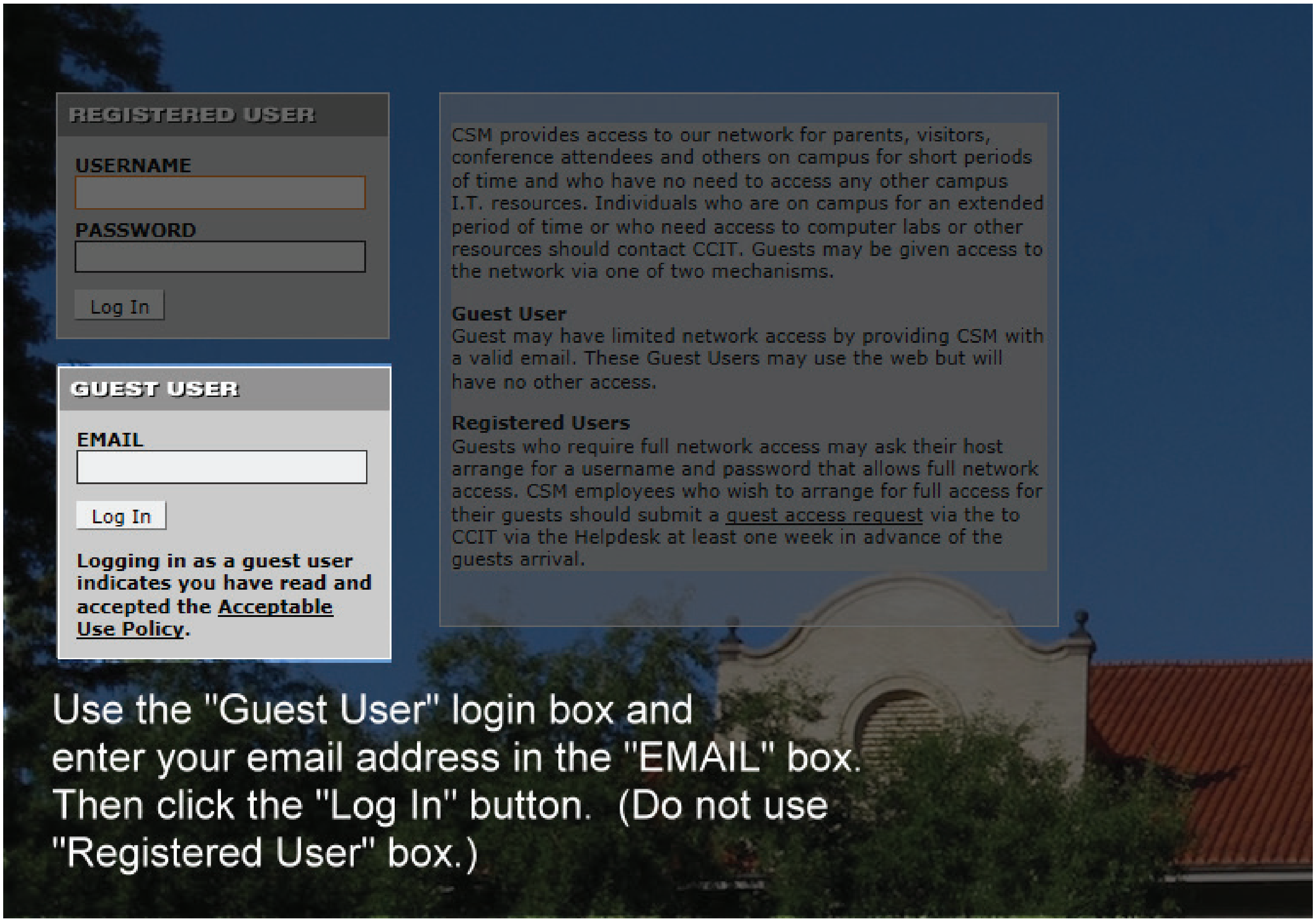
Internet Access (Wi-Fi)

Please see the next page...

Internet Access (Wi-Fi)

To access the internet using the Mines campus Wi-Fi system, do the following:

- Use the feature on your computer to view available Wi-Fi access points. Choose “CSMGuest” from the list of available networks. Do not use CSMWireless or any other Mines/CSM connections that may appear.
- On your computer, point an internet browser to https://www.mines.edu. You should be served a page similar to the one shown in the image below. If not, enter the following in the URL/address box of your browser: 1.1.1.1 and follow the directions below:
- If you get a Browser Warning:
  - The secure Website where you enter your email address is at 1.1.1.1
  - In some cases, depending on your browser’s security settings, you will have to manually accept the security certificate for this site. The process to accomplish this task differs among browsers. The objective is to ACCEPT the security certificate, so you should respond affirmatively to whatever relevent message is presented by your browser.
  - If you are using Internet Explorer (IE), and having trouble accessing the login page, please disable SSL version 2. Do this by going to the “tools” menu, choose “internet options” and then click on the “advanced” tab; scroll down to security and un-check “Use SSL 2.0”, refresh the page. In some cases, again depending on the security settings, IE will just refuse to connect to our Authentication server. In this case, please use Firefox or another modern browser such as Chrome or Edge.
  - Allow 5 to 10 minutes for a connection. You may need to restart your computer.



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Use the "Guest User" login box and enter your email address in the "EMAIL" box. Then click the "Log In" button. (Do not use "Registered User" box.)

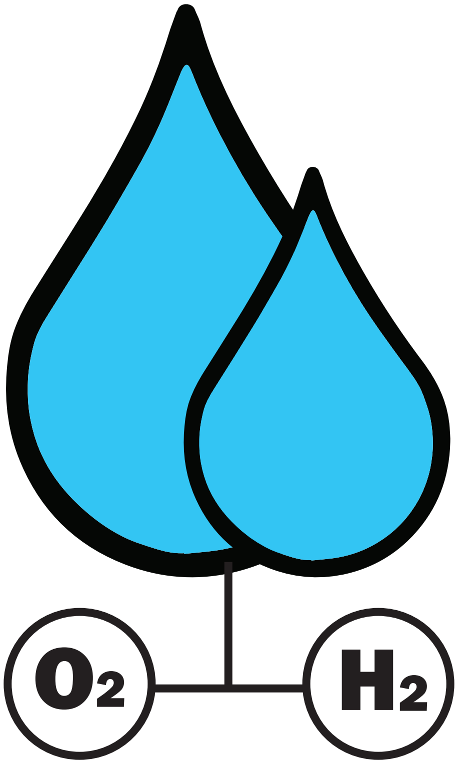
Abstracts

Availability of Presentation Abstracts

Abstracts for most of the presentations made at ICE 2021 will be available on the internet at the address shown below:

https://learn.mines.edu/ice2021

A detailed agenda showing all presentations and functions of the Conference — by date, time, and location — begins on the next page.



Conference Agenda

Sunday • June 19, 2022

18:00 - 20:00 **Green Center Lobby**

Welcoming Reception

Monday • June 20, 2022

07:30 - 08:00 **Green Center Lobby**

Check-in

08:00 - 09:45 **Metals Hall**

Plenary Session 1

Chair: Bryan Pivovar

08:15	120	Hydrogen Program and Electrolyzer Activities at the U.S. Department of Energy	Dave Peterson :: *U.S. Department of Energy*
08:45	115	The Renewable Energy-Electrolysis Nexus	Bill Tumas :: *National Renewable Energy Lab*
09:15	113	The history of water electrolysis - what can we learn from the past?	Tom Smolinka :: *Fraunhofer ISE*

09:45 - 10:15 **Green Center Lobby**

Break

10:15 - 12:15 **Metals Hall**

Plenary Session 2

Chair: Bryan Pivovar

10:15	119	Challenges in Scaling PEM Fuel Cells, Electrolyzers and Systems	Cortney Mittelsteadt :: *Plug*
10:45	122	Large scale deployment of modular pressurised alkaline electrolysers	Kasper Therkildsen :: *Green Hydrogen Systems A/S*
11:15	63	Solid Oxide Electrolysis Cell Performance & Durability – Past, Present and Future	Anne Hauch :: *Haldor Topsøe A/S*
11:45	24	Operating strategies for dispatchable PEM electrolyzers that enable low-cost hydrogen production	Mark Ruth :: *National Renewable Energy Laboratory*

12:15 - 13:30 **Green Center**

Lunch

13:30 - 15:10 Metals Hall

Polymer Electrolyte Membrane Electrolysis 1

Chair: Magnus Thomassen

13:30	88	Understanding Durability of PEM Water Electrolyzers	Siddharth Komini Babu :: *Los Alamos National Laboratory*
13:50	65	Three-dimensional analysis of morphological changes in anodic PEWE catalyst layers by X-ray ptychographic laminography	Carl Cesar Weber :: *Electrochemistry Laboratory, Paul Scherrer Institut*
14:10	39	Degradation Mechanisms of Proton Exchange Membrane Water Electrolyzer Stacks	Benjamin Kimmel :: *German Aerospace Center*
14:30	104	Anode Catalyst Durability in Low Temperature Electrolysis	Shaun Alia :: *National Renewable Energy Laboratory*
14:50	16	Reference Electrodes in PEM Water Electrolysis – a Review and Experimental Investigation of Oxygen and Hydrogen Evolution Reaction Kinetics	Lena Viviane Buehre :: *LUH IfES-EES*

15:10 - 15:40 Green Center Lobby

Break

15:40 - 17:30 Metals Hall

Alkaline Electrolysis 1

Chair: Jens Oluf Jensen

15:40	34	A High-performance Capillary-fed Electrolysis Cell Promises more Cost-competitive Renewable Hydrogen	Aaron Hodges :: *Intelligent Polymer Research Institute, University of Wollongong, Australia* Anh Linh Hoang :: *Intelligent Polymer Research Institute, University of Wollongong, Australia* Gerhard F. Swiegers :: *Intelligent Polymer Research Institute, University of Wollongong, Australia; Australian Research Council's Centre of Excellence for Electromaterials Science, University of Wollongong, Australia*
16:05	22	Durable Alkaline Electrolysis Using High Performance Membranes and Self-Adhesive Ionomers	Paul Kohl :: *Georgia Institute of Technology*
16:25	5	Active and durable electrodes for anion exchange membrane water electrolysis	Svein Sunde :: *Norwegian University of Science and Technology*
16:45	60	Solving the Mystery of Ohmic Resistance in Zero-gap Alkaline Water Electrolyzers	Rodrigo Lira Garcia Barros :: *Eindhoven University of Technology*

17:05	128	Catalyst Development and Elecrode Fabrication for Low-Temperature Water Electrolyzer Operating with Anion Exchange Membrane	Piotr Zelenay :: *Los Alamos National Laboratory*

17:30 - 20:00 Green Center Lobby

Poster Session 1

(Numbers below indicate the location of the poster.)

1	A Comparative Analysis of Conventional Ammonia Production with that based on High Temperature Solid Oxide Electrolysis Technology	Akhil Ashar :: *Colorado School of Mines*
2	Novel approaches in automatic microscopy and spectroscopy data analysis for fuel cells and electrolyzers	Mariah Batool :: *University of Connecticut*
3	High Temperature Electrolysis Technology Demonstration at Idaho National Laboratory	Micah Casteel :: *Idaho National Laboratory*
4	Effect of compression on the membrane electrode assembly of polymer electrolyte electrolyzers	Edgar Cruz Ortiz :: *Hahn-Schickard; Electrochemical Energy Systems, IMTEK – Department of Microsystems Engineering, University of Freiburg*
5	Electron microscopy investigation of porous transport layer surface structures and coatings	David Cullen :: *Oak Ridge National Laboratory*
6	Highly Efficient IrOx Catalyst Integrated Thin Electrodes for Low-cost Water Electrolyzers	Lei Ding :: *University of Tennessee, Knoxville*
7	Physicochemical Evolution of SOECs as a Function of Accelerated Ageing: A Multi-Scale X-ray Characterization Approach	Michael Dzara :: *National Renewable Energy Laboratory*
8	X-ray photoelectron spectroscopy characterization of polymer electrolyte membrane fuel cell and water electrolyzers	Jayson Foster :: *Colorado School of Mines*
9	Reversible PEM Test Station – Advanced Analytical Possibilities for PEM WE Research	Anna Teresa Sophie Freiberg :: *Forschungszentrum Jülich GmbH, Helmholtz Institute Erlangen-Nürnberg for Renewable Energy ; Department of Chemical and Biological Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg*
10	The role of surface area and stability-aspects of nickel-molybdenum HER electrocatalysts for the Alkaline Water Electrolysis	Florian Gellrich :: *DTU Energy*
11	Development of an Open-Source Modelling Framework for Electrolysis Technologies	Michael Gerhardt :: *SINTEF Industry*
12	Understanding The Effects of Different ECS Supports on the Sintering Processes of Pt Nanoparticles	Andres Godoy :: *University of Connecticut*
13	Fluidized bed processing for scaled-up production of Pt/C catalysts for fuel cell applications	Chris Gump :: *Forge Nano, Inc.*
14	Critical Analysis of Published Physical Property Data and Collation into Detailed Models of Alkaline Electrolysis	Aaron Hodges :: *University of Wollongong*
15	Advanced Materials for Efficient and Durable Water Electrolysers	David Hodgson :: *TFP Hydrogen*
16	Thermal management of H2/H2O based reversible solid oxide cell (ReSOC) system for electrical energy storage (EES) applications	Javad Hosseinpour :: *Colorado School of Mines*
17	Accelerating Anion-Exchange Membrane Water Electrolysis Development	Seyed Schwan Hosseiny :: *CENmat*
18	Off-Grid Solar PV-Wind Power-Battery-Water Electrolyser Plant: Simultaneous Optimisation of Component Capacities and System Control	Alejandro Ibanez-Rioja :: *Lappeenranta-Lahti University of Technology LUT*

19	Novel composite oxygen electrodes with tuned open porosity for enhanced performance of solid oxide reversible cells (rSOC)	Stanislaw Jagielski :: *Center for Hydrogen Technologies (CTH2), Institute of Power Engineering, Augustowka 36, 02-981 Warsaw, Poland; Institute of Power Engineering, Mory 8, 01-330 Warsaw, Poland; Institute of Heat Engineering, Warsaw University of Technology, Nowowiejska 21/25, 00-665 Warsaw, Poland*
20	Bipolar polymer electrolyte membranes for electrochemical CO2 conversion	Yi-Lin Kao :: *Technical University of Denmark*
21	Caustic Aqueous Phase Electrochemical Reforming of Ethanol for Compressed Hydrogen Production	Benjamin Kee :: *Washington State University*
22	Electrode engineering for anion-exchange membrane water electrolyzers	Susanne Koch :: *Hahn Schickard; Electrochemical Energy Systems, IMTEK - Department of Microsystems Engineering, University of Freiburg*
23	Monitoring of industrial water electrolysis systems for efficient and safe operation	Joonas Koponen :: *Neovolt*
24	Parametric impedance spectroscopy study on nickel based alkaline electrolysis cells	Mikkel Rykær Kraglund :: *Technical University of Denmark*
25	IrxNb1-xO2 Mixed Metal Oxides as Anode Catalyst for PEM Electrolysis: from Fundamentals to Application	Matthias Kroschel :: *Technical University Berlin*
26	Deep integration of solid oxide electrolyzers with steam cycles – towards repurposing conventional power plants	Jakub Kupecki :: *Institute of Fluid Flow Machinery, Polish Academy of Sciences; Center for Hydrogen Technologies (CTH2), Institute of Power Engineering; Institute of Power Engineering*
27	Water-splitting on Pr2NiO4+6 electrodes with BaZr0.7Y0.3-yPryO3-6 overlayers in protonic-ceramic electrolysis cells	Mayuri Kushare :: *Colorado School of Mines*
28	Optimal operating parameters for advanced alkaline water electrolysis	Rodrigo Lira Garcia Barros :: *Eindhoven University of Technology*
29	A more efficient design philosophy for PEM fuel cell electrodes	John Slack :: *Nikola Corporation*
30	Investigations of SOEC Degradation Using Electron and Ion Microscopy	Heather Slomski :: *Colorado School of Mines*

Tuesday • June 21, 2022

07:30 - 08:00 Green Center Lobby

Check-in

08:00 - 10:00 Metals Hall

Solid Oxide Electrolysis 1

Chair: Neal Sullivan

08:00	112	Emergent Nanomaterials for Solid Oxide Electrolysis	John Irvine :: *University of St Andrews*
08:20	26	Metal-supported solid oxide electrolysis cells	Michael Tucker :: *Lawrence Berkeley National Laboratory*

08:40	55	Investigation of the stability of air electrode in solid oxide electrolysis cells (SOEC) operated under high concentration of steam	Michał Wierzbicki :: *Center for Hydrogen Technologies (CTH2), Institute of Power Engineering, Augustowka 36, 02-981 ; Institute of Power Engineering, Mory 8, 01-330 ; Institute of Heat Engineering, Warsaw University of Technology, Nowowiejska 21/25, 00-665*
09:00	111	Understanding Performance and Durability of Solid Oxide Electroyzers	Olga Marina :: *Pacific Northwest National Laboratory*
09:20	99	A hybrid measurement technique for rapid insight into electrochemical performance	Jake Huang :: *Colorado School of Mines*
09:40	79	Sensitivity analysis of the effects of microstructure of the performance of solid oxide electrolyzer operated at elevated pressure	Jakub Kupecki :: *Center for Hydrogen Technologies (CTH2), Institute of Power Engineering; Institute of Power Engineering; National Fuel Cell Research Center (NFCRC), University of California, Irvine*

10:00 - 10:30 **Green Center Lobby**

Break

10:30 - 12:15 **Metals Hall**

Polymer Electrolyte Membrane Electrolysis 2

Chair: Pierre Millet

10:30	97	Towards better understanding of the Transport-/Catalyst layer Interface	Felix Büchi :: *Paul Scherrer Institut*
10:50	121	Understanding Effect of Porous Transport Layer Morphologies and Catalyst Layer Structure on Oxygen Transport in Polymer Electrolyte Membrane Water Electrolyzer	Iryna Zenyuk :: *University of California Irvine*
11:15	98	Understanding Structure and Catalyst Distribution of Anodic Porous Transport Electrodes in Proton Exchange Membrane Water Electrolyzers	Markus Bierling :: *Helmholtz Institute Erlangen-Nürnberg for Renewable Energy; Department of Chemical and Biological Engineering, Friedrich-Alexander-University Erlangen-Nürnberg*
11:35	56	Design of Catalyst Layers for Fuel Cell and Electrolyzer Application	Alexey Serov :: *Oak Ridge National Laboratory*
11:55	103	Characterization of surfaces and interfaces in polymer electrolyte membrane electrolyzers	Svitlana Pylypenko :: *Colorado School of Mines*

12:20 - 13:30 **Friedhoff Hall**

Lunch

13:30 - 15:20 Metals Hall

Alkaline Electrolysis 2

Chair: Dmitri Bessarabov

13:30	62	The impact of the supporting electrolyte on alternative materials performance for anion exchange membrane electrolysis	Diana De Porcellinis :: *Nel HYDROGEN*
13:55	106	Alkaline water electrolysis powered by fluctuating renewable energies	Thomas Turek :: *TU Clausthal*
14:20	51	Numerical simulation of Marangoni convection near a hydrogen bubble growing on a microelectrode	Aled Meulenbroek :: *Power & Flow group, Department of Mechanical Engineering*
14:40	29	MoNi4-MoO2 coated Ni-foam as a highly efficient cathode material for industrial scale alkaline electrolysis	Justin Albers :: *Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Branch Lab Dresden*
15:00	108	Perspectives of ion-solvating membranes for alkaline electrolysis	Jens Oluf Jensen :: *Technical University of Denmark*
15:20	129	Electrode and MEA Processing Methods for AEM Water Electrolysis	Derek Strasser :: *Giner Inc.*

15:40 - 16:00 Green Center Lobby

Break

16:00 - 17:30 Metals Hall

Solid Oxide Electrolysis 2

Chair: John T. S. Irvine

16:00	123	Progress in Power-to-X with Protonic-Ceramics	Ryan O'Hayre :: *Colorado School of Mines*
16:25	50	On the scaling up of proton ceramic electrolyser technology: progress in materials, cells, stacks and system development	Marie-Laure Fontaine :: *SINTEF AS*
16:45	49	Advancement of Proton Conducting Solid Oxide Electrolysis Cells (p-SOEC) for Hydrogen Production at Idaho National Laboratory	Lei Ding :: *Idaho National Laboratory*
17:10	96	Scaling proton-conducting ceramic fuel cells and electrolyzers from the laboratory to the marketplace	Neal Sullivan :: *Colorado School of Mines*

17:30 - 20:00 Green Center Lobby

Poster Session 2

(Numbers below indicate the location of the poster.)

1	An Open-Source Continuum Model for Anion-Exchange Membrane Water Electrolysis	Michael Gerhardt :: *SINTEF Industry*
2	Synthesis and characterization of PGM-free NiMo cathode and NiFe LDH anode catalysts for AEMWE	Lukas Heinius :: *Technical University Berlin* Pierre Schröer :: *Technical University Berlin*

3	Optimizing Component Interactions to Fabricate High Performance MEAs for Electrochemical Devices	Sadia Kabir :: *Twelve Incorporated*
4	Tubular PEM electrolysis cells – model-based design and experimental characterization	Armin Laube :: *Hamburg University of Applied Sciences; Instituto de Tecnología Química - Universitat Politècnica de València-CSIC*
5	Porous-transport-layer interface design for PEM electrolyzers via laser ablation	Jason Lee :: *Lawrence Berkeley National Lab*
6	Metal Organic Framework based Catalysts for the Oxygen Evolution Reaction in Alkaline Electrolysis	Julia Linke :: *Paul Scherrer Institute*
7	Enhancement of solid oxide electrolyzer (SOE) performance by adjustment of the Ni-8YSZ support microstructure	Anna Niemczyk :: *Institute of Power Engineering - Research Institute; Center for Hydrogen Technologies (CTH2), Institute of Power Engineering*
8	Catalyst Layer Resistance, Utilization, and Degradation in PEM Electrolysis	Elliot Padgett :: *National Renewable Energy Laboratory*
9	Model Based Analysis of Proton-Exchange-Membrane (PEM) Water Electrolyzer Parameters' Ageing	Fabian Pascher :: *Fraunhofer IWES*
10	Carbon-coated stainless steel as bipolar plate material in PEM water electrolyzers	Sebastian Proch :: *Sandvik Materials Technology*
11	PEEK reinforcement for sulfonated polyphenylsulfone membrane	Regina Qelibari :: *IMTEK - Albert-Ludwigs-Universität*
12	PANI/Zeolite-13X based Electrocatalyst for Hydrogen and Oxygen Evolution Reaction	Vinodh Rajangam :: *University of Quebec at Trois-Rivières (UQTR)*
13	Investigation of the interface between the anodic catalyst layer with low Iridium loading and the porous transport layer in PEM water electrolysis	Mirjam Rogler :: *Siemens Energy Global GmbH & Co. KG*
14	Dynamic energy and mass balance model for an industrial alkaline water electrolyzer plant process.	Georgios Sakas :: *Lappeenranta-Lahti University of Technology LUT*
15	FORBLUE: Developing new electrolysis membranes for a better, cleaner future	William Salem :: *AGC Chemicals Americas*
16	Enabling the large scale production of fluorine free electrode assemblies for proton exchange membrane water electrolysis	Clara Schare :: *Hahn-Schickard*
17	Time of Flight Secondary Ion Mass Spectrometry (ToF-SIMS) as a novel approach for characterization of Porous Transport Layers	Genevieve Stelmacovich :: *Colorado School of Mines*
18	Influence of the gas diffusion layer on the performance of a PEM water electrolyzer	Niklas van Treel :: *Hahn-Schickard für angewandte Forschung e. V.*
19	Establishing half- and single- cell baselines for the oxygen evolution reaction (OER) on non- platinum group metal (PGM) oxide electrocatalysts in alkaline media	Emily Volk :: *Mines / NREL Advanced Energy Systems Graduate Program*
20	Low Cost Coating Technology for PEM Water Electrolyzer Metallic Bipolar Plates	Conghua Wang :: *TreadStone Technologies, Inc.*
21	High-speed visualization of in-situ electrochemical reaction and transport at PEM/electrode interfaces in Electrolyzers	Weitian Wang :: *University of Tennessee Space Institute*
22	Vertically aligned carbon nanofibers promise more cost-efficient PEM water electrolyzers	Fabian Wenger :: *Smoltek AB* Qi Li :: *Smoltek AB*
23	Operando measurement of hydrogen crossover in proton exchange membrane electrolysis cells at differential pressures	Jacob Wrubel :: *National Renewable Energy Laboratory*
24	Exploring a novel polyethylene-based ionomer-catalyst ink formulation for single-cell alkaline electrolyzers	Ivy Wu :: *Colorado School of Mines*

25	Development of New Non-precious Catalyst Integrated Electrodes for Efficient Hydrogen Production in Practical PEM Electrolysis	Zhiqiang Xie :: *Department of Mechanical, Aerospace & Biomedical Engineering, UT Space Institute, University of Tennessee, Knoxville, TN 37388, USA*
26	Understanding the transport properties of PTL on the anode side and GDL on the cathode side for water electrolyzers	Abdurrahman Yilmaz :: *Los Alamos National Laboratory; University of Connecticut*
27	The impact of porous transport layer/anode contact on inhomogeneous degradation of membrane electrode assembly	Haoran Yu :: *Oak Ridge National Laboratory*
28	Grid balancing services from hydrogen electrolysers	Federico Zenith :: *SINTEF*
29	Mechanisms of Ni migration in Ni/YSZ/pore electrode of solid oxide electrolysis cells	Qian Zhang :: *Energy Environment S&T, Idaho National Laboratory; Department of Materials Science and Engineering, Northwestern University*

Wednesday • June 22, 2022

07:30 - 08:00 **Green Center Lobby**

Check-in

08:00 - 10:00 **Metals Hall**

Polymer Electrolyte Membrane Electrolysis 3

Chair: Svitlana Pylypenko

08:00	46	Manufacturing Challenges, Opportunities, and Successes for PEM Electrolysis at Scale	Christopher Capuano :: *Nel Hydrogen*
08:20	42	An Overview of the OREO International Collaboration Low-temperature Electrolysis Electrode Processing Activity	Michael Ulsh :: *National Renewable Energy Laboratory*
08:40	102	Low Temperature Electrolysis Catalyst Development, and Giga-manufacturing.	Barr Zulevi :: *Pajarito Powder LLC*
09:00	69	Tuning the Rheology of Anode Inks with Aging for Low-Temperature Polymer Electrolyte Membrane Water Electrolyzers	Sunilkumar Khandavalli :: *Chemistry and Nanoscience Department, National Renewable Energy Laboratory*
09:20	58	Fabrication, Performance, and Durability of Roll-to-Roll Coated Iridium-Based Anodes	Scott Mauger :: *National Renewable Energy Laboratory*
09:40	95	Understanding the Potential Dependence of Ir Dissolution from IrO2 PEM Electrolyzer Anode Catalysts Through Modeling of Time-Resolved Measurements	Deborah Myers :: *Chemical Sciences and Engineering Division, Argonne National Laboratory*

10:00 - 10:30 **Green Center Lobby**

Break

10:30 - 12:20 Metals Hall

Alkaline Electrolysis 3

Chair: EunAe Cho

10:30	114	AEM Electrolyzer Development at Hanwha Solutions	Hoon Chung :: *Hydrogen Technology R&D Center, Hanwha Solutions*
10:55	116	Industrializing alkaline electrolysis production at Stiesdal A/S	Harish Lakhotiya :: *Stiesdal Hydrogen A/S*
11:20	92	Developing high efficiency high rate alkaline water electrolyzers	Asif Ansar :: *DLR-TT*
11:40	33	Agfa's contribution to the hydrogen economy: Zirfon and the impact on the levelized cost of hydrogen	Nick Valckx :: *Agfa*
12:00	19	Metallic Glass NiFeM Nanofoam Anode Catalysts for Highly Efficient Anion Exchange Membrane Water Electrolyzers	Gang Wu :: *University at Buffalo, SUNY*

12:20 - 12:30 Green Center

Bag Lunch

12:30 - 18:00 Green Center

Afternoon Networking Activities

Afternoon Networking Activities (Organized activities include white water rafting, or an additional tour option, sign up required by Monday June 20th at Conference or explore on your own)

18:00 - 22:00 The Fort

Conference Dinner

Please see Page 3 of this program for full information about the Conference Dinner.

Thursday • June 23, 2022

07:30 - 08:00 Green Center Lobby

Check-in

08:00 - 10:00 Metals Hall

Polymer Electrolyte Membrane Electrolysis 4

Chair: Tom Smolinka

08:00	68	Review of morphology and synthesis of Pt-based micro-particles in PEM WE for hydrogen cross-over reduction	Dmitri Bessarabov :: *HySA at North-West University*
08:20	57	Optimal design of a Pt recombination interlayer for the safe hydrogen production with PEM water electrolysers	Agate Martin :: *Institute of Electric Power Systems / Leibniz University Hannover*

08:40	118	Breaking the hydrogen crossover limitations for PEM electrolysers - Hystar's next generation PEM electrolysers	Magnus Thomassen :: *Hystar AS*
09:00	87	Benchmarking efforts for the PEM electrolysis community – a reference protocol	Sebastian Metz :: *Fraunhofer Institute for Solar Energy Systems*
09:20	18	Performance of PEM Water Electrolyser System operating up to 200 bar	Ragnhild Hancke :: *IFE*
09:40	94	Investigation of power electronics as interface between power grid and electrolyser	Lorenz Beck :: *Fraunhofer Institute for Wind Energy Systems*

10:00 - 10:30 Green Center Lobby

Break

10:30 - 11:50 Metals Hall

Solid Oxide Electrolysis 3

Chair: Olga Marina

10:30	23	CO2 and Steam Co-Electrolysis Using a Solid Oxide Electrolyzer	Jamie Holladay :: *Pacific Northwest National Laboratory*
10:50	64	Simulative and experimental investigations of transient operating behaviour of SOEC reactors with multiple stacks for syngas production	Daniele Fortunati :: *German Aerospace Center (DLR)*
11:10	31	Scenarios for reversible operation of solid oxide cell systems to produce hydrogen and electricity as compared to standalone SOEC plants	Aadarsh Parashar :: *Colorado School of Mines*
11:30	37	Reduced order model of co-electrolysis of steam and carbon dioxide in solid oxide electrochemical cells (co-SOE)	Maciej Bakala :: *Center for Hydrogen Technologies (CTH2), Institute of Power Engineering; Institute of Power Engineering; Doctoral School No. 4, Warsaw University of Technology*

11:50 - 12:20 Metals Hall

Closing Session

12:20 - 13:00 Green Center

Bag Lunch

13:00 - 14:00 Green Center

Tour of NREL

Optional tour of NREL H2/Electrolysis facilities (additional information and requirements for NREL tour provided in email and on conference Website)

5

Active and durable electrodes for anion exchange membrane water electrolysis

Dr Alaa Faid[1], Prof Svein Sunde[1]
[1]*Norwegian University of Science and Technology, , Norway*

Alkaline Electrolysis 1, Metals Hall, June 20, 2022, 3:40 PM - 5:30 PM

Active and durable electrodes for anion exchange membrane water electrolysis

Alaa Y. Faid[a], Svein Sunde[a]
[a]*Norwegian University of Science and Technology, Trondheim, Norway*
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Summary. Cost efficient, scalable to large batches, efficient, and stable Ni-based catalysts and electrodes has been developed for oxygen and hydrogen evolution in anion exchange membrane (AEM) water electrolysis.

Abstract. Low-temperature water electrolysis is a sustainable and efficient hydrogen production technology. Anion exchange membrane (AEM) water electrolysis utilizes non-platinum group metal (PGM) electrocatalysts aiming to achieve high efficiency and low-cost green hydrogen. Active, durable, and commercially viable non-PGM hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) catalysts are needed for scaling up electrolyzer technology to giga-scale. In this work, transition metal based OER and HER catalysts were tuned and scaled up with improved mass activity and stability in alkaline electrolytes. In situ Raman spectroscopy has been used to monitor intermediate formation and catalyst oxidation states during HER and OER conditions. The interaction between the catalysts and ionomers and organic electrolytes has been investigated using electrochemical and spectroscopy techniques. The catalysts were used to fabricate electrodes and membrane electrode assemblies (MEAs) and single-cell AEM electrolyzer testing. The MEAs were then optimized for optimum performance (1 A/cm^2 at 1.7 V) and durability for 160 hours in 1M KOH and 60 ^{o}C.

Acknowledgements

Part of this work has been performed in the frame of the CHANNEL project. This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under grant agreement No 875088. This Joint undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research. Part of this work was performed within HAPEEL project "Hydrogen Production by Alkaline Polymer Electrolyte Electrolysis" financially supported by the Research Council of Norway-ENERGIX program contract number 268019 and the INTPART project 261620. P.K.D. The Research Council of Norway is acknowledged for the support to the Norwegian Micro- and Nano-Fabrication Facility, NorFab, project number 245963/F50.

Vertically aligned carbon nanofibers promise more cost-efficient PEM water electrolyzers

DR. Qi Li[1], **DR. Fabian Wenger**[1], DR. Theodora Krasia-Christoforou[2], DR. Alberto Visibile[3], DR. Xin Wen[1], MS. Maria Bylund[1], MS. Simin Zare[1], DR. Amin Saleem[1], MR. Rickard Andersson[1], MR. Victor Marknäs[1], MS. Elisa Passalacqua[1], DR. Ellinor Ehrnberg[1]

[1]Smoltek AB, , Sweden, [2]University of Cyprus, , Cyprus, [3]Chalmers University of Technology, , Sweden

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Vertically aligned carbon nanofibers promise more cost-efficient PEM water electrolyzers

Qi Li[a], Fabian Wenger[a], Theodora Krasia-Christoforou [b], Alberto Visibile[c], Xin Wen[a], Maria Bylund[a], Simin Zare[a], Amin Saleem[a], Rickard Anderson[a], Victor Marknäs[a], Elisa Passalacqua[a], Ellinor Ehrnberg[a]

[a] Smoltek AB, Kaserntorget 7, Gothenburg 411 18, Sweden; [b] University of Cyprus, Nicosia 1678, Cyprus; [c] Chalmers University of Technology, Gothenburg 412 96, Sweden
Corresponding author email: qi.li@smoltek.com; fabian.wenger@smoltek.com

Summary. Vertically aligned carbon nanofibers (CNF) create low-tortuosity conducting 3D nanostructures over porous transport layers (PTLs), acting as supports for ultra-low loading of iridium catalyst with non-compromised performance. Proton exchange membrane water electrolysis (PEMWE) is envisaged to be more efficient using such advanced PTLs.

Abstract. PEMWE is recognized as a key technology for sustainable hydrogen production. However, the necessity of using platinum group metals (PGMs) as catalysts sets up a barrier for establishing GW-scale systems. Especially on the anode side for oxygen evolution, the loading of iridium catalyst must be reduced significantly from currently 2 mg_{Ir} cm^{-2} to 0.05 mg_{Ir} cm^{-2} level to enable large scale application of PEMWE [1]. Even though substantial progress has been made, there remain tremendous challenges to make PEMWE work at ultra-low loadings in practice.

In this work, we pursue to solve the challenges by using CNF modified PTLs and adopting catalyst coated substrate (CCS) or porous transport electrode (PTE) [2-3] concept. A 3D nanostructure over the PTLs top surface is created through chemical vapor deposition of vertically aligned CNFs. The metallic CNFs act as catalyst supports, establishing a direct electronic bridge between iridium catalysts and the PTL, thus increasing the accessibility and maximizing the usage of noble metals. The low tortuosity of the vertically aligned structure can also enhance the gas diffusivity and water management, thereby further boosting the catalysis. The CNF 3D nanostructure over PTLs also shows promises in improving conventional membrane electrode assembly (MEA) based PEMWE. Especially for MEAs of a low iridium loading, additional points of electrical contacts between the catalyst in MEAs and the PTLs are provided by CNF. To a large extent, the CNF structure eliminates the need and difficulty in forming a percolating conductive network across thin and low-loading MEAs.

Hitherto, several key validations have been completed for the CNF enhanced PEMWE proof-of-concept: (1) Uniform CNF growth has been demonstrated on titanium PTLs, exhibiting vertical alignment and a suitable fill factor; (2) Corrosion protection of CNF has been shown with a conducting, pinhole-free and conformal coating of titanium nitride (TiN) thin film, enabling stability at potential < 1.6 V vs. RHE (reversible hydrogen electrode) in a static testing environment; (3) Well-dispersed iridium catalyst nanoparticles were deposited onto the TiN coated CNF surfaces; (4) The intrinsic electrical conductivity of CNF and its contact resistance to a titanium substrate have been estimated to be as low as 60 mΩ·cm and < 0.6 mΩ·cm, respectively; (5) Mechanical strength of TiN coated CNFs was investigated in hot-pressing experiments, indicating the vertical CNF can withstand high compaction pressure without structural collapse. Alternative corrosion protection materials and coating methods for widened stability window, catalyst deposition technique, full cell demonstration and scale-up production are being followed up to advance more cost-efficient PEMWE for green hydrogen.

References. [1] M. Bernt, et al. *Chem. Ing. Tech.*, 2020, 92, 31; [2] A. S. Pushkarev, et al. *Electrochem. Acta*, 2021, 399, 139436; [3] M. Bühler, et al. *J. Mater. Chem. A*, 2019, 7, 26984.

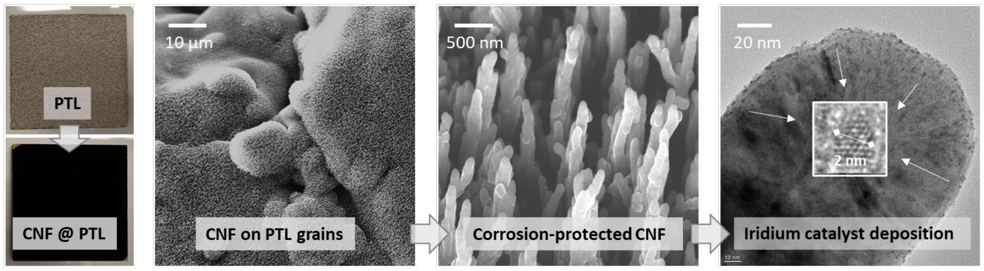

Figure 1. Vertically aligned CNF enhanced PTL for ultra-low iridium loading

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Enhancement of solid oxide electrolyzer (SOE) performance by adjustment of the Ni-8YSZ support microstructure

Dr. Anna Niemczyk[1,2], Mr. Stanisław Jagielski[1,2,3], Prof. Jakub Kupecki[1,2,4], Dr. Ryszard Kluczowski[1,5], Ms. Magdalena Kosiorek[1,2,3], Dr. Agnieszka Żurawska[1,2]

[1]Institute of Power Engineering - Research Institute, , Poland, [2]Center for Hydrogen Technologies (CTH2), Institute of Power Engineering, , Poland, [3]Institute of Heat Engineering, Warsaw University of Technology, , Poland, [4]National Fuel Cell Research Center (NFCRC), University of California, Irvine, Engineering Laboratory Facility, , The United State of America, [5]Ceramic Department (CEREL), Institute of Power Engineering, , Poland

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Enhancement of solid oxide electrolyzer (SOE) performance by adjustment of the Ni-8YSZ support microstructure

Anna Niemczyk[a,b], Stanisław Jagielski[a,b,c], Jakub Kupecki[a,b,d], Ryszard Kluczowski[e], Magdalena Kosiorek[a,b,c], Agnieszka Żurawska[a,b]

[a] Center for Hydrogen Technologies (CTH2), Institute of Power Engineering, Augustowka 36, 02-981 Warsaw, Poland;
[b] Institute of Power Engineering, Mory 8, 01-330 Warsaw, Poland;
[c] Institute of Heat Engineering, Warsaw University of Technology, Nowowiejska 21/25, 00-665 Warsaw, Poland;
[d] National Fuel Cell Research Center (NFCRC), University of California, Irvine, Engineering Laboratory Facility, Irvine, CA 92697-3550, USA;
[e] Ceramic Department (CEREL), Institute of Power Engineering, Techniczna 1, 36-040 Boguchwala, Poland
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Summary. The relation between the porosity of Ni-8YSZ-based support which was fabricated using high-pressure injection molding and SOE performance is presented. The microstructural modifications of the support were achieved using alternative pore formers (graphite, PMMA, and rice starch) with varied content, coupled with a manipulation of the sintering temperature.

Abstract. The development of SOE which is observed in the recent decade is mainly focused on the extension of their lifespan and minimizing their manufacturing costs. Various strategies were presented in the literature, including modification of the composition and microstructure of the fuel and air electrodes. By the fine-tuning of the microstructural parameters, such as the size and distribution of pores, the electrochemical properties of the SOE may be controlled. An insufficient open porosity of the electrode or electrode-based support may hinder gas diffusion to the TPB resulting in a high concentration overpotential which directly translates into the lower performance of solid oxide electrochemical cells.

In this work, a correlation between the porosity of the Ni-8YSZ support and the performance of SOE is presented. In order to optimize the microstructure of the support, which is manufactured by high pressure injection molding, a sacrificial template method was applied. Three different types of pore formers were considered - graphite, PMMA, and rice starch, and their content in the support varied from 25 vol.% to 35 vol.%, was investigated. Moreover, to evaluate the influence of sintering temperature on the porosity of the support part of samples with graphite were sintered in the reduced temperature due to implementation of Sc- and Ce-doped zirconia electrolyte (10Sc1CeSZ) instead of the standard 8YSZ electrolyte (sintering temperature decreased by 50 °C). Overall nine different batches of cells (all in the size of 50 mm x 50 mm with a thickness of ca. 1 mm), while seven with 8YSZ electrolyte and two with 10Sc1CeSZ, were

prepared and studied. All cells were evaluated in terms of their microstructure using the tools of SEM analysis, and electrochemical performance in the electrolysis mode. The current density-voltage dependences and EIS spectra with refinement gained in various conditions of temperature and inlet gases are presented. It was observed that the type of the pore former, therefore different microstructure of the support, has a considerable impact on the SOE performance.

The presented research was financially supported by the National Science Centre, Poland, within project no. 2018/31/D/ST8/00123.

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Electrode engineering for anion-exchange membrane water electrolyzers

Ms. Susanne Koch[1,2], Ms. Sophia K. Kilian[1,2], Mr. Joey L. Disch[1,3], Dr. Lukas Metzler[1], Mr. Philipp A. Heizmann[1,3], Dr. Matthias Breitwieser[1,2], Dr. Severin Vierrath[1,2,3]

[1]Hahn Schickard, , Germany, [2]Electrochemical Energy Systems, IMTEK - Department of Microsystems Engineering, University of Freiburg, , Germany, [3]University of Freiburg, Institute and FIT – Freiburg Center for Interactive Materials and Bioinspired Technologies, , Germany

Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Electrode engineering for anion-exchange membrane water electrolyzers

Susanne Koch[a,b], Sophia K. Kilian[a,b], Joey L. Disch[a,c], Lukas Metzler[a], Philipp A. Heizmann[a,c], Matthias Breitwieser[a,b], Severin Vierrath[a,b,c]

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Summary. We fabricated anion-exchange membrane water electrolyzer CCMs with variations in the catalyst layers that allow targeted water management and trade-off optimization between durability and performance.

Abstract. In anion-exchange membrane (AEM) water electrolysis durability provides a particular challenge due to the often strongly hydrophilic nature of the hydrocarbon ionomers and membranes. [1] While reinforcements and modified polymer chemistry have greatly improved stability and handling of the membrane, overall durability and often reproducibility are still lacking. This is typically attributed to the mechanical durability of the catalyst layer and the polymers used as binder.

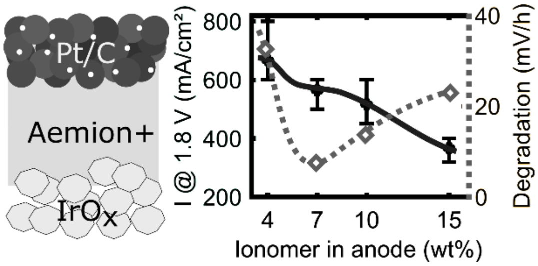

Fig. 1 Schematic of a catalyst-coated membrane as used in this work (left) and an overview of the current density and degradation rate vs. the ionomer content in the anode catalyst layer (right). Based on [2].

Here, we present approaches to optimize catalyst layers for specific operation modes in AEM water electrolyzers using commercial Aemion+™ materials. The ionomer content in the catalyst layer is varied to optimize for performance and durability in a system fed with aqueous KOH at both the anode and cathode side (Fig. 1). [2]

We further investigated dry cathode operation, where only the anode side is supplied with liquid KOH. This mode introduces unique challenges for the non-fluorinated anion-exchange polymers, whose conductivity and mechanical properties are strongly influenced by the water content. [3] To analyze the water content inside an operating AEM water electrolyzer we employed in-situ neutron imaging. Varying the anion-exchange-capacity of the cathode binder ionomer, showed that a higher binder IEC helps to retain the membrane humidification (Fig. 2).[4]

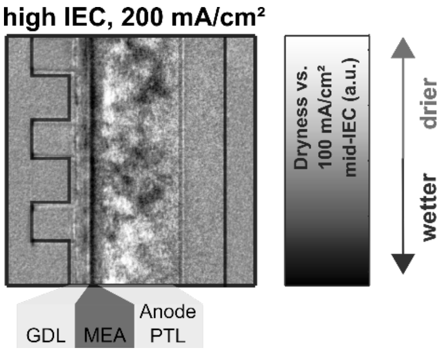

Fig. 2 Relative dryness inside an AEM water electrolyzer during operation at 200 mA/cm² vs. the measurement at 100 mA/cm² of the mid IEC cell. Based on [4].

1. Li D, Motz AR, …, Kim YS. Durability of anion exchange membrane water electrolyzers. Energy Environ Sci. 2021;14(6):3393–419.

2. Koch, S, …, Vierrath, S. The effect of ionomer content in catalyst layers in anion-exchange membrane water electrolyzers prepared with reinforced membranes (Aemion+™). Journal of Materials Chemistry A.

3. Dekel DR, …, Diesendruck CE. Effect of Water on the Stability of Quaternary Ammonium Groups for Anion Exchange Membrane Fuel Cell Applications. Chem Mater. 2017 May 23;29(10):4425–31.

4. Koch S, …, Vierrath S. Water management in anion-exchange membrane water electrolyzers under dry cathode operation. Submitted. 2022;

9

Tubular PEM electrolysis cells – model-based design and experimental characterization

Mr. Armin Laube[1,5], Mr. André Hofer[2], Mr. Simon Fischer[3], Ms. Beatrix Sánchez Batalla[4], Dr. Antonio Chica[5], Dr. Thorsten Struckmann[1]
[1]Hamburg University of Applied Sciences, Scientist, Germany, [2]Friedrich-Alexander University Erlangen-Nürnberg, Scientist, Germany, [3]Uniwell Rohrsysteme GmbH & Co. KG, Manager, Germany, [4]Dechema Forschungsinstitut, Scientist, Germany, [5]Instituto de Tecnología Química - Universitat Politècnica de València-CSIC, Scientist, Spain

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Tubular PEM electrolysis cells – model-based design and experimental characterization

Armin Laube[a,e], André Hofer[b], Simon Fischer[c], Beatriz Sánchez Batalla[d], Antonio Chica[e], Thorsten Struckmann[a],

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[b]Friedrich-Alexander University Erlangen-Nürnberg, Cauerstr. 3, 91058 Erlangen, Germany
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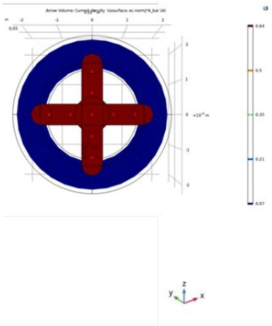
Summary. We present experimental and simulation results for tubular PEM electrolysis cell designs with a reduced amount of noble catalysts and without the need for titanium bipolar plates, enabling a production by coextrusion. The experimental characterisation shows mass activities that are comparable to commercial planar cells.

Abstract. Major challenges to increase the production of hydrogen with PEM electrolysis are the scarcity of noble metals needed for catalysts and high system costs. The costs of commercial PEM electrolysis cells are dominated by the bipolar plates (about 50% of stack costs [1]). Corrosion resistant titanium and high requirements for production tolerances to reach leak tightness of planar cell stacks are the main cost drivers. Despite of the current research progress, further improvements for these challenges are necessary. The tubular design enables the utilization of components fabricated cost efficiently by coextrusion as already demonstrated for tubular redox flow batteries [2]. Furthermore, it features a reduction of the sealing length and a higher stability against pressure differences. We combine the tubular approach with a catalyst coating by atomic layer deposition to additionally realize a significant reduction of noble catalyst loadings [3]. Based on a feasibility study for tubular MEAs [4], this work presents a design study of tubular cells containing porous transport electrodes with a low catalyst coating by atomic layer deposition. The design process is divided into a model-based analysis of the conducting tubular structure as well as experimental characterizations of components in a planar cell design and of complete tubular PEM electrolysis cells. With the tubular design, we are able to eliminate the titanium based bipolar plates and include extruded components while the mass activity of the catalysts is kept at a high level.



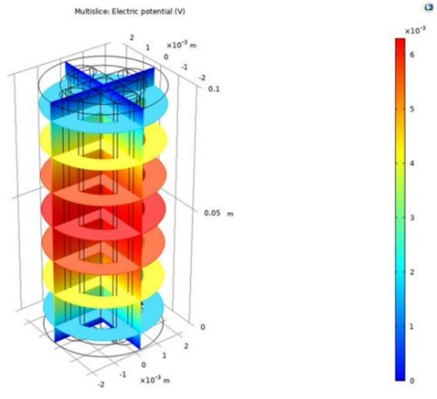


Figure 1: Model based conductivity analysis of tubular electrode structures (left), tubular PEM electrolysis cell with a-catalyst coating by atomic layer deposition and extruded membrane (right)

[1] L. Bertuccioli, A. Chan, D. Hart, F. Lehner, B. Madden, E. Standen, Study on development of water electrolysis in the EU, Tech. rep., E4tech (Feb. 2014).
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[4] A. Laube et al., Tubular membrane electrode assembly for PEM electrolysis, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.03.135

10

Grid balancing services from hydrogen electrolysers

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

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Summary. We evaluate the potential of several types of grid services in France, Italy, Norway and Spain to provide an alternative income for electrolysers producing green hydrogen from wind power. Results indicate that providing grid services with electrolyser spare capacity can be profitable, especially in grids with little dispatchable power generation.

Abstract. The possibility of improving the economy of early green-hydrogen production plants by using their electrolysers to supply grid services to the power grid was previously investigated by several authors and is often cited as critical to their profitability, but reported results have been inconsistent. In particular, the uncertainty on capital and operational costs of the plant hampers a precise estimate of the levelised cost of hydrogen (LCOH).

To isolate the contribution of grid services to the profitability of an already available electrolyser plant, we define the *value of curtailed hydrogen* as the ratio of income from grid services to the reduction in hydrogen production they require. This quantity is independent from most plant properties, in particular capital cost and maintenance. The value of curtailed hydrogen in €/kg can be readily compared to hydrogen price targets, and gives an indication of how provision of grid services compares with income from hydrogen sales.

We simulated a year of operation of such an electrolyser plant within the fence of a 45 MW wind park, under the assumption that no power can be imported, both in a nominal operation of maximum production and three different regulatory regimes: up, down and symmetric regulation. The simulations were run for two electrolyser sizes: one matching the wind park, and another far smaller, 2,5 MW.

As regulatory rules and prices vary widely between countries, we ran simulations with historical data from 2017 for four countries: Norway, Italy, Spain and France. For each country, we considered their specific remuneration schemes, but we also used standardised regimes to maintain comparability. Wind power production profiles were selected from the relevant countries and match the same year of spot and grid-service prices.

Results indicate that several factors can influence the value of curtailed hydrogen: up-regulation is clearly the most profitable regime, followed by symmetric and down-regulation. Countries with large amounts of non-controllable energy production (e.g. solar and wind), like Spain, fare significantly better than countries with large amounts of controllable hydro power, like Norway. Interestingly, the size of the electrolyser does not seem to impact our metric (even if it will likely influence the LCOH).

As non-controllable energy resources such as wind and solar are today the cheapest sources of power, it is expected grid service demand will rise in the medium-long term, further improving the case for participation of electrolysers in the grid service market.

It appears in conclusion that renewables and hydrogen generation can solve each other's main problems: the lack of flexibility in renewable generation can be compensated by electrolysers, which in turn are able to monetise their unused hydrogen generation capacity.

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Reversible PEM Test Station – Advanced Analytical Possibilities for PEM WE Research

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Reversible PEM test station – advanced analytical possibilities for PEM WE research

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Summary. Reversible PEM stacks would be a great leap toward improved usage of fluctuating renewable energy supply for local application. Test stations that offer both fuel cell and electrolysis mode have to be custom made. One possible technical outline that also offers additional analytical possibilities for PEM WE research is presented.

Abstract. For optimum usage of fluctuating renewable energy supply, the usage of hydrogen gas as a form of chemical energy storage is considered to be one of the most promising options that would be able to reduce or eliminate the necessity of using flexible power generation by fossil fuels, which are currently needed to satisfy the real-time energy demand. Reversible PEM stacks have gained research interest therewith, as they would optimize the system power density for local application.

The catalyst layers in such stacks would need to be active for both, the fuel cell and water electrolysis mode. Testing such catalyst layers in one test station is important to ensure that reasonably fast mode switches would be possible for the catalyst chosen on each electrode with sufficient life time of the stack system.

The requirements for a membrane electrode assembly (MEA) to run in fuel cell or water electrolysis mode are comparable, but not identical. Both systems are operated at similar elevated temperatures (60-80°C), which concomitantly offers the possibility for significant reduction of operating costs when both modes are operated in one stack. On the other hand, feed and exhaust handling is more challenging as PEM WE systems are generally operated with a liquid water feed to the oxygen evolution reaction electrode while running the hydrogen evolution reaction electrode without feed but at elevated back-pressures (20-50 bar).[1,2] PEM FC electrodes, on the other hand, are fed with humidified reactant gases on both electrodes. Liquid water formation has to be strictly avoided during PEM FC operation to prevent local electrode degradation.

Here we present a possible layout for a lab-scale reversible PEM test station. It was chosen to have the electrode sides fixed with respect to the active gas, i.e., the hydrogen evolution and oxidation are happening on the same electrode when switching operation mode from WE to FC in order to prevent down-time for inert flushing.[3] The combination of both FC and WE functionalities in one test station allows advanced analytical possibilities for PEM WE research. Being able to supply a two-phase flow (liquid water and gaseous oxygen) to the WE anode enables mimicking of operation conditions happening close to the outlet of large PEM WE cells. The possibility to supply humidified gases to either electrode enables a deeper understanding of the impact of indirect cathode compartment humidification through the

membrane of a PEM WE MEA. In addition, pressure drop analysis over the flow field as commonly used for PEM FC optimization enables a thorough study on the impact of gas diffusion media and flow field design on overall PEM WE performance under different operating conditions. The analysis possibility of such a reversible test station is further expanded by exhaust analysis using a mass spectrometry system.

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Carbon-coated stainless steel as bipolar plate material in PEM water electrolyzers

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Carbon-Coated Stainless Steel as a Bipolar Plate Material in PEM Water Electrolyzers

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Summary. ***Carbonize*** PEM electrolyzers to ***decarbonize*** hydrogen?

Abstract. The ***anode*** electrode of a ***PEM water electrolyzer*** experiences potentials of >1.5 V vs. RHE during operation [1]. Recent measurements with an *in situ* reference electrode suggest that, contrary to conventional wisdom, the potential of the anode bipolar plate is closer to the component's open circuit potential, which is around 1 V vs. RHE [2] for platinum-coated titanium. Here we demonstrate in a single cell that a ***carbon-coated 316L stainless-steel current collector*** rests comfortably at potentials around 1 V vs. RHE where the material is known to be stable (see **Error! Reference source not found.**). An additional feature of this material is ***low and stable contact resistance*** (≈ 2 mΩ cm^2 @ 1.4 MPa) and no contamination of the catalyst-coated membrane is observed after 30 days @ 2 A cm^{-2}. Therefore, carbon-coated stainless steel presents a potentially ***cost-effective solution*** for GW-scale application of water electrolysis since it might replace (Pt-coated) titanium.

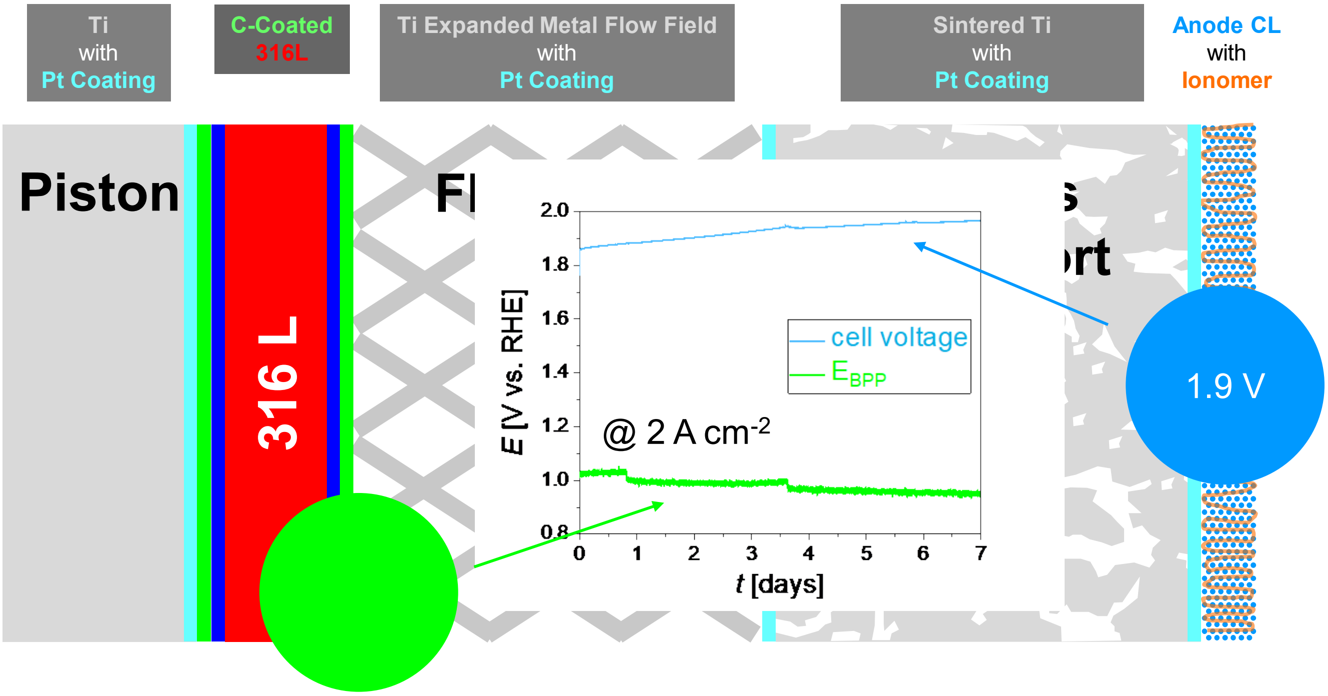

Figure 2. Anode compartment of a single-cell PEM water electrolyzer. The cell voltage (blue) is compared to the potential at the surface of the carbon-coated 316L stainless-steel current collector (green, measured in situ).

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Metal Organic Framework based Catalysts for the Oxygen Evolution Reaction in Alkaline Electrolysis

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

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Summary. The studied Ni and Co-MOF-74 catalysts are subject to electronic and structural transformations during OER, whereby Ni-MOF-74 increases its OER activity during operation. Using operando XAS and XRD analyses the changes of the catalyst’s electronic/local structure are extracted revealing research perspectives regarding the OER activity and stability of MOF-74 catalysts.

Abstract. Alkaline electrolysis is an appealing technology to produce hydrogen from water using earth-abundant, non-noble metal catalysts. However, the kinetics of the oxygen evolution reaction (OER) limit the activity of the catalyst and hence, the development of performance stable and active OER catalysts is of great importance for further commercialization of alkaline water electrolyzers. In metal organic frameworks (MOFs) a porous structure is created by linking metal atoms/clusters with other metal centres using organic ligands. The resulting structure with a high surface area and dispersed metal centres is a promising catalyst for OER, also including the application as model catalysts.

MOF catalysts with Ni and Co metal centres show impressive OER activity. Both, Co-MOF-74 and Ni-MOF-74 exhibit higher oxygen evolution reaction activity than their oxide counterparts (in form of nanoparticles, whose OER performance was published by Fabbri et al. in 2017 (Nature Materials 16) and Abbott et al. in 2018 (J. Mater. Chem. A 6) at operating conditions of 1.55 V_{RHE}, reaching 6.32 A/g_{Ni} and 6.1 A/g_{Co}, respectively.

Interestingly, rotating disk electrode (RDE) measurements indicate that Ni-MOF-74 undergoes electronic and structural transformations during stability measurements that result in an increased OER activity. This transformation has been studied in a flow-cell setup by operando X-ray absorption spectroscopy (XAS), which successfully monitored the changes occurring in the Ni metal centers during OER. The measurements clearly show that Ni-MOF-74 develops into a highly OER active and stable catalytic species. Figure 1 shows the current measured during 5 CV cycles from 1 V_{RHE} to 1.55 V_{RHE} and the corresponding EXAFS spectra. The structural transformations due to potential cycling were monitored showing that different structures are present at low and high potentials. Thereby, the Ni metal centers return to their initial state upon long-term storage under non-electrolytic conditions. However, X-ray diffraction (XRD) measurements indicate that this return does not

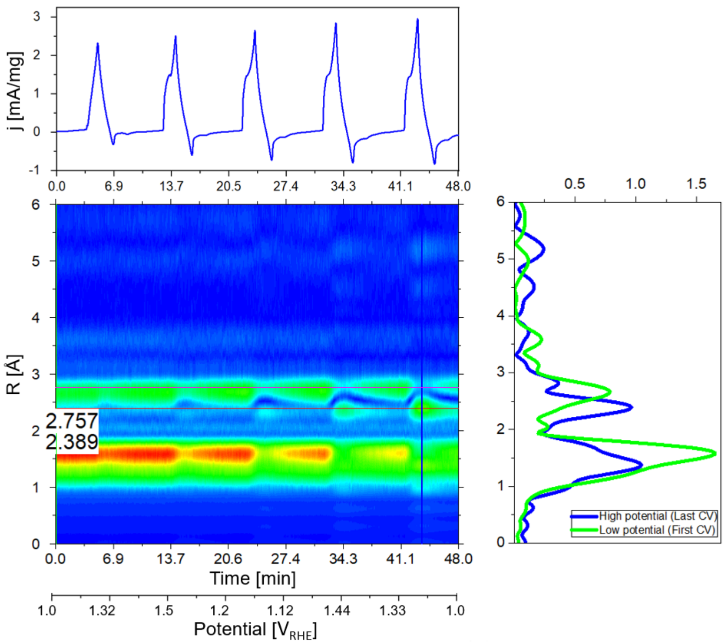

Figure 3 - Operando XAS Measurement of Ni-MOF-74

The crystalline MOF structure changes into an amorphous structure during OER and even though the Ni centers return to their original state after long-term storage in air, the structure stays amorphous. The study focuses on elucidating the structure–performance relations of the nickel oxide, hydroxide and oxyhydroxide species originating from the Ni-MOF-74 structure to understand the key structural parameters that lead to such an active species in order to define activity descriptors for the development of highly OER active and stable non-noble metal catalysts for alkaline electrolysis.

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An Open-Source Continuum Model for Anion-Exchange Membrane Water Electrolysis

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An open-source continuum model for anion-exchange membrane water electrolysis

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Summary. We present an open-source, transient, multiphysics continuum model of an anion-exchange membrane electrolyser cell. This model is validated with experimental data and calculates cell polarization performance under a variety of operating conditions as well as pH and water activity gradients throughout the cell.

Abstract.

Anion-exchange membrane (AEM) electrolysis has the potential to produce green hydrogen at low cost by combining the advantages of conventional alkaline electrolysis and proton-exchange membrane electrolysis. The alkaline environment in AEM electrolysis enables the use of less expensive catalysts such as nickel, whereas the use of a solid polymer electrolyte enables differential pressure operation. Recent advancements in AEM performance and lifetime have spurred interest in AEM electrolysis, but many open research areas remain, such as understanding the impacts of water transport in the membrane and salt content in the electrolyte. Furthermore, integrating electrolyser systems into renewable energy grids necessitates dynamic operation of the electrolyser cell, which introduces additional challenges related to heat management and degradation. Computational modelling of AEM electrolysis is ideally suited to tackle many of these open questions by providing insight into the transport processes and electrochemical reactions occurring in the cell under dynamic conditions. However, few computational modelling studies of AEM electrolysis have been presented in the scientific literature, and to our knowledge no open-source solution exists specifically for the simulation of AEM electrolysis cells.

In this work, a transient continuum modelling framework for anion-exchange membrane (AEM) electrolysis is presented and applied to study electrolyzer cell dynamic performance. The one-dimensional cell model contains coupled equations for multiphase flow in the porous transport layers, a parameterized solution property model for potassium hydroxide electrolytes, and coupled ion and water transport equations to account for water activity gradients within the AEM. The model is validated with experimental results from an AEM electrolyser cell. We find that pH gradients develop within the electrolyte due to the production and consumption of hydroxide, which can lead to voltage losses and cell degradation. The influence of parallel liquid electrolyte and solid electrolyte paths is explored and discussed. Finally, initial studies of transient operation will be presented.

This work has been performed in the frame of the CHANNEL project. This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under grant agreement No 875088. This Joint undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

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Novel composite oxygen electrodes with tuned open porosity for enhanced performance of solid oxide reversible cells (rSOC)

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Novel composite oxygen electrodes with tuned open porosity for enhanced performance of solid oxide reversible cells (rSOC)

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Summary. Two novel oxygen electrodes made of composite LSC/GDC material for fuel electrode-supported rSOC cells were elaborated. The open porosity of the electrodes was tuned by addition of two different pore formers including graphite and PMMA. The electrodes were assessed by in-situ electrochemical measurements followed by SEM/EDS imaging.

Abstract. The installed capacity of the renewable energy sources (RES) has been gradually increasing during recent years imposing the necessity for the elaboration of energy storage systems (ESS) that could balance the intermittence of green energy sources. At present, the well-established battery-based systems are limited only to small-scale applications for the techno-economic reasons. This draws much attention to alternative technologies based on hydrogen as an intermediate energy carrier such as power-to-gas, power-to-liquid or power-to-ammonia. These concepts, among other ESS technologies, stand out characterised by the highest range of energy storage capacity and charge/discharge power, being applicable for combined heat and power (CHP) working mode at discharge. The key component of these systems, known under a common name of *power-to-x* are the reversible electrochemical cells and stacks operated interchangeably between the fuel cell and electrolysis modes. Next to the proton exchange membrane (PEM), reversible solid oxide cells (rSOC) exhibit an outstanding electrical efficiency, can operated in wide range of viable conditions, and can be fed by wide range of fuels including natural gas, hydrocarbonaceus energy carriers, ammonia and other. This boosted and continuously stimulates the development of solid oxide electrochemical cell as a potential cutting-edge solution in field of reversible electrolysis/fuel cell operation for implementation of power-to-X concept.

The performance of reversible solid oxide cells (rSOC) as the key components of stacks and systems remains under continuous development, while the functional layer of the oxygen electrode is given much focus. Especially in electrolysis mode, oxygen electrode material must exhibit high ionic conductivity and open porosity of microstructure tuned for effective oxygen gas removal from the electrolyte/electrode interface. In this study two novel oxygen electrodes were elaborated from composite material containing mixed conducting LSC perovskite and GDC ionic conductor with an addition of two different pyrolizable pore formers: graphite and PMMA for increased electrode open porosity. The electrodes were screen printed on the fuel electrode supported 50 mm x 50 mm cells. The work was aimed at boosting the electrochemical performance of the rSOCs, simultaneously preventing the oxygen electrode delamination under high current electrolysis. The electrochemical performance of the cells was assessed experimentally in SOE and rSOC modes under different temperature levels, and inlet fuel compositions with current-voltage dependences and electrochemical impedance spectroscopy (EIS). Similar studies were conducted for a reference cell with state-of-art LSC electrode. Moreover, the microstructures of the obtained oxygen electrodes were investigated using imaging with SEM/EDS techniques. It was concluded that investigated oxygen electrode material modifications resulted in significant reduction of cells polarization during operation in rSOC and SOEC modes.

The presented research was financially supported by the National Science Centre, Poland, within project no. 2018/31/D/ST8/00123.

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Reference Electrodes in PEM Water Electrolysis – a Review and Experimental Investigation of Oxygen and Hydrogen Evolution Reaction Kinetics

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Polymer Electrolyte Membrane Electrolysis 1, Metals Hall, June 20, 2022, 1:30 PM - 3:10 PM

Reference Electrodes in PEM Water Electrolysis – a Review and Experimental Investigation of Oxygen and Hydrogen Evolution Reaction Kinetics

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Summary. •This contribution deals with an overview and classification of reference electrodes (RE) as well as an extended loss breakdown of PEMWE through a salt bridge RE. The RE setup is shown and qualitative measurements are discussed.

Abstract. Membrane electrode assemblies (MEA) and specifically the anode catalyst are of particular interest in PEM water electrolysis (WE) research as they are considered key components for the capital expenditure and operating expenditure of a PEMWE system (1). An effective method to understand the operation of the MEA is to apply diagnostic tools during the operation of the electrolysis cell. Previous studies in this regard have been mainly limited to the total cell voltage. However, the individual electrode behavior cannot be investigated in the standard setup. To improve the MEA design, the individual electrode behavior is crucial. This can be captured by using a reference electrode (RE).

In this work, a salt bridge is used for the first time as RE concept for polarization curves and electrochemical impedance spectroscopy (EIS). The implementation is shown in figure 1.a. Via a porous transport layer impregnated with Nafion, the reference electrode can access the ionic potential of the catalyst layer under investigation. This isolates the kinetic overvoltage from other cell voltage contributions such as ohmic membrane losses, see figure 1.b. The experiments in this study include polarization curves with conventional materials and operating conditions. In addition, EIS is performed to test the applicability of the measurement method in RE operation. Exemplary results are shown in Figure 1.c.

In addition, a previous analysis of RE from fuel and electrolytic cells is presented and a classification by electrode type and positioning is made. The key results are subsequently summarized. First, a distinction is made according to the principle behavior of the electrode or its possible configurations. The principal electrode behavior includes the dynamic hydrogen electrode (DHE), the quasireference electrodes, external REs and other configurations. Concrete concepts follow from this. For example, the DHE can be implemented with two platinum wires. By applying a current in the microampere range, the hydrogen evolution reaction takes place in the presence of water. The platinum wire in hydrogen atmosphere becomes the RE (2). Quasireference electrodes are very commonly used with ionic liquids. They are often metal wires (3). A platinum wire is used in a recent work for recording individual electrochemical impedance spectra of anode and cathode (4). Any type of RE can be used as an external RE, such as the silver-silver chloride electrode. Another possibility is to create a free-standing catalyst strip by laser ablation of the MEA. This strip can be used as a reversible electrode to measure the voltage difference with the active catalyst layer participating in the reaction (5).

In addition to the behavior of the electrode, a subdivision is made into the position of the RE. In order to separate the potential of one of the two electrodes from the total potential, the measurement can be made as close as possible to the electrode under investigation. This can be implemented by a direct measurement in the catalyst layer (6) or a special geometry of the active area (7). Alternatively, the potential can be measured at the membrane and a correction of the ohmic membrane losses can be used to infer the electrode potential to be investigated. Here, too, two implementations are possible. On the one hand, the RE can be positioned between two membrane halves (4). On the other hand, the membrane can be contacted outside the active area (8).

One requirement chosen for the presented concept is the applicability of the RE independent of the geometry of the MEA. Furthermore, the RE should be insensitive to misalignment of the catalyst layers. The exact alignment of the anodic and cathodic catalyst layers is challenging and even small deviations lead to a shift of the potential in the membrane (8). For the two reasons mentioned above, the concept of salt bridge with external RE is used in the direct approach at the electrode.

Figure

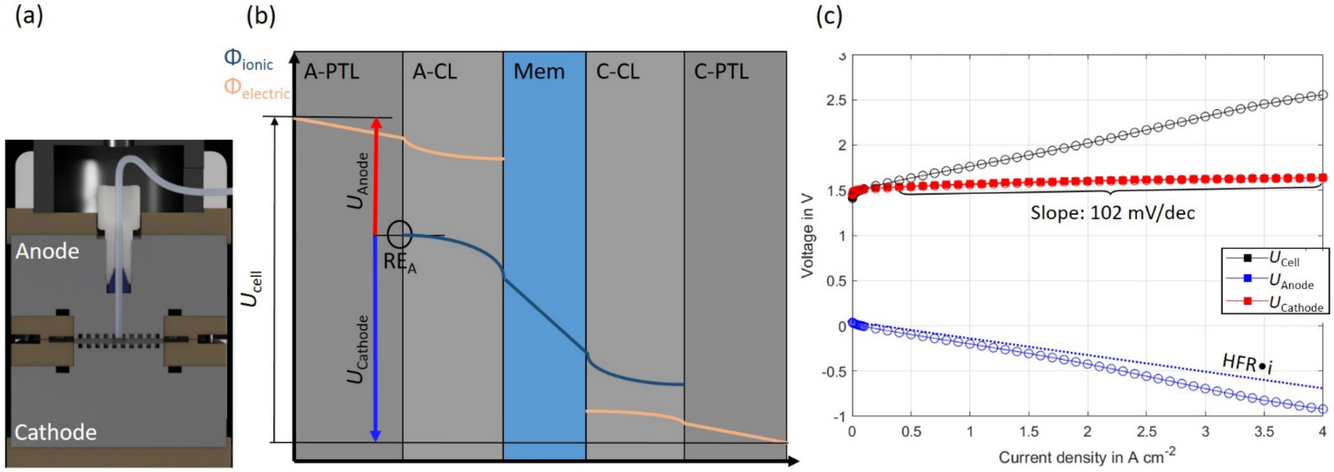

Fig. 1. (a) Technical drawing of electrolyzer test cell current collector and flow field with salt bridge implementation. (b) Schematic of ionic and electric potential distribution across the cell with indication of salt bridge reference electrode potential access point and contributions to measured values. (c) Experimental data of polarization curve using salt bridge reference electrode showing individual contributions from reference to anode potential U_{Anode} (including OER kinetic losses) and from reference to cathode potential $U_{Cathode}$ (including ohmic membrane resistance and HER kinetic losses).

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Development of an Open-Source Modelling Framework for Electrolysis Technologies

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Development of an Open-Source Modelling Framework for Electrolysis Technologies

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Summary. In this work, we outline a framework for transient modelling of electrolysis cells capable of modelling alkaline, anion-exchange membrane, proton-exchange membrane, and solid-oxide electrolysis cells. The similarities and differences to simulating each electrolysis technology will be discussed.

Abstract. Hydrogen production by electrolysis is critical for a green energy future. The main electrolysis technologies receiving research interest today can be split into three broad categories: alkaline electrolysis, polymer-electrolyte membrane electrolysis, and solid-oxide electrolysis. Each technology has its benefits and drawbacks, but a key challenge facing all electrolysis technologies is dynamic operation of the electrolyser system. Dynamic operation would enable integration with intermittent renewable energy sources such as wind turbines and solar panels, making the generation of emissions-free hydrogen possible. The consequences of dynamic operation, especially highly dynamic operation such as high-voltage ripple currents arising from power conversion, have so far received little attention in the scientific literature.

Computational modelling of these electrolyser technologies is an ideal strategy for understanding the impact of dynamic operation on electrolyser performance and lifetime. The MODELYS project aims to improve understanding of electrolyser performance and degradation under dynamic conditions by developing a universal modelling framework, validated with experimental data, applicable to alkaline, AEM, PEM, and SOE cells and stacks. Such a modelling framework can provide guidance for optimizing system performance and lifetime while contributing to understanding of local processes inside an electrolysis cell such as heat generation, reaction distribution, and bubble formation.

In this work, a framework for transient modelling of electrolysis cells will be outlined, allowing greater understanding of degradation mechanisms arising from cell startup, shutdown, and load fluctuations due to intermittent operation. We provide first a general overview of thermodynamics and transport equations common to all electrolyser systems relevant for industrial applications. Specific considerations for each technology (alkaline electrolysis, anion-exchange membrane

and proton-exchange membrane electrolysis, and solid-oxide electrolysis) are discussed, such as bubble formation in the low-temperature systems and blistering or delamination in the high-temperature technology.

Our preliminary literature review indicates research gaps at smaller length scales, where the assumptions of continuum porous-electrode models are less accurate but molecular-scale models are too small in scope to capture the relevant physics. In particular, modelling methods and techniques that had been extensively applied to fuel cells have seen less uptake in the electrolysis community. We highlight these gaps and discuss potential approaches to filling them.

This work has been performed within the MODELYS project "Electrolyzer 2030 – Cell and stack designs" financially supported by the Research Council of Norway under project number 326809.

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Performance of PEM Water Electrolyser System operating up to 200 bar

Dr Ragnhild Hancke[1], Dr Piotr Bujlo[1], Dr Thomas Holm[1], Dr Øystein Ulleberg[2]

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Polymer Electrolyte Membrane Electrolysis 4, Metals Hall, June 23, 2022, 8:00 AM - 10:00 AM

Performance of PEM water electrolyser system operating up to 200 bar

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Summary. High-pressure PEM electrolysis capable of electrochemical H_2 compression up to 200 bar (compatible with industrial applications such as gas grid injection and methanol and ammonia production) can be economically viable. In this work, polarization curves and EIS data have been recorded up to 190 bar and 80°C for a 12 kW PEMEL stack.

Abstract. Hydrogen compression is a key part of the green hydrogen supply chain, but mechanical compressors are prone to failure and add system complexity and cost. High-pressure water electrolysis can alleviate this problem through electrochemical compression of the gas internally in the electrolyzer and thereby eliminating the need for an external hydrogen compressor. A detailed techno-economic assessment [1] wherein high-pressure PEM water electrolysers operating at 80, 200, 350, and 700 bar were compared to state-of-the-art systems operating at 30 bar in combination with a mechanical compressor was carried out. This showed that it is possible to achieve economically viable solutions with electrolyser systems operating up to 200 bar.

To implement high-pressure PEM electrolyzers, several challenges related to system operability, durability, and safety needs to be addressed. As part of the national infrastructure "The Norwegian Fuel Cell and Hydrogen Centre", IFE has installed a flexible PEMEL system platform for testing of small-scale prototype electrolyzers up to 200 bar, 410 A, and 33 kW [2]. The test rig is integrated with a sophisticated power conditioning system making it possible to, e.g., use a Li-ion battery system to test different hybrid electric topologies and to emulate different loads. This one-of-a-kind PEMEL test facility is well suited to study performances of next-generation stacks and systems, and to tailor and test control strategies that safeguards the system and maximizes efficiency and durability.

The system at IFE has now been fully commissioned, including testing up to the rated pressure of 200 bar on the H_2 side. A small-scale (2 Nm^3/h) prototype high-pressure stack was used as reference technology for these tests. The stack was characterized by recording polarization curves at temperatures up to 80°C and pressures up to 190 bar. Electrochemical impedance spectroscopy was used to obtain information about the electrode processes. The first results (Figure) show that at 80°C the voltage efficiency (HHV) decreases from 71.3 % at 30 bar to 68.8 % at 150 bar, while it at 50°C decreases from 66.3 % at 30 bar to 64.4 % at 150 bar. The EIS spectra show no clear trend with respect to changing pressure.

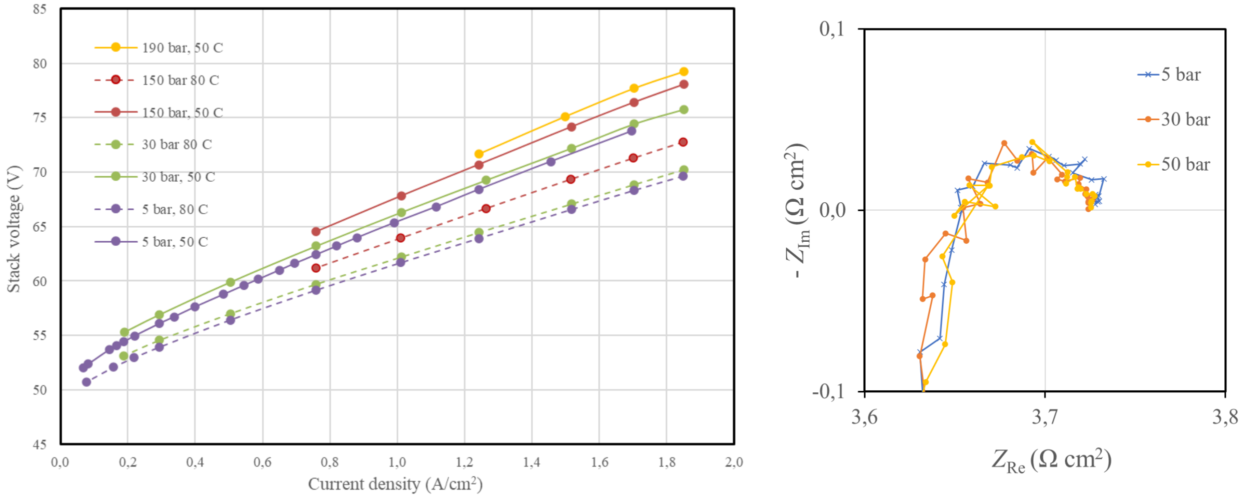

Figure: Polarization curves (left) recorded at 50°C (solid lines) and 80°C (stippled lines) at various pressures, and EIS plots (right) recorded at 5, 30 and 50 bar showing no clear trend as a function of pressure.

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Metallic Glass NiFeM Nanofoam Anode Catalysts for Highly Efficient Anion Exchange Membrane Water Electrolyzers

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Alkaline Electrolysis 3, Metals Hall, June 22, 2022, 10:30 AM - 12:20 PM

Metallic Glass NiFeM Nanofoam Anode Catalysts for Highly Efficient Anion Exchange Membrane Water Electrolyzers

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Summary. We developed a variety of trimetallic NiFeM (M: Co, Cu, or Mn) nanofoam OER catalysts with unique amorphous oxide shells and crystalline mix-phased metallic glass core structures, which has been successfully implemented into MEAs for AEM-based water electrolyzers. The NiFeMn delivered a remarkably enhanced current density of 2.0 A cm-2 at 1.7 V in an AEM-based MEA, superior to the IrO2 reference, when 0.1 M KOH solution was supplied to an AEMWE. The NiFeCu catalyst, on the other hand, generates a very encouraging current density of 1.2 A cm-1 at the voltage of ~2.3 V in AEMWE when pure water is used, also approaching the IrO2 reference anode.

Abstract.: Alkaline anion-exchange membrane water electrolyzers (AEMWEs) are now receiving intensive attention due to their feasibility to use sustainable, low-cost precious metal group-free (PGM-free) catalysts for hydrogen production through water splitting. Especially, the development of highly efficient PGM-free anodes for the oxygen evolution reaction (OER) is critical for accelerating commercialization of cost-effective AEMWEs. Herein, we report a series of highly porous ternary NiFeM (M: Cu, Co, and Mn) metallic glassy nanofoam network catalysts with well-defined core-shell structures, which are composed of an amorphous metal oxide shell for the active sites towards OER and the metallic glass alloy core for high overall electrical conductivity. NiFeCu and NiFeMn nanofoams demonstrated promising OER activities and stabilities in the half-cell rotating disk electrode (RDE) test, especially in high voltage regions. Notably, the ternary NiFeM catalysts are further integrated with unique ionomer and AEM into AEMWEs, showing superior performance to traditional NiFe and commercial IrO2 catalysts when flowing diluted KOH electrolyte. When directly using pure water, they performed comparably to commercial IrO2 in AEMWEs, representing a new class of highly efficient PGM-free anode catalysts for viable AEMWEs toward clean hydrogen generation.

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Development of New Non-precious Catalyst Integrated Electrodes for Efficient Hydrogen Production in Practical PEM Electrolysis

DR. Zhiqiang Xie[1], Dr. Shule Yu[1], Mr. Xiaohan Ma[2,3], Dr. Kui Li[1], Ms. Lei Ding[1], Mr. Weitian Wang[1], Dr. David A. Cullen[2], Mr. Harry M. Meyer III[4], Dr. Haoran Yu[2], Dr. Jianhua Tong[3], Dr. Zili Wu[2,4], Dr. Feng-Yuan Zhang[1]
[1]Department of Mechanical, Aerospace & Biomedical Engineering, UT Space Institute, University of Tennessee, Knoxville, TN 37388, USA, , United States, [2]Center for Nanophase Materials Sciences,Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA, , United States, [3]Department of Materials Science and Engineering, Clemson University, Clemson, SC, 29634, , United States, [4]Chemical Science Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA, , United States

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Development of New Non-precious Catalyst Integrated Electrodes for Efficient Hydrogen Production in Practical PEM Electrolysis

Zhiqiang Xie[a], Shule Yu[a], Xiaohan Ma [b,c,], Kui Li[a], Lei Ding[a], Weitian Wang[a], David A. Cullen[b,*], Harry M. Meyer III[d], Haoran Yu[b], Jianhua Tong[c], Zili Wu[b,d], Feng-Yuan Zhang[a,*]
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Summary. The ionomer-free MoS_2 electrode with created heterophase and rich defects is developed and studied in proton exchange membrane electrolyzer cells for the first time. High catalytic activity and stability for the HER in acidic media are demonstrated. Over 44 times higher mass activity and outstanding cell performance are achieved.

Abstract. The fossil fuels as dominant energy resources have aroused global concerns about CO_2 emission and climate change. A proton exchange membrane electrolyzer cells (PEMEC) stands out as a promising technique to generate green hydrogen as a clean energy carrier with high purity and high efficiency, when integrated with intermittent renewable energy resources.[1] To further reduce system cost and mitigate the risk of global supply chain interruptions for precious metals, it is imperative to develop low-cost non-precious catalysts with competitive catalytic activities and durability.[2-4]

In this presentation, we will introduce a new ionomer-free integrated electrode composed of engineered 1T-2H heterophase and defect-rich MoS_2 nanosheets (MoS_2NSs), which demonstrates greatly boosted hydrogen evolution reaction (HER) activities in both liquid and solid electrolytes. More impressively, it achieves more than 44 times higher mass activity than a high-loading and ionomer-mixed MoS_2 electrode, which also outperforms most previously reported high-loading non-precious catalyst-based electrodes in PEMECs. This study offers new insights into how catalyst optimization and electrode fabrication can significantly enhance the performances of PGM-free catalyst-based electrodes and greatly decrease the total cost of practical energy devices for cost-efficient hydrogen production and utilization.

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Porous-transport-layer interface design for PEM electrolyzers via laser ablation

Dr Keonhag Lee[1], Dr Andrew Tricker[1], Dr Xiong Peng[1], Dr Nemanja Danilovic[1], Dr Adam Weber[1]

[1]*Lawrence Berkeley National Lab, , United States of America*

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Porous-transport-layer interface design for PEM electrolyzers via laser ablation

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United States of America;
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Summary. Laser ablation is used to fabricate enhanced porous-transport-layer/catalyst layer interface that improves performance of proton-exchange-membrane water electrolysis. Laser ablated PTLs provide improved contact against the catalyst layer while maintaining bulk properties for effective mass transport during operation. The designed PTLs are specifically impactful towards electrolyzers with ultra-low catalyst loading.

Abstract. Proton-exchange-membrane water electrolysis (PEMWE) powered by renewables produces clean hydrogen that can be fed into a variety of sectors. Of many different components, the anode catalyst layer/porous transport layer (CL/PTL) interface significantly influences PEMWE performance, impacting ohmic, kinetic, and mass-transport overpotentials. Large pores at the CL/PTL interface can cause catalyst-layer deformation, thereby intensifying degradation. Moreover, deformation leads to inadequate interfacial contact area resulting in high ohmic and kinetic overpotentials.[1,2] On the other extreme, low surface porosity at the CL/PTL interface results in accumulation of oxygen gas and inhibiting water transport, thereby increasing mass-transport overpotentials.[3] A hierarchical structured PTL exhibiting high bulk porosity and low tortuosity while ensuring sufficient contact at the CL/PTL is required to minimize overpotentials. In this presentation, we control interfacial properties of the PTL through a subtractive method, namely, laser ablation. Laser ablation is a promising technique for tailoring the interfacial pore structure of PTLs. During laser ablation, heat alters the structure and morphology of the titanium at the interface, forming a unique morphology advantageous to electrolyzer performance. Laser-ablated PTLs provide enhanced contact against the CL without further altering the bulk pore structure elsewhere, thereby optimizing between the two properties. Furthermore, we will also discuss the impact of laser-modified PTLs on thinner catalyst layers of ultra-low loadings. Overall, we show that laser ablation is an effective approach to enhance PTL interfacial properties and subsequently PEMWE performance and durability.

Acknowledgements. This work was funded under the H2NEW Consortium by the Energy Efficiency and Renewable Energy, Hydrogen and Fuel Cell Technologies Office, of the U. S. Department of Energy under contract number DE-AC02-05CH11231.

References.

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3. X. Peng et al., *Adv. Sci.*, **8** (2021).

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Durable Alkaline Electrolysis Using High Performance Membranes and Self-Adhesive Ionomers

Dr. Paul Kohl[1]

[1]*Georgia Institute of Technology, Professor, United States*

Alkaline Electrolysis 1, Metals Hall, June 20, 2022, 3:40 PM - 5:30 PM

Durable Alkaline Electrolysis Using High Performance Membranes and Self-Adhesive Ionomers

Paul A. Kohl[a]

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Summary. Water electrolysis using anion conductive polymers has several advantages, however, durability remains a challenge. A family of high-IEC hydroxide conducting polymers (>200 mS/cm) have been used to make membranes and covalently bonded, self-adherent, hydroxide conducting ionomers for durable three-dimensional electrodes.

Abstract. Low-temperature water electrolysis using anion conductive polymer electrolytes has several potential advantages over acid-based polymer electrolyzers. However, the formation of durable membranes and high surface area electrodes remains a challenge. In particular, the adhesion and connectivity of high surface area, particulate catalysts to the porous transport layer is critically important to the long-term cell lifetime.

In this study, a family of covalently bonded, self-adherent, hydroxide conducting ionomers has been synthesized and tested under alkaline electrolysis conditions. The ionomers are based on hydroxide conducting poly(norbornene) polymers used in fuel cell and electrolyzers. Ionomers used in electrolysis electrodes, especially at the oxygen gas producing anode, must provide adhesion between the catalyst particles, porous transport layer and solid polymer membrane. Simple mixtures of ionomer and catalyst can suffer from poor catalyst adhesion because only physical adhesion is used to bind the components together.

The terpolymer and tetrapolymer ionomers used in this work have been functionalized to provide cites for chemical bonding of bis(phenyl)-A-diglycidyl ether to the ionomer, catalyst, and porous transport layer. The resulting electrodes show excellent adhesion of the catalyst particles to the porous transport layer, as determined by adhesion measurements. Electrolyzer results show stable voltage performance over long periods of time.

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CO2 and Steam Co-Electrolysis Using a Solid Oxide Electrolyzer

Dr. Jamelyn Holladay[1], Dr. Olga Marina[1]

[1]*Pacific Northwest National Laboratory, Chief Research Engineer, United States*

Solid Oxide Electrolysis 3, Metals Hall, June 23, 2022, 10:30 AM - 11:50 AM

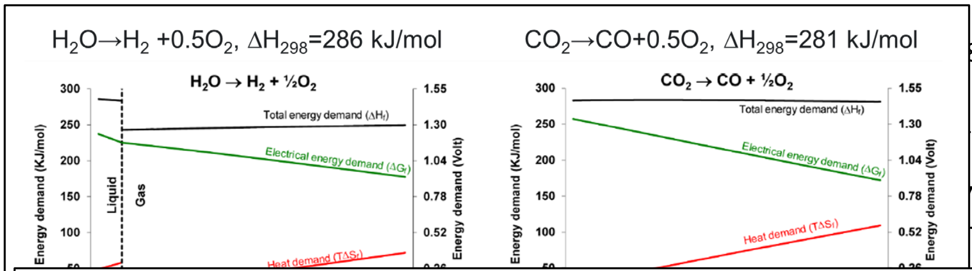
CO_2 and Steam Co-Electrolysis Using a Solid Oxide Electrolyzer

Jamie Holladay[a], Olga Marina[a]

[a]Pacific Northwest National Laboratory, USA;
Corresponding author email: Jamie.holladay@pnnl.gov

Summary. Electrochemical activation of CO_2 at high temperatures has potential to leverage both heat and electricity to achieve fast reaction kinetics. PNNL's solid oxide electrolyzer (SOEC) technology reported here achieved >1A/cm^2 @ 1.3V and 800°C. After 900h of testing, almost no degradation was observed even when varying the CO_2/H_2O ratio from 95/1 to 64/16.

Abstract. High temperature solid oxide electrolysis (SOEC) is a flexible platform where the same materials and cells can be used to split water producing hydrogen, reduce CO_2 to CO or, when operated in reverse, produce electric power. This presentation will report on the performance of PNNL's SOEC materials and cell designs for CO_2 and steam co-electrolysis for syn-gas, mixture of H_2, CO and CO_2, production. SOEC's can efficiently co-electrolyze CO_2 and steam because at elevated temperatures the voltages required for water splitting and CO_2 reduction are very similar (Figure 1).



h steam electrolysis and CO_2
850°C and voltages from 1.2
n excess of 1.8A/cm^2 were
, 81/9 and 64/16 in PNNL's
the same time. The cells
'5 A/cm^2 at 1.2V and 800°C.
h and performance.

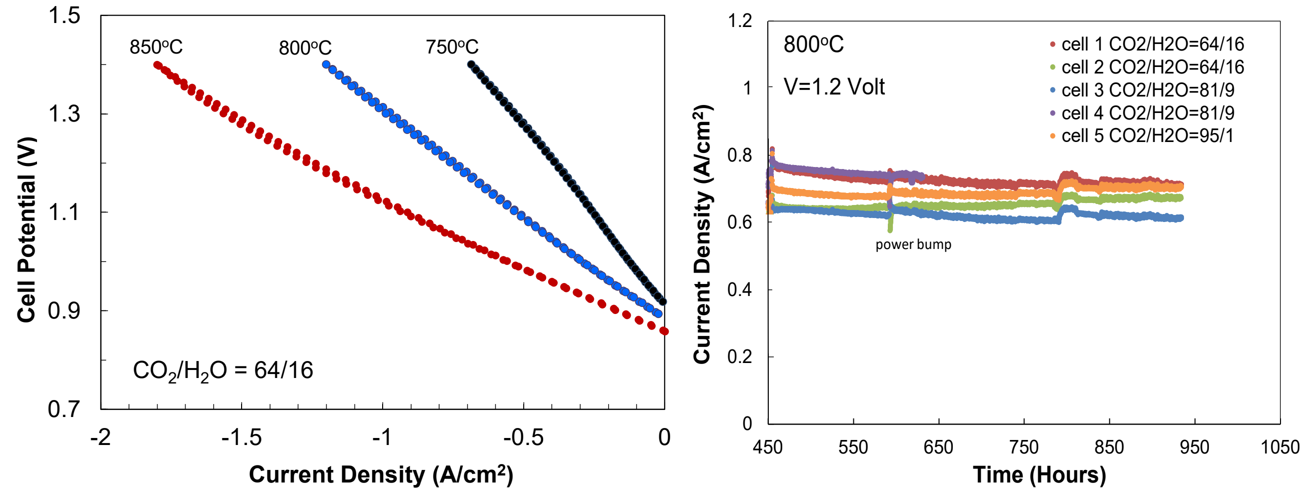


Figure 5. (A) SOEC Co-Electrolysis Performance at Temperatures Ranging from 750 to 850°C. (B) SOEC Button Cell Testing Showing Consistent Performance over a CO_2/H_2O range from 91/5 to 64/16 and 900h.

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Operating strategies for dispatchable PEM electrolyzers that enable low-cost hydrogen production

Mr. Alex Badgett[1], Mr. Mark Ruth[2], Dr. Bryan Pivovar[2]

[1]National Renewable Energy Laboratory, Researcher, United States, [2]National Renewable Energy Laboratory, Group Manager, United States

Plenary Session 2, Metals Hall, June 20, 2022, 10:15 AM - 12:15 PM

Operating strategies for dispatchable PEM electrolyzers that enable low-cost hydrogen production

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Summary.

PEM electrolyzers with reduced capital costs have the potential to produce low-cost electrolytic hydrogen when operated at low electricity prices even if capacity factors are relatively low (≈50%), such as in wholesale power markets or when directly connected to wind or solar generation. This work explores some of the technical and economic considerations for electrolyzers with temporally variable energy sources and implications on durability requirements specific to those operating configurations.

Abstract.

Hydrogen is a pathway to enabling decarbonization across multiple economic sectors that cannot be directly decarbonized with electricity including heat for industrial operations, medium- and heavy-duty transportation applications, long-duration energy storage, and as a feedstock for chemical synthesis. Producing hydrogen at low costs and carbon footprint is likely essential to economically decarbonize these otherwise “hard to decarbonize” sectors. Low-temperature polymer electrolyte membrane (PEM) electrolysis produces hydrogen from water and electricity and is a rapidly developing pathway towards making hydrogen at the scales required for decarbonization applications.

The levelized cost of electrolytic hydrogen is dependent on the capital cost, efficiency, and durability of the electrolyzer system as well as the price of electricity supplied to the electrolyzer and the annual utilization of the electrolyzer (capacity factor). Electricity price and capacity factor depend on the source of energy that the system uses and impact other economic factors. Electricity price and capacity factor and the connections between other aspects of hydrogen production via PEM electrolyzers are the focus of this work.

PEM electrolyzers have conventionally been operated at high capacity factors using electricity purchased from utilities with a constant price throughout the year. To achieve lower effective electricity prices, recent work[1] has investigated opportunities for electrolyzers to purchase electricity in wholesale markets, where the cost of electricity varies hourly. This option can lead to lower electricity costs when the electrolyzer is a controllable load that ramps up and down rapidly and turns on and off frequently. This configuration and operating strategy capitalizes on times of low wholesale electricity prices and results in lower hydrogen levelized costs than constant operation due to reduced electricity costs

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even though the reduced capacity factor increases the cost of recovering the capital investment. Cycling on and off frequently also has implications for electrolyzer durability. An electrolyzer configuration where it is directly connected to renewable generation such as wind or solar, only running when the generator is producing energy, has similar implications on operating strategy, hydrogen levelized cost, capacity factor, and durability.

This work provides insight into the relationships between dispatchable electrolyzer operating strategies and the cost of producing hydrogen from these systems, outlining strategies and opportunities to minimize production costs while minimizing operations that are likely to negatively impact system durability and efficiency. We find strategies that minimize electrolyzer cycling and the resulting durability impacts while increasing the hydrogen levelized cost only slightly above the minimum. We also find opportunities for batteries to minimize the number of cycles in systems directly connected to renewable generation. These findings outline key opportunities for future electrolyzer deployments and the synergistic benefits between electrolyzers and increased deployment of renewable energy generation like wind and solar. They also inform research and development that is reducing electrolyzer capital cost while managing durability impacts.

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Highly Efficient IrOx Catalyst Integrated Thin Electrodes for Low-cost Water Electrolyzers

Ms. Lei Ding[1], Dr. Kui Li[1], Mr. Weitian Wang[1], Dr. Zhiqiang Xie[1], Dr. Shule Yu[1], Dr. Jacob Wrubel[1], Dr. Guido Bender[1], Dr. Haoran Yu[1], Dr. David A. Cullen[1], Mr. Alex Keane[1], Dr. Kathy Ayers[1], Mr. Christopher B. Capuano[1], Dr. Feng-Yuan Zhang[1]

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Highly Efficient IrO_x Catalyst Integrated Thin Electrodes for Low-cost Water Electrolyzers

Lei Ding[a], Kui Li[a], Weitian Wang[a], Zhiqiang Xie[a], Shule Yu[a], Jacob Wrubel[b], Guido Bender[b], Haoran Yu[c], David A. Cullen[c], Alex Keane[d], Kathy Ayers[d], Christopher B. Capuano[d], and Feng-Yuan Zhang [a,*]

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Summary. A highly active IrO_x catalyst integrated thin electrode is developed as a highly efficient anode for oxygen evolution reactions in the proton exchange membrane electrolyzer cells (PEMECs).

Abstract. To mitigate environmental issues caused by traditional fossil fuels, it is necessary to develop high-efficiency proton exchange membrane electrolyzer cells (PEMECs) to produce green hydrogen, one of the most promising renewable energy carriers.[1-4] For the PEMECs, electrodes play crucial roles, and high-performance electrodes with simplified fabrication processes are highly desired for green hydrogen production in the practical PEMECs.[5, 6]

In this study, a highly active IrO_x catalyst integrated thin electrode is developed as a highly efficient anode for oxygen evolution reactions in the PEMECs. Via a simple CV electroplating at room temperature, the IrO_x with high activity can be facilely deposited on a thin tunable liquid gas diffusion layer to obtain the thin electrode. As a result, the fabricated electrode shows outstanding cell performance of 1.77 V at 2 A/cm^2 when combined with a Nafion117 membrane, outperforming most of the reported cell performances. Meanwhile, good stability is demonstrated at a high current density of 1.8 A/cm^2. Overall, due to the remarkable performance, good stability, and simple and efficient fabrication method, the electrode can be easily scaled up and shows great potential to boost the industrial application of the PEMECs, thus accelerating renewable energy evolution.

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Metal-supported solid oxide electrolysis cells

Dr. Michael Tucker[1], Dr. Fengyu Shen[1], Dr. Martha Welander[1]

[1]*Lawrence Berkeley National Laboratory, Staff Scientist, United States*

Solid Oxide Electrolysis 1, Metals Hall, June 21, 2022, 8:00 AM - 10:00 AM

Metal-supported solid oxide electrolysis cells

Michael C. Tucker, Fengyu Shen, Martha Welander

Lawrence Berkeley National Laboratory, Energy Storage and Distributed Resources Division, United States
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Summary. Metal-supported solid oxide electrolysis cells (MS-SOECs) are rugged, tolerant to aggressive operating conditions, and comprised of low-cost materials. Post-mortem analysis identified Cr migration as a primary degradation mode, which was mitigated by addition of a Cr-barrier coating. This greatly improved performance and durability.

Abstract. High-temperature electrolysis (HTE) is an efficient technology for converting steam to hydrogen. The performance, durability, and applications of metal-supported solid oxide electrolysis cell technology will be presented, with a brief review of the relevant literature. The unique MS-SOEC developed at Lawrence Berkeley National Laboratory (LBNL) is a symmetric cell architecture design, with thin zirconia ceramic backbones and electrolyte sandwiched between porous metal supports (Fig 1). The MS-SOEC offers a number of advantages over conventional all-ceramic cells, including low-cost structural materials (e.g. stainless steel), mechanical ruggedness, excellent tolerance to redox cycling, and extremely fast start-up capability.

An inherent limitation of this design is the intimate contact between the electrode and the porous stainless steel, which is a source of chromium (Cr). Cr migrates from the support to the electrode during cell fabrication and operation, and reacts with the oxygen evolution electrocatalyst (LSCF). This Cr poisoning reduces performance and durability. To overcome this limitation, Cr-blocking coatings have been applied to the porous stainless steel. A variety of coating compositions and deposition techniques have been evaluated. The best coating dramatically reduces the amount of Cr detected in the electrode both after catalyst infiltration at 800°C and after 1000 h continuous operation at 700°C (Fig 1). Detailed post-mortem analysis reveals that in addition to Cr migration, electrocatalyst coarsening is a primary degradation mode. Other common SOEC degradation modes, such as Ni migration, oxygen electrode delamination, and micro-void formation were not observed.

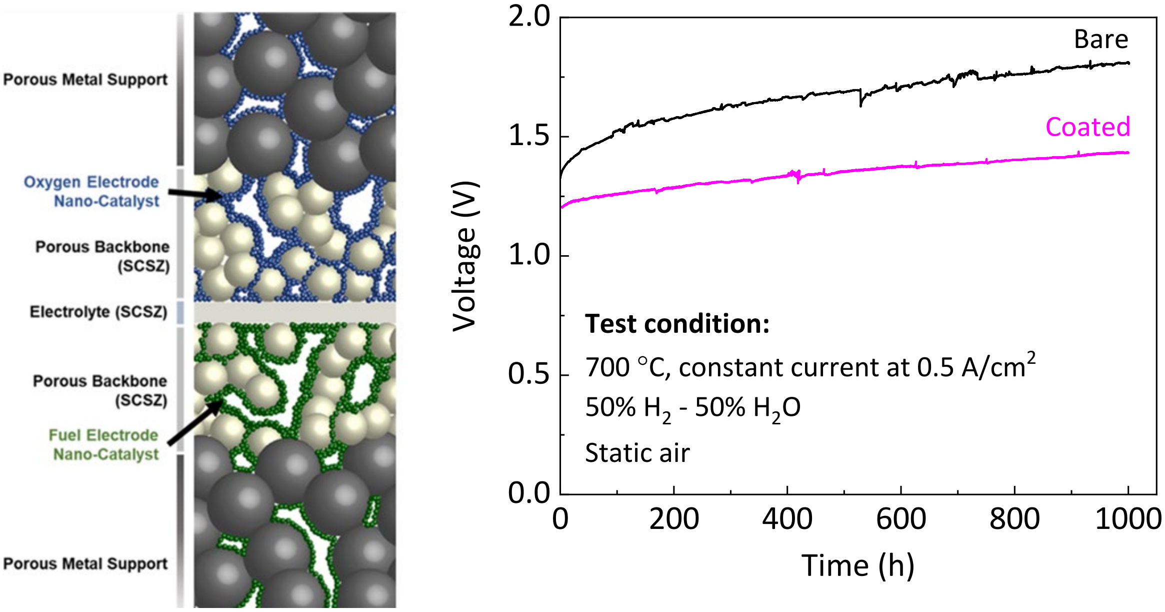

Figure 1. MS-SOEC structure and long-term operation with and without a coating on the interior surface of the oxygen-side metal support.

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High-speed visualization of in-situ electrochemical reaction and transport at PEM/electrode interfaces in Electrolyzers

MR. Weitian Wang[1], Dr. Shule Yu[1], Dr. Kui Li[1], Dr. Zhiqiang Xie[1], Ms. Lei Ding[1], Dr. Fengyuan Zhang[1]

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

High-speed visualization of *in-situ* electrochemical reaction and transport at PEM/electrode interfaces in Electrolyzers

Weitian Wang[a], Shule Yu[a], Kui Li[a], Zhiqiang Xie[a], Lei Ding[a] and Feng-Yuan Zhang [a,*]

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Summary. The reaction and bubble dynamics in the PEM/electrode interfaces were visualized, which provide more insights in the PEM electrolyzers.

Abstract. The proton exchange membrane (PEM) electrolyzer is one of the most promising devices to produce green hydrogen for large-scale energy storage. Various visualization techniques, including neutron imaging, X-ray imaging, and optical imaging, et al, have been developed to explore the inherent mechanism and improve performance of PEM electrolyzer [1-5]. Due to the absence of characterization methods, the observation of two-phase transport in the impeded area of porous transport layers (PTLs) is challenge, such as reaction interface between catalyst and PEM, the bipolar plate land blocked area. In this study, a two-side transparent PEM electrolyzer cell was developed, which enables the direct observation of catalyst/PEM interface. Benefit from the novel cell design, the gas occupation in the catalyst/PEM interface and blocked pores of PTLs was directly observed for the first time, which provide more insights about the reaction/transport mechanism.

1. Li, Y., et al., *High-speed characterization of two-phase flow and bubble dynamics in titanium felt porous media for hydrogen production.* Electrochimica Acta, 2021. **370**: p. 137751.
2. Wang, W., et al., *Insights into the rapid two-phase transport dynamics in different structured porous transport layers of water electrolyzers through high-speed visualization.* Journal of Power Sources, 2021. **516**: p. 230641.
3. Wang, W., et al., *Exploring the Impacts of Conditioning on Proton Exchange Membrane Electrolyzers by In Situ Visualization and Electrochemistry Characterization.* ACS Applied Materials & Interfaces, 2022.
4. Li, K., et al., *Visualizing Highly Selective Electrochemical Co2 Reduction On A Molecularly Dispersed Catalyst.* Materials Today Physics, 2021: p. 100427.
5. Yu, S., et al., *Tuning Catalyst Activation and Utilization Via Controlled Electrode Patterning for Low-Loading and High-Efficiency Water Electrolyzers.* Small. **n/a**(n/a): p. 2107745.

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Optimal operating parameters for advanced alkaline water electrolysis

Dr. Matheus de Groot[1,2], Mr. Joost Kraakman[1], Mr. Rodrigo Lira Garcia Barros[1]

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Optimal operating parameters for advanced alkaline water electrolysis

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Summary. Thinner diaphragms and increased temperatures enable advanced alkaline electrolyzers to operate at higher current densities. However, to keep the electrolyzer sufficiently flexible the operating pressure needs to be kept at a moderate level to avoid excessive gas crossover.

Abstract. Advanced zero-gap alkaline electrolyzers can be operated at significantly higher current densities than traditional alkaline electrolyzers. We have investigated how their performance is influenced by diaphragm thickness, temperature and pressure. For this a semi-empirical current-voltage model has been developed based on experimental data of a 20 Nm3/h electrolyzer [1]. The model was extrapolated to thinner diaphragm thicknesses and higher temperatures showing that a cell potential of 1.85 V is possible at a nominal current density of 1.8 A cm^{-2} with a 0.1 mm diaphragm at 100 °C. However, these operating parameters also lead to increased gas crossover, which limits the ability to operate at low loads. A gas crossover model has been developed based on available experimental data [2], which shows that crossover is mainly driven by diffusive transport of hydrogen, caused by the operating pressure and the local supersaturation at the diaphragm interface. To enable a low minimum load of 10% the operating pressure should therefore be kept below 8 bara for a 0.1 mm diaphragm and an operating temperature of 100 °C**.**

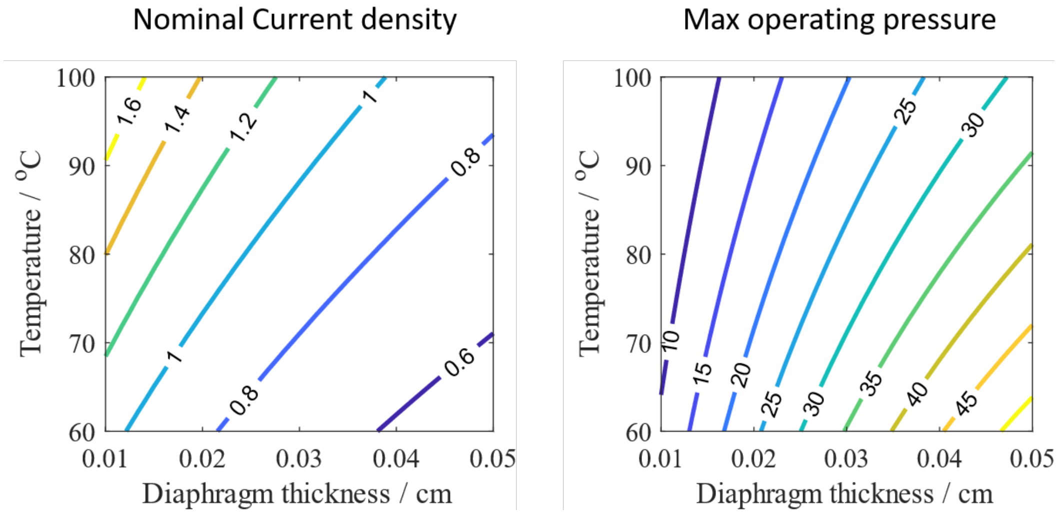

Figure: Left: contour plot of the achievable nominal current density at a cell potential of 1.85 V as a function of temperature and diaphragm thickness for a zero-gap alkaline electrolyzer with an activated Raney-Ni cathode. Pressure

= 10 bara, 30 wt% KOH. Right: contour plot of the maximum allowable pressure to enable a minimum load of 10% based on the nominal current density for 10 bar, with separated lye circuits.

[1] Fischer UR, Voigt A, Tannert D, Krautz HJ. Pressure and Temperature Influence on Alkaline Water Electrolysis Performance. Eur. PEFC H2 forum, 2015.

MoNi4-MoO2 coated Ni-foam as a highly efficient cathode material for industrial scale alkaline electrolysis

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Alkaline Electrolysis 2, Metals Hall, June 21, 2022, 1:30 PM - 3:20 PM

$MoNi_4$-MoO_2 coated Ni-foam as a highly efficient cathode material for industrial scale alkaline electrolysis

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Summary. This contribution demonstrates the applicability of Ni-Mo based cathode materials for the alkaline electrolysis of water. A novel route for $MoNi_4$-MoO_2 fabrication on Ni-foam is presented. Starting with $NiMoO_4$ a two-step heat treatment leads to a catalyst with unique morphology and exceptionally high surface area. The resulting electrodes exhibit excellent activity towards HER with overpotentials below 100 mV at 300 mA/cm^2 in 30 wt.-% KOH at 60 °C.

Abstract. In the rapidly expanding field of catalyst development for hydrogen evolution reaction in alkaline environments a mixture of $MoNi_4$ and MoO_2 has attracted great attention due to its outstanding activity [1,2]. On the other hand, the cause of the high activity shown in some cases is unclear. In this paper, a production method and a structural analysis of the produced material are presented and discussed. We propose a reduction and subsequent thermal heat treatment to produce a $MoNi_4$-MoO_2 catalyst on Ni-foam from commercially available $NiMoO_4 \cdot nH_2O$ powder (Figure 1a). The whole process is to be scaled up. It starts with a $NiMoO_4$ powder used as precursor or catalyst itself in the petrochemical industry and Ni foam which both are available in large quantities [3]. The unambiguous identification of phases can be done by x-ray diffraction. At the same time, we present a yet unseen morphology of µm-sized plates embedded in nanoscale particle network. $MoNi_4$-MoO_2/Ni cathodes show overpotentials below 100 mV at an industrial relevant current density of 300 mA/cm^2 in alkaline environments for several hours and very low Tafel slopes (< 30 mV/dec).

The two-step heat treatment consists of a reduction followed by a sintering step. First the $NiMoO_4$ is reduced to Ni with small amounts of Mo and MoO_2 which are both very fine (Figure 1a). After this the coating is only loosely attached to the Ni substrate. In order to create $MoNi_4$ and improve the attachment of the coating to the substrate a sintering step is necessary. The resulting morphology consists of plates with some µm in size embedded in a nanoscale network of particles (Figure 1b). The $MoNi_4$-MoO_2/Ni electrodes show excellent HER performance presumably because of their high surface area and the intrinsic activity of $MoNi_4/MoO_2$ [4]. An electrode sintered at 800 °C had an overvoltage of 95 mV after 10 h at 300 mA/cm^2 in 30 wt-% KOH (Figure 1c). These results clearly demonstrate that Ni-Mo alloys can be seen as an excellent alternative for non-PGM catalysts in the alkaline electrolysis. More details regarding electrochemical and structural analysis are given in the contribution.

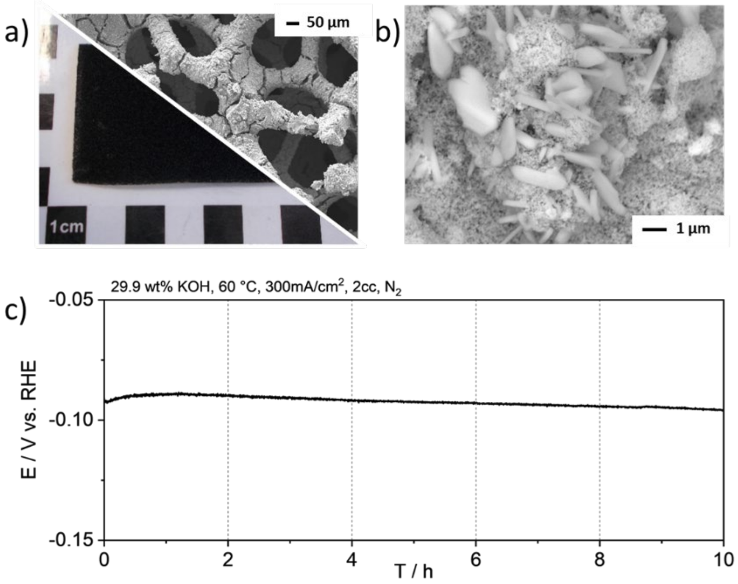

Figure 1: a) photo and SEM image of $MoNi_4$-MoO_2/Ni-foam b) high resolution SEM image c)10 h test at – 300 mA/cm^2

[1] J. Zhang, T. Wang, P. Liu, Z. Liao, S. Liu, X. Zhuang, M. Chen, E. Zschech, and X. Feng, Nature communications 8, 15437 (2017)

[2] L. Xiao, S. Zhang, J. Pan, C. Yang, M. He, L. Zhuang, and J. Lu, Energy Environ. Sci. 5, 7869 (2012)

[3] L. M. Madeira, M. F. Portela, and C. Mazzocchia, Catalysis Reviews 46, 53 (2004)

[4] Y. An, X. Long, M. Ma, J. Hu, H. Lin, D. Zhou, Z. Xing, B. Huang, and S. Yang, Adv. Energy Mater. 9, 1901454 (2019)

Exploring a novel polyethylene-based ionomer-catalyst ink formulation for single-cell alkaline electrolyzers

Ms. Lipin Wu[1], Ms. Morgan Ezell[1], Ms. Kaylee Beiler[1], Mr. Kevin Dunn[1], Mr. Andrew Johnson[1], Mr. Dominic Carmosino[1], Ms. Mei-Chen Kuo[1], Dr. Nora Buggy, Dr. Andrew Herring[1]

[1]*Colorado School of Mines, PhD Candidate, United States*

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Exploring a novel polyethylene-based ionomer-catalyst ink formulation for single-cell alkaline electrolysis

Ivy Wu, Morgan S. Ezell, Kaylee J. Beiler, Kevin C. Dunn, Andrew M. Johnson, Dominic J. Carmosino, Mei-Chen Kuo, Nora C. Buggy, and Andrew M. Herring*

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Summary. We report a novel triblock copolymer (polychloromethylstyrene-*b*-polyethylene-*b*-polychloromethylstyrene) membrane electrode assembly system for alkaline water electrolysis. In a single-cell electrolyzer with 1M potassium carbonate at 50°C, we achieved 1A cm^{-2} at 1.9 V using 4.5mg cm^{-2} ionomer on a Ni foam anode.

Abstract. Generation of hydrogen from water is an extremely attractive endeavour to reduce energy dependence on non-renewable sources like fossil fuels. However, development of non-precious metal catalysts and durable, high performing materials are needed to realize the technology. We investigated the performance and durability of a polyethylene-based anion exchange ionomer and membrane material in both half-cell and single-cell electrolyzers. Polychloromethylstyrene-*b*-polyethylene-*b*-polychloromethylstyrene quaternized with methylpiperidine ionomer was synthesized and deposited onto Ni foam anodes, with various loadings (0-4.5mg cm^{-2}) of CoO. Coupled with a Pt/C cathode, single-cell electrolysis experiments were performed at 50°C in 1M potassium carbonate. We achieved 1A cm^{-2} at 1.9V using 4.5mg cm^{-2} ionomer and no CoO, a 200mV improvement from the non-polyethylene-based version of the ionomer. Furthermore, these results highlight the negative effects of over-crowding on the electrochemically active surface area by loading too much material at the reaction interface, as addition of CoO did not significantly improve electrolyzer performance. The kinetics of the highest-performing material on the oxygen evolution reaction was also explored by performing half-cell studies to validate the single-cell experiments.

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Scenarios for reversible operation of solid oxide cell systems to produce hydrogen and electricity as compared to standalone SOEC plants

Mr. Aadarsh Parashar[1], Dr. Robert Braun[1]

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Solid Oxide Electrolysis 3, Metals Hall, June 23, 2022, 10:30 AM - 11:50 AM

Scenarios for reversible operation of solid oxide cell systems to produce hydrogen and electricity as compared to standalone SOEC plants

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Summary. A scenario-based comparison is done between a standalone SOEC plant generating only hydrogen with 90% capacity factor with a reversible plant generating both hydrogen and electricity having 100% capacity factor, both excluding the planned and unplanned downtime in the plant.

Abstract. Solid oxide electrolyzer systems present a promising solution for hydrogen and other renewable fuel production. When paired with renewable sources of electricity, it also becomes an environment-friendly source of fuel production or energy storage, depending on the end use of the products. This study aims to utilize the reversible operation capabilities of solid oxide-based electrochemical systems to optimize the deployment scheme of a plant to explore both hydrogen production during off-peak demand times and electricity production during peak demand times.

We consider a net 100 kW_e system in fuel cell mode with an electrolyte-supported stack operating at an average temperature of 800 ^oC. We assume thermoneutral voltage during SOEC operation and assume SOFC operation at 0.5 A cm^{-2} for maximizing efficiency. The electricity for hydrogen production is assumed to come from renewable sources [1], while the price of electricity sold during SOFC mode is assumed to be at the U.S. national average [2]. The capacity factor for the standalone SOEC plant is taken from DOE targets [3] and the reversible plant is assumed to have a 100% capacity factor excluding scheduled and unscheduled downtime. Various scenarios are investigated, including but not limited to lost hydrogen production potential, specific electricity consumption for hydrogen production (Figure 1), and net profit/loss in operating the plant in reversible mode with a higher capacity factor as compared to the standalone system having a slightly lower capacity factor (Figure 2).

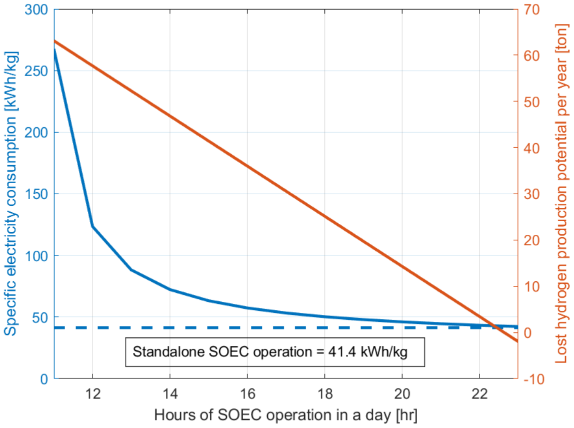

Figure 1: Specific energy consumption in standalone SOEC vs reversible operation

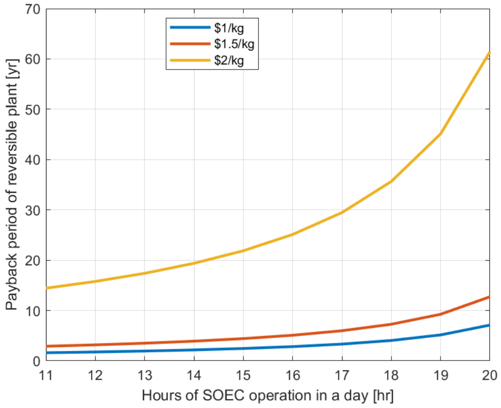

Figure 2: Simple payback period of a reversible solid oxide plant according to money saved by operating in reversible mode with various hydrogen market selling price

[1] James Vickers, David Peterson, and Katie Randolph, “Cost of Electrolytic Hydrogen Production with Existing Technology”, DOE Hydrogen and Fuel Cells Program Record, 20004, Sept 2020. https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf

[2] Electric Power Monthly – U.S. Energy Information Association (EIA). https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a [Accessed on 22nd April 2022].

[3] DOE Technical Targets for Hydrogen Production from Electrolysis | Department of Energy. https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-electrolysis [Accessed on 22nd April 2022].

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Establishing half- and single- cell baselines for the oxygen evolution reaction (OER) on non- platinum group metal (PGM) oxide electrocatalysts in alkaline media

Ms. Emily Volk[1], Dr. Stephanie Kwon[1,2], Dr. Shaun Alia[1,3]

[1]Mines / NREL Advanced Energy Systems Graduate Program, PhD Student, United States of America, [2]Colorado School of Mines, Department of Chemical and Biological Engineering, Assistant Professor, United States of America, [3]National Renewable Energy Laboratory, Chemistry and Nanoscience Center, Senior Scientist, United States of America

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Establishing half- and single- cell baselines for the oxygen evolution reaction (OER) on non- platinum group metal (PGM) oxide electrocatalysts in alkaline media

Emily Volk[a], Stephanie Kwon[a,b], Shaun Alia[a,c]

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Summary. Non-PGM transition-metal oxide electrocatalysts for OER were screened in alkaline media and compared to the current state-of-the-art, IrO_2. Inferences are made to possible differences in the OER mechanism on non-PGMs versus IrO_2 and comparisons are made between half- and single- cell performance.

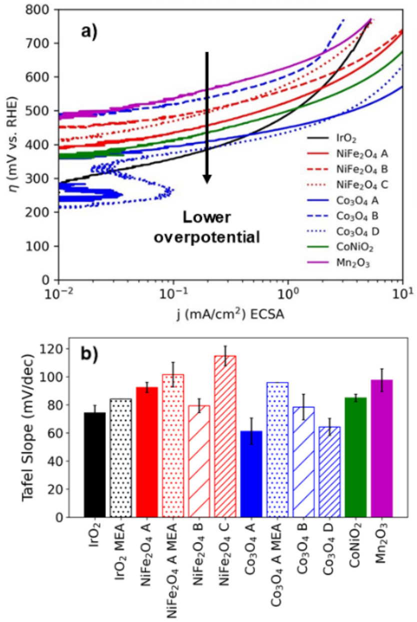

Fig. 1 a) Tafel Plots of metal oxides for OER (296K). The current density is normalized by the electrochemically active surface area (ECSA). Scan rate: 20mV/s, RDE rotation rate: 2500rpm. A, B, C, D indicate different suppliers. b) Tafel slopes as calculated from the linear region (1.5 and 1.7V vs RHE). MEA tests were performed at 353K in 1M KOH, cathode catalyst was Pt on high surface area carbon, membrane/ionomer were from Versogen.

Abstract. *Background and Motivation.* Electrochemical H_2 production is a promising strategy to provide clean energy and drive industrial decarbonization. However, this process is currently limited by high overpotentials of OER at the anode and a harsh near-surface environment (low pH, high voltage) in acidic media which necessitates the use of costly and rare platinum group metal (PGM) materials. As electricity costs have dropped, system/materials costs have become major inhibitors to the scalability of this technology; reducing dependence on PGMs is essential. Earth-abundant and cost-effective non-PGM transition metals, which corrode in acidic media, present as their solid oxide or hydroxide forms in alkaline media [1]; recent advances in anion exchange membrane (AEM) technology [2] have opened doors for catalyst development and integration research in alkaline electrolysis systems such as AEM electrolyzers. However, while OER has been studied extensively on IrO_2 in acidic media [3], not much is understood about i) the mechanism or ii) what the optimal catalyst candidates are in alkaline media. To address these gaps, a comprehensive catalyst screen for non-PGM metal oxides in both half-cell, rotating disc electrode (RDE) setups and single-cell, membrane electrode assembly (MEA) setups was performed. *Results.* 1st row transition-metal oxides were first tested using an RDE setup and compared to IrO_2. The electrochemically active surface area (ECSA) was determined by the double layer capacitance method [4], and specific capacitance (C_s) was determined at the same conditions as RDE experiments. Results in Fig. 1 indicate that i) Co_3O_4 may be a better catalyst than conventional IrO_2 or $NiFe_2O_4$ catalysts (low overpotential, low Tafel slope); ii) there may be a possible potential dependence of the mechanism for IrO_2 versus non-PGM metal oxides (as shown by the change in Tafel slope occurring at η = 400-500mV); iii) the notable performance differences among the catalysts provided from different suppliers, suggesting OER kinetics may be sensitive to subtle structural or compositional changes. A selection of catalysts was further tested in MEA setups to assess how RDE performance translates to AEM devices. Voltage breakdown analyses were performed to evaluate the contributions of ohmic losses, kinetic losses, and transport/other losses to the overpotential. Preliminary MEA results show performance trends of $IrO_2 \approx Co_3O_4 >> NiFe_2O_4$, which is comparable to RDE results. The Tafel slopes for the same catalysts determined from RDE vs MEA data increased (Fig. 1b); next steps will look to isolate kinetic differences from those arising due to differences in how catalysts integrate into MEAs. *Impact and Future Work.* This work establishes baselines for non-PGM metal oxide catalysts at relevant conditions for AEM systems and guides future work to elucidate possible differences in the OER mechanism between IrO_2 and non-PGM transition-metal oxide catalysts. The work ultimately aims to inform the optimized design of OER electrocatalysts for AEM devices and facilitate the deployment of H_2 at scale. *References.* [1] Pourbaix, *Atlas of Electrochemical Equilibria in Aqueous Solutions*, NACE, Houston **(1974)**. [2] Lindquist, *ACS Applied Materials & Interfaces* (**2021**). [3] Naito, *Inorganic Chemistry Frontiers* **(2021)**. [4] Trasatti, *Pure and Applied Chemistry* **(1991)**.

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Agfa’s contribution to the hydrogen economy: Zirfon and the impact on the levelized cost of hydrogen

Dr Nick Valckx[1]
[1]*Agfa, Business Manager, Belgium*

Alkaline Electrolysis 3, Metals Hall, June 22, 2022, 10:30 AM - 12:20 PM

Agfa’s contribution to the hydrogen economy: Zirfon and the impact on the levelized cost of hydrogen

Nick Valckx 1[a], Author Ruben De Bruycker 2[a], Hanne Verwaest 3[a], Elke Dom 4[a]

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Summary. Zirfon is currently the standard separator for Alkaline Water Electrolysis (AWE). In this presentation it will be shown what the impact is of Zirfon on the Levelized Cost Of Hydrogen (LCOH).

Abstract.

Around the world, ZIRFON H2 separators for Alkaline Water Electrolysis (AWE) are appreciated by electrolyzer manufacturers and owners of hydrogen production projects for their durability and sustained high productivity. With unparalleled ionic conductivity and tuned bubble management, ZIRFON separators allow alkaline electrolyzers to operate at record-high current densities and low cell voltage. That is traditional membranes. To the benefit of the installation's overall OPEX, electrolyzers equipped with ZIRFON separators will thus generate more hydrogen at a notably lower energy cost compared to the same system using conventional membranes. So, realizing the performance of Proton Exchange Membrane technology (PEM) water electrolysis but at notably lower cost. In **Figure 1** is an actual I-V curve with Zirfon UTP220, obtained with with Raney Ni electrodes – Platinum Group Metal free in 30% KOH at 90deg. Here a voltage below 2V can be obtained at a current density of 20kA/m2.

With these obtained I-V data it was also possible to perform an LCOH analysis. This analysis is summarized in **Figure 2**. The basic assumptions here are 1GW plant, electricity price 50€/MWh, 4000hr/y operation. Here it can be observed that traditional alkaline is very similar to the cost of PEM electrolysis. With traditional alkaline is meant a stack with a PPS felt or asbestos separator with performance as can be observe in **Figure 1**. Though, when using Zirfon UTP500, you’ll obtain an ‘Advanced Alkaline Electrolysis’, i.e. resulting in a direct reduction of 0,3 EUR/kg cost by efficiency/performance gains. With our latest development, Agfa’s UTP220, this can be further reduced with an extra 0,4EUR/kg. Further assumptions are reduction in CAPEX as well as remote locations with plenty of solar and wind energy at an average cost of 20EUR/MWh.
This finally results in an LCOH for alkaline electrolysis based green H2 of 1,3EUR/kg.

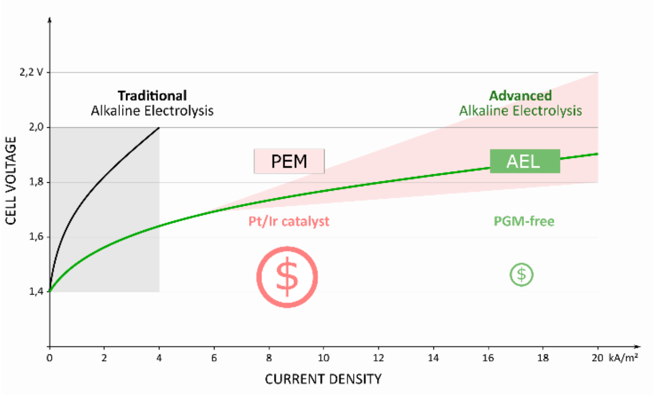

Figure 1: AEL can equal PEM performance at lower cost

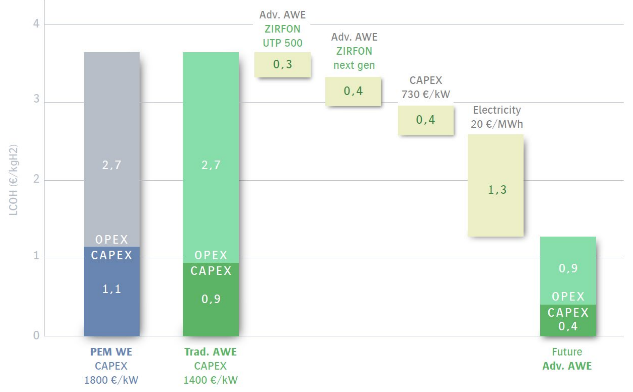

Figure 2: LCOH analysis of impact Zirfon on total green H2 cost

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A High-performance Capillary-fed Electrolysis Cell

Promises more Cost-competitive Renewable

Hydrogen

Mr Aaron Hodges[1], Mr Anh Linh Hoang[1], Dr George Tsekouras[1], Dr Klaudia Wagner[1,2], Dr Chong-Yong Lee[1,2], Prof. Gerhard Swiegers[1,2], Prof Gordon Wallace[1,2]

[1]Intelligent Polymer Research Institute, University of Wollongong, Australia, Scientist, Australia, [2]Australian Research Council's Centre of Excellence for Electromaterials Science, University of Wollongong, Australia, Scientist, Australia

Alkaline Electrolysis 1, Metals Hall, June 20, 2022, 3:40 PM - 5:30 PM

A High-performance Capillary-fed Electrolysis Cell Promises more Cost-competitive Renewable Hydrogen

Aaron Hodges[a], Anh Linh Hoang[a], George Tsekouras[a], Klaudia Wagner[a,b], Chong-Yong Lee[a,b], Gerhard F. Swiegers[a,b,*]
Gordon G. Wallace[a,b]

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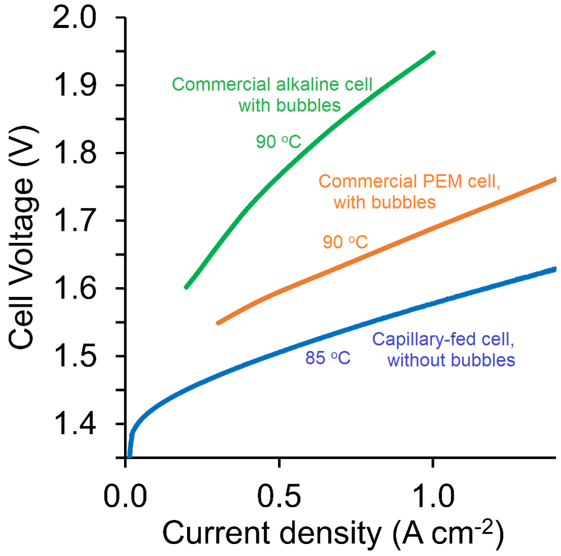
Corresponding author email: swiegers@uow.edu.au

Summary. A new design of water electrolyzer operates at 98% efficiency HHV (1.51 V) at 0.5 A cm^{-2}. Water is delivered by capillary action via a thin, porous, interelectrode separator. This configuration is inherently bubble-free. Segregation of liquid and gas phases allows direct production of gas and consolidation of electrolyzer auxiliary systems.

Abstract. Renewable, or green, hydrogen will play a critical role in the decarbonisation of hard-to-abate sectors and will therefore be important in limiting global warming. However, renewable hydrogen is not cost-competitive with fossil fuels, due to the moderate energy efficiency and high capital costs of traditional water electrolysers. Here a unique concept of water electrolysis is introduced, wherein water is supplied to hydrogen- and oxygen-evolving electrodes via capillary-induced transport along a porous inter-electrode separator, leading to inherently bubble-free operation at the electrodes. An alkaline capillary-fed electrolysis cell of this type demonstrates water electrolysis performance exceeding commercial electrolysis cells, with a cell voltage at 0.5 A cm^{-2} and 85 °C of only 1.51 V, equating to 98% energy efficiency HHV, with an energy consumption of 40.4 kWh/kg hydrogen (vs. ~47.5 kWh/kg in commercial electrolysis cells). High energy efficiency, combined with the promise of a simplified balance-of-plant, brings cost-competitive renewable hydrogen closer to reality.



2.0
1.9
1.8
1.7
1.6
1.5
1.4
Cell Voltage (V)
0.0
0.5
1.0
Current density (A cm-2)
Commercial alkaline cell with bubbles
90 oC
Commercial PEM cell, with bubbles
90 oC
Capillary-fed cell, without bubbles
85 oC

Investigation of the interface between the anodic catalyst layer with low Iridium loading and the porous transport layer in PEM water electrolysis

MS Mirjam Rogler[1], Dr Michel Suermann[1], Dr Richard Wagner[1], Dr Markus Ungerer[1], Mr Jochen Straub[1]

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Investigation of the interface between the anodic catalyst layer with low Iridium loading and the porous transport layer in PEM water electrolysis

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Summary. The interface between anodic catalyst layer and the porous transport layer interface has significant optimization potential for the performance of PEM water electrolysis cells. In this study, the main overpotentials and kinetic reaction parameters are determined as a function of the anodic catalyst loading and PTL type.

Abstract. Hydrogen carries out a growing role as an energy carrier in the energy transition from a fossil to a sustainable and renewable era. A promising technology for converting (renewable) electrical energy into chemical energy, i.e., hydrogen, is proton exchange membrane water electrolysis (PEMWE). However, there are still technological gaps and optimization potentials to more significantly reduce the levelized cost of hydrogen, e.g., by reducing the Iridium loading. [1] It is properly recognized that the anodic interface between catalyst layer (CL) and porous transport layer (PTL) has a significant impact on both performance and durability of the PEMWE cells and offers major optimization potential. [2, 3] Low Iridium loading usually leads to thin and inhomogeneous catalyst layers resulting in relatively poor in-plane electrical conductivity. [4] The contacted catalyst area is determined by the PTL properties, e.g. porosity. [5] Thus, the CL/PTL interface affects all three main overpotentials, i.e., ohmic, kinetic and mass transport.

In this work, these three main overpotentials and further relevant kinetic reaction parameters such as the apparent exchange current density and Tafel slope are determined of PEMWE cells with various Iridium loadings and different PTL structures. In this way, generic trends and dependencies can be identified. As expected, it can be shown that the kinetic overpotential increases with decreasing Iridium loading. Furthermore, this straight-forward correlation can be related to the interfacial contact area between the CL and PTL and the in-plane electrical conductivity of the CL itself. For instance, a relatively poor in-plane conductivity of the CL can be (partly) offset with a relatively good CL/PTL interfacial contact (area). The results provide insight into general design parameters to tackle challenges which come along with reducing Iridium loading.

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[2] T. Schuler, T. J. Schmidt and F. N. Büchi, *J. Electrochem. Soc.,* **166**(10), F555-F565 (2019).
[3] T. Schuler, R. de Bruycker, T. J. Schmidt and F. N. Büchi, *J. Electrochem. Soc.,* **166**(4), F270-F281 (2019).
[4] M. Bernt, A. Siebel and H. A. Gasteiger, *J. Electrochem. Soc.,* **165**(5), F305-F314 (2018).
[5] D. Kulkarni, A. Huynh, P. Satjaritanun, M. O'Brien, S. Shimpalee, D. Parkinson, P. Shevchenko, F. DeCarlo, N. Danilovic, K. E. Ayers, C. Capuano and I. V. Zenyuk, *Applied Catalysis B: Environmental,* **308,** 121213 (2022).

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Off-Grid Solar PV-Wind Power-Battery-Water Electrolyser Plant: Simultaneous Optimisation of Component Capacities and System Control

MR. Alejandro Ibanez-Rioja[1], Mr. Pietari Puranen[1], Mr. Lauri Järvinen[1], Dr. Antti Kosonen[2], Dr. Katja Hynynen[2], Dr. Vesa Ruuskanen[2], Dr. Jero Ahola[3], Dr. Pertti Kauranen[3]
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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Off-Grid Solar PV-Wind Power-Battery-Water Electrolyser Plant: Simultaneous Optimisation of Component Capacities and System Control

Alejandro Ibáñez-Rioja[a], Pietari Puranen[a], Lauri Järvinen[a], Antti Kosonen[a], Katja Hynynen[a], Vesa Ruuskanen[a], Jero Ahola[a], Pertti Kauranen[a]

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Summary. Off-grid alkaline water electrolysis system integrated with solar PV, wind power and a battery is modelled and optimised to minimise the levelised cost of hydrogen for a 30-years lifetime plant. Including solar PV and wind power production data from installations located in southeastern Finland shows that hydrogen cost will drop to 2.05 €/kg by 2025.

Abstract. The operation of a large-scale hydrogen production system formed by a 100MW nominal load alkaline water electrolyser is simulated with 300 seconds time resolution with a finite-state machine-based control. Simulations are based on solar PV and onshore wind power production data collected from installations located in southeastern Finland. Methodology of the study is based on a previously published article [1], whereas the techno-economic models have been improved to increase the reliability and accuracy of the simulations.

Battery energy storage based on lithium-ion technology is integrated in the system for a short-term energy storage. Its total energy capacity is optimised simultaneously with the system control, solar PV peak power capacity and total wind nominal power. The degradation of the PV panels, battery and electrolyser stack are considered in the simulation. The economic model includes the capital and operational expenditures (CAPEX and OPEX) of each component as well as the replacement costs for the alkaline water electrolyser and battery. The learning curve of the components are considered in the cost estimation, enabling the simulation of different installation years.

The optimization of the system aims to find a total of 11 variables that minimise the levelised cost of hydrogen (LCOH) for a 30-years lifetime production plant. The first 8 variables are related with the control of the system and the remining 3 are the components capacities, which are referred to the alkaline electrolyser nominal power. The minimisation of the LCOH is approached by the implementation of particle swarm optimisation algorithm (PSO). The computational resources used to perform the simulations and optimisations are provided by the CSC – IT Center for Science, Finland [2].

The result of the optimisation shows that the integration of solar PV is not economically beneficial in the studied area of southeastern Finland with the current components price framework. Considering the installation costs in year 2025, the optimal configuration of the system is formed by a wind farm of 1.37 times the nominal capacity of the electrolyser with no battery, which leads to a LCOH of 2.05 €/kg.

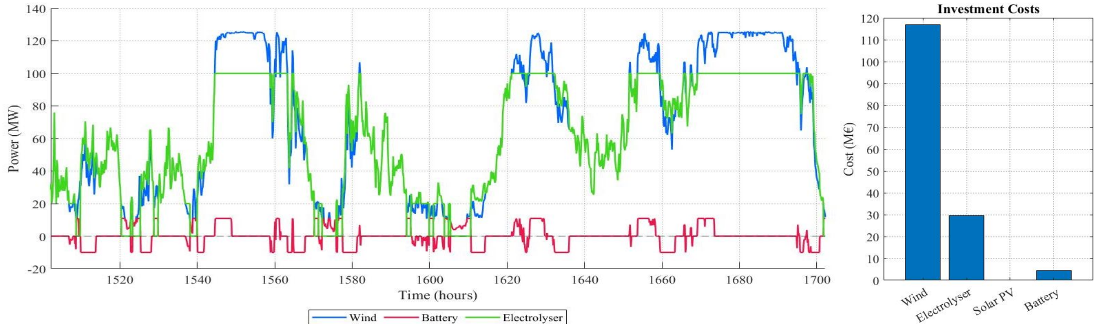

Figure 6. On the left, excerpt from the optimal operation time series considering installation costs in year 2040. Solar PV is not economically beneficial and therefore it was excluded. For a 100MW electrolyser, optimal battery capacity is 43.6 MWh and total nominal wind power is 124.4MW which is leading to a LCOH of 1.7 €/kg. On the right, the investment costs.

[1] Ibáñez-Rioja, A., Puranen, P., Järvinen, L., Kosonen, A., Ruuskanen, V., Ahola, J., & Koponen, J. (2022). Simulation methodology for an off-grid solar–battery–water electrolyzer plant: Simultaneous optimization of component capacities and system control. *Applied Energy*, 307, 118157. doi: 10.1016/j.apenergy.2021.118157

[2] ICT Solutions for Brilliant Minds | CSC - CSC Company Site. (2022). Retrieved 25 April 2022, from https://www.csc.fi/en/home

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Reduced order model of co-electrolysis of steam and carbon dioxide in solid oxide electrochemical cells (co-SOE)

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Solid Oxide Electrolysis 3, Metals Hall, June 23, 2022, 10:30 AM - 11:50 AM

Reduced order model of co-electrolysis of steam and carbon dioxide in solid oxide electrochemical cells (co-SOE)

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Summary. A reduced order model of solid oxide electrolyzer was developed and implemented in Aspen HYSYS software in order to simulate operation of SOE under H_2O/CO_2 co-electrolysis conditions. The model based on electric circuit equivalent of co-electrolyzer (co-SOE) finds application in simulating conversion of steam and carbon dioxide into the mixture of carbon monoxide and hydrogen. Various working conditions were studies and the modelling activities were supported by literature data to perform preliminary validation of the model.

Abstract. The energy sector is now focused on a gradual transition toward climate neutral economies. The continuously increasing penetration renewable energy sources (RES) in the markets is evident worldwide. However, the intermittent character of renewables such as wind or solar, hinders broader implementation in the energy mix. Curtailment of the energy is often observed due to the lack of sufficient storage capacities. In order to accommodate and fully utilize the electricity produced in RES grids need to integrate storage systems of various types. The existing storage technologies such as pumped-hydro storage or battery-based systems do not offer sufficient capacity to allow for full carbon-neutral system. For that reason much attention is now drawn to alternative solutions such as Power-to-X (P2X) technologies. These systems use hydrogen as an energy carrier which can be stored, converted back to electricity and heat, for example in fuel cells, or used as a feedstock in downstream process which generate synthetic fuels of various types. Electrolyzers are key components of P2X systems, while solid oxide electrolyzers offer a great advantage due to their outstanding efficiency and ability to be thermally integrated with P2X processes. Moreover, SOE offers the possibility of simultaneous conversion of H_2O and CO_2 into syngas, a mixture of hydrogen and carbon monoxide which are substrates for production of zero-emission hydrocarbonaceous fuels when electrolysis feeds the Fischer-Tropsch synthesis with renewable syngas. Such a mode of operation is known as co-electrolysis (co-SOE) and differs from the standard working conditions of steam electrolysis. Co-SOE needs further investigation in order to determine feasible operating conditions.

In this study a reduced order model of co-SOE was developed and implemented in Aspen HYSYS software. Novel numerical tool is based on a well-established model, which was previously proposed, validated and used in numerous computational simulations in both fuel cell and steam electrolysis mode, aiding in system design and integration [1,2]. The proposed model assumes local chemical equilibrium among the four species present in the set of reactions. Equilibrium can be reached due to the fact that reaction takes place at high temperature in the presence of catalyst - nickel in the fuel electrode. Implemented model was validated based on literature data. Experimantal results used in

validation process include current-voltage characteristics and outlet gas composition measurements. Numerical tool was used to investigate the effects of temperature, current density and feedstock composition on the operating voltage and syngas quality exiting SOE. It was concluded that syngas with different H_2/CO ratios can be produced by setting the right working conditions for co-electrolyzer and these parameters can be used to tune the parameters of the mixture downstream of co-SOE conditions.

[1] J. Milewski et al. Advanced methods of solid oxide fuel cell modelling. Green Energy and Technology, 2011.
[2] J. Kupecki et al. Energy analysis of a 10 kW-class power-to-gas system based on a solid oxide electrolyzer (SOE). *Energy Conversion and Management*, *199*, 2019.

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Enabling the large scale production of fluorine free electrode assemblies for proton exchange membrane water electrolysis

MS Clara Schare[1], Mr Andreas Münchinger[1], Ms Regina Qelibari[2], Mr Lukas Metzler[2], Mr. Giorgi Titvinidze[3], Mr. Severin Vierrath[1,2], Ms Carolin Klose[1,2]

[1]Hahn-Schickard, Scientist, Germany, [2]Electrochemical Energy Systems, IMTEK - Department of Microsystems Engineering, University of Freiburg, Georges-Koehler-Allee 103, Scientist, Germany, [3]Agricultural University of Georgia, Professor, Georgia

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Enabling the large scale production of fluorine free electrode assemblies for proton exchange membrane water electrolysis

Clara Schare[a], Andreas Münchinger[a], Regina Qelibari[b], Lukas Metzler[b], Giorgi Titvinidze[c] , Severin Vierrath[a,b], Carolin Klose[a,b]

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Summary. An all-hydrocarbon MEA based on sulfonated poly(phenylene sulfone)s was fabricated via directly coating electrodes onto the membrane, while maintaining state-of-the-art performance. The presented fabrication route is suitable for large scale production of hydrocarbon MEAs.

Abstract. Upscaling of hydrogen production to the gigawatt scale requires automated and high throughput production of membrane-electrode-assemblies (MEAs). The most common process for the fabrication of state-of-the-art MEAs is the decal method: Two electrodes are hot pressed from transfer sheets onto each side of the membrane. To enable good adhesion of the electrodes to the membranes, a temperature above the glass transition temperature is requiered for the hot pressing step. However this method is not suitable for some promising hydrocarbon ionomers not exhibiting glass transition temperatures below the decomposition temperature.

Recently, hydrocarbon polymers have gained increasing attention due to their lower gas permeation and high ionic conductivity, while potentially lowering the material cost when compared to perfluorosulfonic acids (PFSA). In previous work [1], we showed the high potential of full hydrocarbon MEAs with sulfonated poly(phenylene sulfone) (sPPS) as membrane and ionomer binder in the electrodes. These sPPS-cells reached 3.5 A cm^{-2} at 1.8 V outperforming state-of-the-art PFSA-cells (1.5 A cm^{-2} at 1.8 V). To significantly lower the production time and assist in shifting from the small-scale spray coating method to a more scalable method we present directly coated electrodes onto a sPPS membrane while maintaining comparable cell performance.

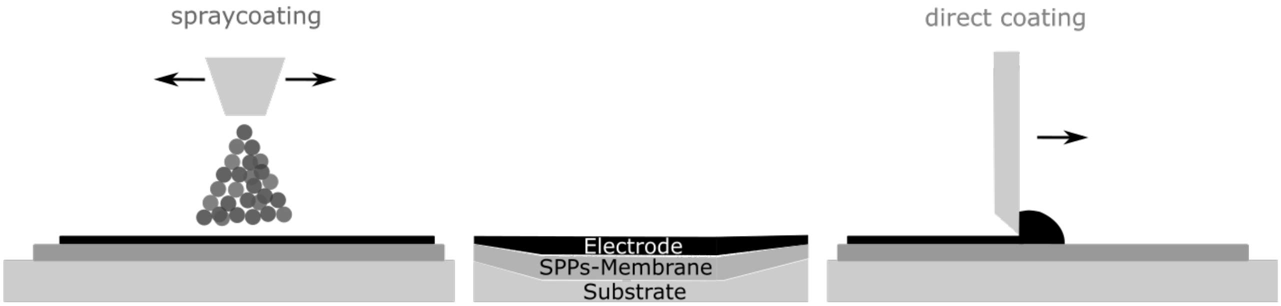

Fig. 1 Schematic of MEA production methods. On the left side the small scale spray coating method as used in previous work. On right side the presented more scaleable direct coating method.

Literature

[1] Klose, Carolin, et al. "All-Hydrocarbon MEA for PEM Water Electrolysis Combining Low Hydrogen Crossover and High Efficiency." *Advanced Energy Materials* 10.14 (2020): 1903995.

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Degradation Mechanisms of Proton Exchange Membrane Water Electrolyzer Stacks

MR Benjamin Kimmel[1], Prof. Dr. K. Andreas Friedrich[3], Dr. Aldo S. Gago[2], Dr. Pawel Gazdzicki[2], Dr. Indro Biswas[1], Dr. Tobias Morawietz[1]

[1]German Aerospace Center, Scientist, Germany, [2]German Aerospace Center, Group Leader, Germany, [3]German Aerospace Center, Professor, Head of Department, Germany

Polymer Electrolyte Membrane Electrolysis 1, Metals Hall, June 20, 2022, 1:30 PM - 3:10 PM

Degradation Mechanisms of Proton Exchange Membrane Water Electrolyzer Stacks

Benjamin Kimmel[a], Tobias Morawietz[a], Indro Biswas[a], Pawel Gazdzicki[a], Aldo S. Gago[a]*, K. Andreas Friedrich[a]

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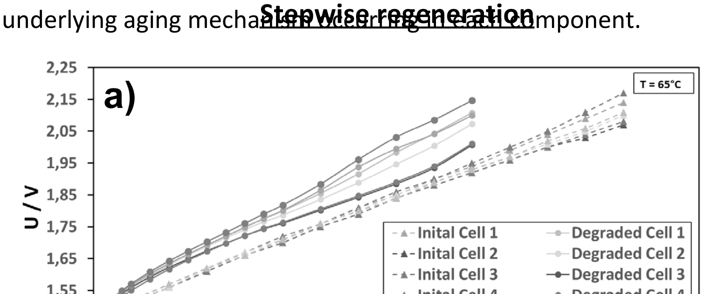
Summary. Components of an aged commercial PEMWE stack were analysed with electrochemical and physical methods. The impact of individual components on degradation and underlying mechanisms were identified. Contaminations were analysed and it was found that the CCM was the component most prone to degradation.

Abstract. Decarbonization of our energy production has become an important factor to fight climate change. Therefore, the implementation and expansion of technologies which use renewable energy is mandatory. Proton exchange membrane water electrolyzers (PEMWE) are ideal for producing of green hydrogen for transport, industry and heat. Important advantages are their compactness and high flexibility to operate under dynamical conditions. To be competitive it is necessary on the one hand to reduce the investment costs and on the other hand to ensure a long life of electrolyzers to limit operational expenses. Therefore, it is necessary to gain a deep understanding about degradation processes of PEMWE and link them to operation modes. Here we analyse the cell components of a commercial PEMWE stack, which has been operated by a customer for long periods of time under highly dynamic conditions using a wind mill coupled with batteries, with the help of electrochemical and physical methods. Samples of the operated components were cut at specific locations and characterized in a 4 cm^2 single cells. The aged components were successively replaced by new ones or regenerated to isolate and quantify the contribution of individual components on performance losses. This way, we have identified the catalyst coated membrane (CCM) as the component strongest affected by degradation. By using X-ray photoelectron spectroscopy (XPS) we identified different types of contamination like Pb and Fe. Remarkably, they were found on aged and unused components which is an indication for impurities due to the production process. In addition, the XPS analysis shows Ca traces which is characteristic of CCM contamination when insufficiently deionized water is used for cleaning cell components, in particular the Ti porous transport layers (PTL) used in the anode and cathode cell compartments. Scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDS) analyses reveal that Ca compounds leads to a degradation of the stack. In particular, the CCM notably degrades by defects of the catalytic layer. Signs of erosion and crystal growth was observed on the cathodic side of the Bipolar Plate (BBP) by means of SEM and atomic force microscopy (AFM), while the electronic conductivity remained unchanged. In contrast a pronounced oxidation, thus a low conductive area, is measured for the BPP on the anode side. The combination of electrochemical characterization with stepwise regeneration processes and physical ex situ analysis enables the possibility to draw conclusions about the impact of different components on degradation and to analyse the underlying aging mechanism occurring in each component.



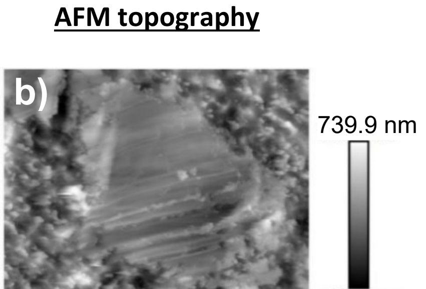


Figure 1: a) Performance comparison between initial performance and after operation. Images of the physical analysis b) AFM topography of the anodic BPP, c) SEM of the anode-side CCM, d) AFM conductivity measurement of the anodic BPP

Dynamic energy and mass balance model for an industrial alkaline water electrolyzer plant process.

Georgios Sakas[1], Mr. Alejandro Ibáñez-Rioja[1], Dr. Vesa Ruuskanen[1], Dr. Antti Kosonen[1], Dr. Jero Ahola[1], Mr. Olli Bergmann[2]

[1]Lappeenranta-Lahti University of Technology LUT, , Finland, [2]Oy Woikoski, , Finland

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Dynamic energy and mass balance model for an industrial alkaline water electrolyzer plant process

Georgios Sakas[a], Alejandro Ibáñez-Rioja[a], Vesa Ruuskanen[a], Antti Kosonen[a], Jero Ahola[a], Olli Bergmann[b]

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Summary.

This poster presentation demonstrates a parameter adjustable dynamic mass and energy balance model process for a 3 MW and 16 bar industrial water electrolyzer plant process, Fig.1. The process model is based on semi-empirical mathematical models solved via object-oriented programming in MATLAB® system blocks and Simulink environment.

Abstract.

The aim of the process model is to enable future optimization studies on the cost and energy efficiency of industrial-scale alkaline water electrolyzers. The electrochemical and thermal models are experimentally verified with measurements from an analogous real industrial plant of the same power capacity and pressure range under the same operating system design. The mass and energy balances of each unit operation are solved via the MATLAB Simulink interface and the resulted thermodynamic properties of each unit are dynamically connected to each other to create a zero-dimensional transient model process. The results revealed that at steady-state and nominal power operation, the shunt currents are the main contributor to relatively low Faraday efficiency of 86 %, and heat loss to ambient from the stack was just 2.6 % of the total power loss.

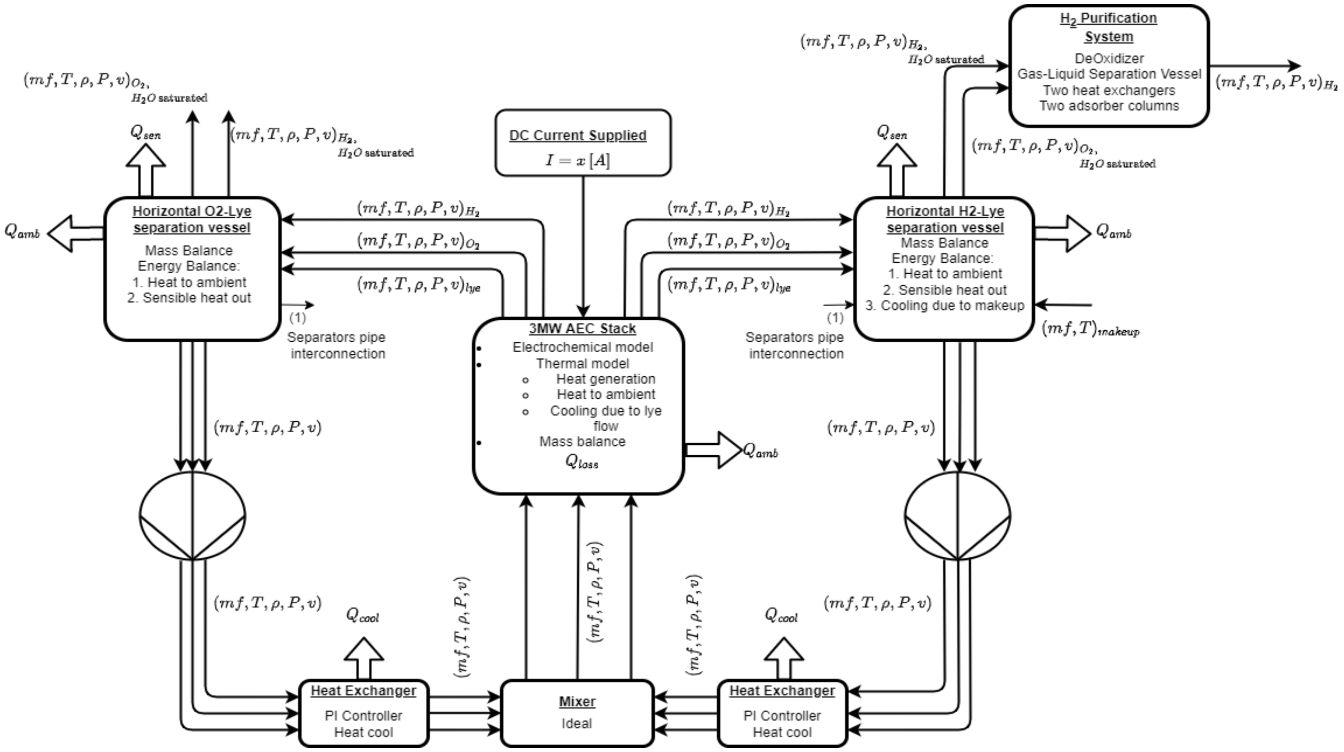

Figure 7. MATLAB Simulink diagram.

[1] Sakas, G., Ibáñez-Rioja, A., Ruuskanen, V., Kosonen, A., Ahola, J. and Bergmann, O., 2022. Dynamic energy and mass balance model for an industrial alkaline water electrolyzer plant process. *International Journal of Hydrogen Energy, 47*(7), pp.4328-4345.

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Synthesis and characterization of PGM-free NiMo cathode and NiFe LDH anode catalysts for AEMWE

Mr. Pierre Schröer[1], Mr. Lukas Heinius[1]
[1]*Technical University Berlin, Scientist, Germany*

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Synthesis and characterization of PGM-free NiMo cathode and NiFe LDH anode catalysts for AEMWE

Lukas Heinius[a], Pierre Schroeer[a], Malte Klingenhof[a], Philipp Hauke[a] and Peter Strasser[a]

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Summary. Maximum three lines summary for a catchy fast glance

The decreasing amounts of fossil fuel and progressive global warming cause a need for green energy carriers like hydrogen. Hydrogen generated by electrolysis can substitute fossil fuels. The alkaline anion exchange membrane electrolysis (AEMWE) has the opportunity to combine the advantages of PEM electrolysis with the cheap materials of the alkaline electrolysis.

Abstract.

Anion exchange membrane water electrolysis (AMWE) presents the opportunity to combine the advantages of PEM-electrolysis with cheap and abundant materials for fuelling the possible Hydrogen economy. Here we studied different materials that exhibit promising activity and stability under alkaline conditions.

Anode catalyst: The long discussed NiFe-based layered double hydroxides are still the most active OER catalyst for AEMWE[1], even when compared to noble metal catalysts, due to its structure and access to metallic active sites. Here a facile synthesis protocol and scale up method are presented, to produce material with optimized Ni:Fe ratios up to multi gram scale per synthesis batch. Further it is shown that the exchange of the interlayered counter ion influences the interlayer distance in the material and therefore on the activity of the material for OER.

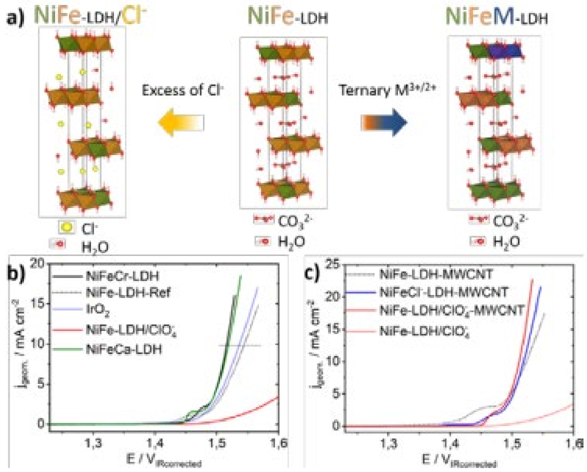

Figure 8: a) Modified NiFe LDH for OER through anion exchange and for OER b) RDE measurements on NiFe based materials, in 0.1M KOH at room temperature c) comparison between NiFe-LDH/ClO4- NiFe-LDH after anionic exchange, supported on MWCNT's

Cathode catalyst: Nickel-molybdenum supported on carbon was chosen as a catalyst, due to its high activity and low overpotential even in pH regions from 13 to 8. In order to find the best catalyst composition, different nickel-molybdenum ratios and supporting materials were tested at various pH values and temperatures and their overpotentials at 10mA/cm^2 are compared. The catalysts were characterized by XRD, ICP-OES and electron microscopy.

The best NiFe LDH and NiMo materials were then tested as anode and cathode catalysts respectively in an AEMWE setup.

[1] Dionigi, F.; Greeley, J.; Strasser, P**.,** ***Angew Chem Int Ed*** **2021**, 60, 14446-14457.

An Overview of the OREO International Collaboration Low-temperature Electrolysis Electrode Processing Activity

Mr. Michael Ulsh[1], Dr. Jansa Jankovic[2], Dr. Svitlana Pylypenko[3]

[1]National Renewable Energy Laboratory, Group Manager, United States, [2]University of Connecticut, Professor, United States, [3]Colorado School of Mines, Professor, United States

Polymer Electrolyte Membrane Electrolysis 3, Metals Hall, June 22, 2022, 8:00 AM - 10:00 AM

"An overview of the OREO International Collaboration low-temperature electrolysis electrode processing activity"

Jasna Jankovic[a], Svitlana Pylypenko[b], and Michael Ulsh[c]
[a]University of Connecticut, US; [b]Colorado School of Mines, US; [c]National Renewable Energy Laboratory, US
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Summary. The OREO International Collaboration brings together institutions with broad electrode processing capabilities and universities providing a consistent set of advanced characterization tools to explore the impact of ink formulation, coating and drying parameters on low-temperature electrolysis anode coatability, morphology, and performance.

Abstract. Industry and government aspirations continue to converge regarding the need for energy-system-wide solutions to environmental, sustainability, and climate challenges. The Department of Energy's new Hydrogen Energy Earthshot seeks to address these challenges, supported by elements of the Bipartisan Infrastructure Law, by enabling activities that will achieve a clean hydrogen production goal of $1 for 1 kg in 1 decade. Identified key enablers for low-cost electrolytic hydrogen include low-cost capital expenses, increased durability and lifetime, low-cost manufacturing processes, and manufacturing at megawatt scale. The Overall Research on Electrode Coating Processes project, or OREO, a collaboration of the University of Connecticut, the Colorado School of Mines, the Fraunhofer Institute for Solar Energy in Freiburg, Germany, and the National Renewable Energy Laboratory, seeks to contribute to these key enablers by bringing together a unique network of experts in electrolyzer (and fuel cell) ink/electrode fabrication, advanced characterization, and in situ device testing. These partners have the capabilities (a) to evaluate and compare material and process parameters across a wide range of different processes of interest to industry and, critically, (b) to be able to access a common and unique platform of characterization tools to enable the understanding of the impact of materials, inks and processes on the nano- and micro-scale structure of the electrode, and how this impacts MEA performance. Such a collaboration at this scale has not been attempted before. This approach offers an opportunity to overcome a number of challenges that individual groups face and enables an unprecedented scientific advancement and sharing of information and knowledge beneficial for the entire electrolyzer community. The unique combination of expertise, available facilities, and technical and commercial experience, as well as a potential to expand the partnership to a larger network in the future, including industry, enables cost-saving and acceleration of commercialization of electrolyzers. The collaboration and critical process-related challenges for electrolysis electrodes will be reviewed, and recent OREO activities focused on these challenges, to be presented in detail via individual presentations, will be previewed.

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Bipolar polymer electrolyte membranes for electrochemical CO2 conversion

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[1]Technical University of Denmark, PhD student, Denmark

Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Bipolar polymer electrolyte membranes for electrochemical CO_2 conversion

Yi-Lin Kao[a], Ramato Ashu Tufa[a], David Aili[a]

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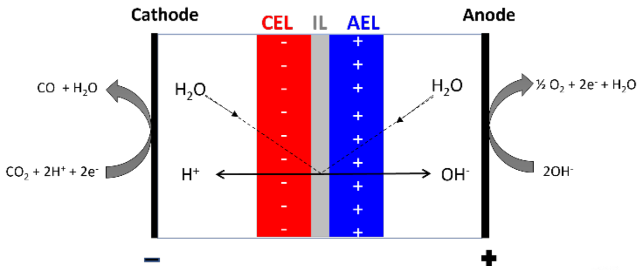
Summary. Bipolar membranes derived from the same polymer backbone could potentially enhance junction cohesion by simple and fast 2D fabrication methods.

Abstract. Many design strategies are being discussed for improving the efficiency and selectivity of low temperature CO_2 electrolysis.[1] Such reactors typically make use of anion exchange membranes, but the electrochemically driven parasitic CO_2 pumping results in a substantial CO_2-loss at the anode under typical reaction conditions in a flow cell configuration.[2] CO_2 electrolysis based on bipolar membranes (BPM) can not only prevent product-crossover but also retain the unreacted CO_2 at the cathode side, which shows a great potential in enhancing the utilization efficiency of electrolysis.

Most proof-of-concept studies of BPM in context with CO_2 electrolysis in the literature used BPMs based on simple lamination of arbitrarily chosen anion exchange layers (AEL) and cation exchange layers(CEL).[3] Recent BPM fabrication often involves 3D junction design via electrospinning, which has proven an effective way to enhance the interfacial contact area and the overall water dissociation rate over BPMs based on 2D junction designs (lamination, layer casting and spraying).[4] In this project, BPMs derived from styrene-ethylene-butylene-styrene (SEBS) based AEL and CEL will be prepared in order to create a miscible junction which could potentially improve cohesion of the two layers made of simple and fast 2D fabrication methods.



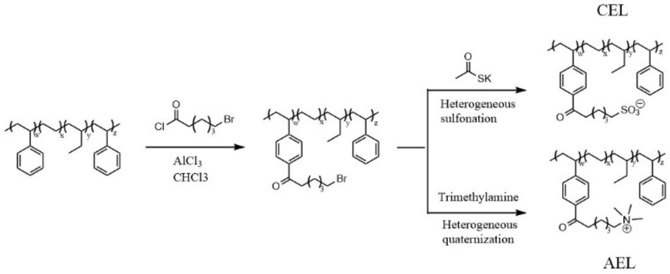


Figure 9 (left). Configuration of a BPM based CO_2 electrolysis

Figure 10(right). Synthetic pathway for SEBS-based AEL and CEL

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FORBLUE: Developing new electrolysis membranes for a better, cleaner future

Mr. William Salem[1]

[1]*AGC Chemicals Americas, Engineer, United States*

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

FORBLUE: Developing new electrolysis membranes for a better, cleaner future

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Summary.

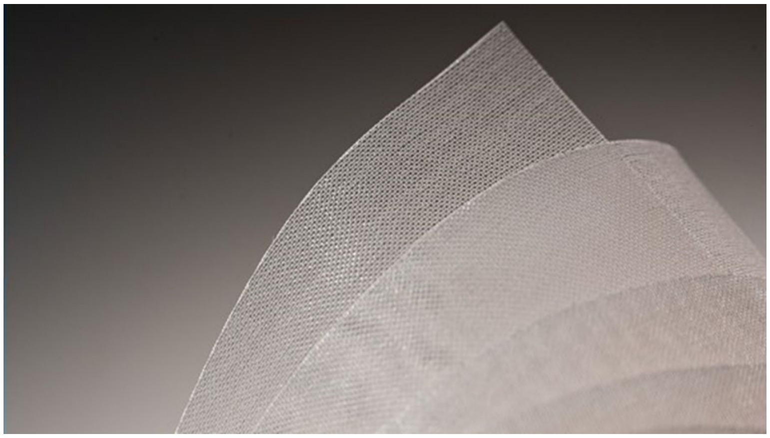
FORBLUE is a family of products under AGC Chemicals branded as separation solutions for various chemicals and processes. Separation applications include: perfluorinated ion exchange membranes and hydrocarbon ion exchange membranes for water electrolysis and redox flow batteries and fluoroelectrolyte polymer dispersions utilized in fuel cells. Recently, AGC has developed new membrane technology with ion exchange capacity and mechanical strength better than competitive offerings.

Abstract.

Fluorine-based ion exchange membranes have often been considered the standard membranes for polymer-based water electrolysis because of their ability to generate a higher current density and withstand the corrosive environments better than competitive technologies. AGC Chemicals, based out of Tokyo, Japan, and US headquarters in Exton, PA, has a family of products specializing in separation solutions for various chemicals and processes. The five members of the FORBLUE family include

- S-SERIES: Perfluorinated ion exchange membrane for polymer electrolyte membrane water electrolysis (PEMWE), redox flow batteries, and various other electrolysis,
- SELEMION: Hydrocarbon ion exchange membrane for anion exchange membrane water electrolysis, redox flow batteries, and electrodialysis,
- i-SERIES: Perfluorosulfonic acid polymer dispersion for proton exchange membrane fuel cells (PEMFCs),
- FLEMION: Perfluorinated ion exchange membrane for caustic soda production and caustic potash manufacturing, and
- sunsep: Perfluorosulfonic acid hollow tubes for humidification or dehumidification of various gases.

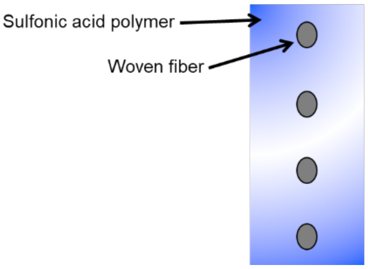
A recent member of the FORBLUE family, S-SERIES, was established in 2017. The product line is perfluorinated ion exchange membranes with different membrane thicknesses, fiber reinforcement availability, and counter ion mechanisms. Recently, AGC has developed a new generation of S-SERIES membranes with smaller thicknesses and lower equivalent weight (EW). The decreased EW leads to a higher ion exchange capacity (IEC) and lower electric resistance than standard and competitive membranes.



FORBLUE S-Series membrane

FORBLUE™ S-SERIES

Various electrolytic applications



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Mechanisms of Ni migration in Ni/YSZ/pore electrode of solid oxide electrolysis cells

Dr. Qian Zhang[1,2], Mr. Dalton Cox[2], Mr. Sicen Du[3], Dr. Katsuyo Thornton[3], Dr. Scott Barnett[2], Dr. Peter Voorhees[2]

[1]Energy Environment S&T, Idaho National Laboratory, , United States, [2]Department of Materials Science and Engineering, Northwestern University, , United States, [3]Department of Materials Science and Engineering, University of Michigan, , United States

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Mechanisms of Ni migration in Ni/YSZ/pore electrode of solid oxide electrolysis cells

Qian Zhang[a,b], Dalton Cox[a], Sicen Du[c] , Katsuyo Thornton[c], Scott Barnett[a], Peter Voorhees[a]

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Summary.

Phase field modelling and simulation are employed to study the mechanisms of Ni migration in Ni/YSZ/pore electrode. Quantitative predictions of the evolution of the microstructures of the Ni/YSZ/pore system due to the migration of Ni particles is studied through both theoretical analysis and data analysis.

Abstract.

SOECs can have a significant impact on climate change over the next decade and beyond, in applications such as balancing renewable grid electricity via electrolytic fuel production. However, long-term performance degradation remains a key issue that may limit further implementation of SOECs. Ni-YSZ fuel electrodes has been widely used in SOECs but Ni depletion and disconnection near the interface of electrode and electrolyte introduced by directional Ni migration are known to be important contributors to SOECs degradation. A phase field model is proposed that employs the Ni-YSZ 3D microstructure as the initial condition and large-scale numerical simulation is implemented that predicts the directional Ni migration. The results are thus directly comparable to experimental observations. The mechanism for Ni transport is a spatial gradient in surface tensions, *i.e.,* a decrease in the Ni/YSZ contact angle with increasing distance from the electrolyte. The Ni evolves due to surface diffusion or capillary driven evaporation and condensation. Quantitative predictions of the evolution of the microstructures of the Ni/YSZ/pore system due to the migration of Ni particles is studied through both theoretical analysis and data analysis.

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Manufacturing Challenges, Opportunities, and Successes for PEM Electrolysis at Scale

Mr. Christopher Capuano[1]

[1]Nel Hydrogen, Director, CR&D, United States of America

Polymer Electrolyte Membrane Electrolysis 3, Metals Hall, June 22, 2022, 8:00 AM - 10:00 AM

Manufacturing Challenges, Opportunities, and Successes for PEM Electrolysis at Scale

Hydrogen generation via electrolysis has gained much attention internationally as not only a sustainable source of fuel for the transportation, but as a carrier of energy to capture stranded renewable energy due to the carbon-free chemical cycle and response characteristics of the technology. The barrier to entry preventing this technology from being widely adopted is the overall cost associated with both the upfront capital expense as well as the operating cost incurred over the product life. The majority of this cost is driven by 1) low electrical efficiencies due to the high ohmic resistance of thicker membranes required by electrolysis systems to electrochemically compress generated hydrogen for storage and the polarization resistance associated with the oxygen evolution reaction (OER) on iridium catalysts typically used, 2) high cost of system and cell stack materials, which need to be durable for up to 100,000hrs at an average cell potential of 2V, and 3) the lack of a robust supply chain for high volume manufacturing of complex components to further drive down cost through economies of scale.

With 95% of hydrogen currently being produced through the reformation of cheap natural gas, significant cost reductions are necessary for electrolysis to become a viable alternative to the incumbent. Commercial proton exchange membrane (PEM)-based electrolysis has reached scales of several hundred kg/day. It provides a relevant pathway for industrial scale hydrogen generation with tremendous opportunity for continuing cost reduction by leveraging system and manufacturing scaling laws and advancements in PEM fuel cell materials, automated manufacturing, and analysis tools. Order of magnitude improvements in some of the highest cost elements are already achieved by NEL Hydrogen and with more research funding being directed towards hydrogen production, the realization of these reductions is occurring at a faster rate. While many improvements in stack design and materials of construction have been identified and implemented, there are still numerous opportunities to explore that would move electrolysis towards a viable, cost-effective alternative to natural gas reformation. This talk will describe some of the areas of success, where research is still needed, and ultimately how each of these improvements translate into cost and the path to reformation parity.

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Accelerating Anion-Exchange Membrane Water Electrolysis Development

Dr Seyed Schwan Hosseiny[1], Mr. Abissaid Martinez Septimo[2], Mr. Sambal Shashank Ambu[2], Mr. Julien Fage[2], Dr. Miriam Goll[2]
[1]CENmat, CEO, Germany, [2]CENmat, Scientist, Germany

Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Accelerating Anion-Exchange Membrane Water Electrolysis Development

Dr. Seyed Schwan Hosseiny[a], Julien Fage[a], Abissaid Martinez Septimo[a], Sambal Shashank Ambu[a], Dr. Miriam Goll[a]

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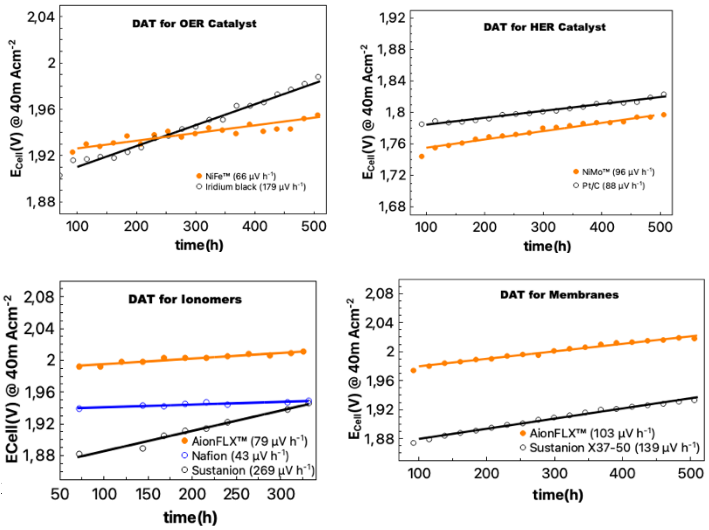
Summary. The development of performant materials and components for the anion-exchange membrane water electrolysis (AEMWE) was accelerated through a novel, facile, economic, and time-efficient Dissociative Analysis Technique (DAT) to investigate the degradation of materials and components in-situ and operando independently from each other. This allowed the development of a highly efficient AEMWE that overcomes bottlenecks in terms of efficiency, durability, and value chain dependencies. The newly developed and critical raw material free AEMWE catalysts, membranes, ionomers, electrodes, and cell design allow the operation at 2A/cm^2 >1000h (at the time of the abstract submission) while maintaining a cell potential below 2.2V at 50°C with a 0.1M KOH solution.

Abstract. The AEMWE technology promises to overcome the bottlenecks of the proton-exchange membrane water electrolysis (PEMWE) and alkaline water electrolysis (AWE). The AEMWE is highly interesting as in theory it can be operated without critical raw materials, does not need perfluorinated membranes, can deliver high-pressure hydrogen, etc… and is therefore thought to be the electrolyser technology of the future. However, many shortcomings such as inefficient catalysts, membranes, ionomers, electrodes, and cell designs or the inability to be operated at high current densities are just some obstacles to the commercialization and scale-up of this technology. Yet, the stability of the stack materials especially catalysts, membranes, ionomers, and electrodes pose one of the biggest challenges to the future of the AEMWE as the green hydrogen production technique. Since the stability of the electrolysis can only be investigated for the entire electrolysis cell the materials development relies on expensive, time-consuming, and complex technologies to investigate each component independently within the electrolysis cell. This however is a bottleneck to the commercialization and widespread use of AEMWE as it drastically decelerates the development of the technology. Therefore, a facile, economical, and time-efficient Dissociative Analysis Technique (DAT) was developed to quickly analyze the stability of potential materials and components for the AEMWE in-situ and operando. The rapid identification of stability performances through DAT lead to a complete redesign of the AEMWE, eradicating the need for critical raw materials, reducing costs, and greening the chemistry of membranes and ionomers, lowering the complexity of the electrochemical cell design, enhancing the safety for operators, reducing the environmental



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impact, and ensuring that the scale-up process is not hindered by dependencies of restricted materials and components suppliers. With help of DAT CENmat developed the most efficient, economic, and durable AEMWE on the market within a very short time without the need for critical raw materials using CENmat's materials such as NiFe™ for OER, MoCa™ for HER and AionFLX™ as anion-exchange membrane and ionomer. Figure 1 depicts the degradation rate of CENmat's materials in comparison to commercial materials. Additionally, the combination of these highly performant and durable catalysts, membrane, and ionomers from CENmat allow switching from a catalyst-coated membrane (CCM) based cell design to a catalyst-coated substrate (CCS) design, lowering the complexity of the cell assembly drastically as pristine membranes without catalyst coatings can be used for assembly of the cell. In our presentation, we will be introducing DAT and looking at the performance of various materials and components in-situ and operando with respect to their degradation and highlighting how DAT has supported the development of the AEMWE at CENmat.

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PEEK reinforcement for sulfonated polyphenylsulfone membrane

Ms. Regina Qelibari[1]

[1]*IMTEK - Albert-Ludwigs-Universität, Scientis, Germany*

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

PEEK reinforcement for sulfonated polyphenylsulfone membrane

Regina Qelibari[a], Giorgi Titvinidze[b,c], Andreas Münchinger[c], Severin Vierrath[a,c], Carolin Klose[a,c]

[a]Electrochemical Energy Systems, IMTEK - Department of Microsystems Engineering, University of Freiburg, Georges-Koehler-Allee 103, 79110 Freiburg, Germany; [b]Agricultural University of Georgia, 240 David Aghmashenebeli Alley, 0131 Tbilisi, Georgia; [c]Hahn-Schickard, Georges-Koehler-Allee 103, 79110 Freiburg, Germany
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Summary: Sulfonated hydrocarbon polymers obtain desired features for the use as proton exchange membranes in electrolyzers. To increase the long-term stability of hydrocarbon membranes a reduction of the high water content in the membrane is required. The integration of a woven open mesh PEEK substrate to reduce membrane softening is presented.

Abstract: The desired features of fluorine-free hydrocarbon ionomers enable a pathway for researchers to focus on proton exchange membranes that potentially can be synthesised more environmental-friendly with lower material cost compared to state of-the-art perfluorinated sulfonic acid (PFSA) ionomers. Due to their particular morphology which facilitates a decrease of the gas crossover while maintaining high proton conductivity, they propose to be a promising alternative to PFSA membranes. In our group, the high potential of hydrocarbon membrane based electrolyzers has been shown with sulfonated-polyphenylensulfone (sPPS) based membrane electrode assemblies (MEA). The sPPS-MEAs reached more than two times higher current densities at 1.8 V and three times lower gas crossover compared to state-of-the-art PFSA-MEAs (Nafion N115) [1]. However, a challenge that needs yet to be overcome is the high water uptake of sPPS materials related to its chemical structure (high acidity of sulfonic acid group, high polarity of the main backbone): it is theorized that membrane degradation is partly due to a softening of the membrane caused by a high water content in the sPPS-membrane. Thus, reducing the water content in sulfonated hydrocarbon membranes is the main strategy to improve the long-term stability of the sPPS-MEAs. We show that by integration of a woven open mesh PEEK substrate a reduction of the water content up to 53% at room temperature compared to the parent membrane can be achieved (Figure 1). The archieved reduction of the water uptake having positive effects on the mechanical characteristics of the membrane opens an avenue for hydrocarbon membranes in next generation electrolyzers.

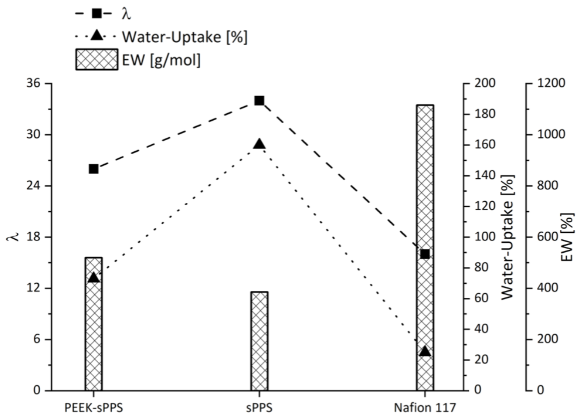

Figure 12: *Water-uptake, λ and equivalent weight for PEEK-reinforced sPPS- , pure sPPS- and Nafion 117-membrane at room temperature.*

Literature: [1] Klose, Carolin, et al. "All-Hydrocarbon MEA for PEM Water Electrolysis Combining Low Hydrogen Crossover and High Efficiency." *Advanced Energy Materials* 10.14 (2020): 1903995.

Advancement of Proton Conducting Solid Oxide Electrolysis Cells (p-SOEC) for Hydrogen Production at Idaho National Laboratory

Ms. Lei Ding[1], Dr. Hanping Ding[1], Dr. Wei Wu[1], Mr. Joshua Gomez[1]

[1]*Idaho National Laboratory, Group lead, distinguished materials engineer, USA*

Solid Oxide Electrolysis 2, Metals Hall, June 21, 2022, 4:00 PM - 5:30 PM

Advancement of Proton Conducting Solid Oxide Electrolysis Cells (p-SOEC) for Hydrogen Production at Idaho National Laboratory

Dong Ding, Hanping Ding, Wei Wu and Josh Gomez
Idaho National Laboratory, Idaho Falls, ID 83404 (USA)
Corresponding author email: dong.ding@inl.gov

Summary. A brief summary of p-SOEC development at Idaho National Laboratory.

Abstract. Proton Conducting Solid Oxide Electrolysis Cells (p-SOEC) is an emerging and attractive technology for hydrogen production through water electrolysis at intermediate temperatures. Economically competitive p-SOEC systems have distinct advantages over conventional oxygen-ion conducting ceramic electrochemical cells, but further technology development and widespread market acceptance will require continuous innovation of materials and structures in order to improve cell performance, enhance system lifetime and reduce cost. Herein, we report the advancement of p-SOEC with materials R&D, interface engineering, as well as cell fabrication and manufacturing in INL. We highlight how DOE support through HydroGEN accelerates move up the technology readiness level.

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On the scaling up of proton ceramic electrolyser technology: progress in materials, cells, stacks and system development

Dr Marie-Laure Fontaine[1]

[1]*SINTEF AS, Manager, Norway*

Solid Oxide Electrolysis 2, Metals Hall, June 21, 2022, 4:00 PM - 5:30 PM

On the scaling up of proton ceramic electrolyser technology: progress in materials, cells, stacks and system development

Marie-Laure Fontaine

SINTEF Industry, Norway
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Summary. Innovation in high temperature electrolysis is sought with the use of novel ceramic proton ceramic electrolysers combined with new materials sets, tubular concept of cells and stacks enabling pressurized operations demonstrated at 10 bar.

Abstract. In the European GAMER project (*Game changer in high temperature steam electrolysers with novel tubular cells and stacks geometry for pressurized hydrogen production*), we develop a novel tubular Proton Ceramic Electrolyser (PCE) stack technology to produce dry pressurized hydrogen using high volume production of tubular PCEs. The cells contain $BaZr_{1-x-y}Ce_xY_yO_{3-\delta}$ with x=10-20% and Y=10-20% (BZCY)-based electrolyte, BZCY-Ni tubular hydrogen electrode and a composite $Ba_{0.5}Gd_{0.8}La_{0.7}Co_2O_{6-\delta}$ (BGLC)-BZCY steam + O_2 electrode. The cells are integrated in tubular steel shells forming the so called "single engineering units" (SEU). The SEUs have ca. 50-60 cm^2 active surface area and are qualified for pressurized steam electrolysis operation at intermediate temperature (600°C) and up to 10 bar pressure. They exhibit high faradaic efficiency and reasonable area specific resistance, positvely affected by the increased operational pressure as will be discussed. A dedicated design assembly of the SEUs mounted to produce racks of 16 SEUs mounted in series has been developed in the project, as well as an integrated system design with necessary balance of plant components (figure 1). This work was carried out with the support of advanced modelling and simulation work, flowsheets of integrated processes, combined with robust engineering routes for demonstrating efficient thermal and electrical integration in a 10 kW electrolyser system aiming at delivering pure hydrogen at minimum 30 bars outlet pressure. This presentation gives an overview of the project's main results, spanning from cell manufacturing and SEU production, SEU testing up to 10 bar, the rack design and assembly development together with system design, building and current stage of development.

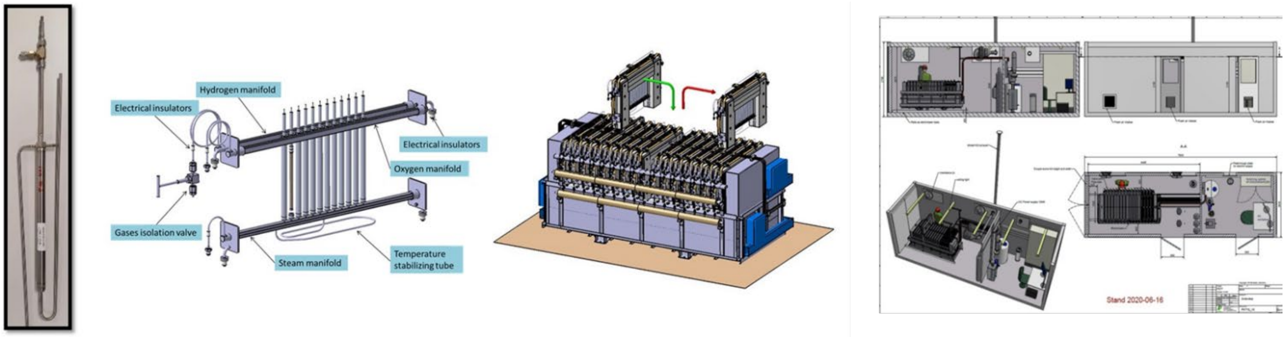

Figure 1. From left to right: one SEU, one rack, hot-box with 16 racks, pilot plant of electrolyser with BoP

This presentation is given on behalf of the GAMER consortium: cell and SEU manufacturer (Coorstek Membrane Science AS), system integrator (MC2 Ingenieria y Sistemas SL), RTD performers (SINTEF, University of Oslo, CSIC-ITQ), end-users (Carbon Recycling International, Shell Global Solutions International B.V.). The GAMER project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement (number 779486). This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Clean Hydrogen Europe Research.

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Numerical simulation of Marangoni convection near a hydrogen bubble growing on a microelectrode

MR. Aled Meulenbroek[1], MR. Bas Bernts[1], MR. Niels Deen[1,2], MR. Albertus Vreman[1,2,3]
[1]Power & Flow group, Department of Mechanical Engineering, , The Netherlands, [2]Eindhoven Institute of Renewable Energy Systems, , The Netherlands, [3]Nobian Industrial Chemicals, , The Netherlands

Alkaline Electrolysis 2, Metals Hall, June 21, 2022, 1:30 PM - 3:20 PM

Numerical simulation of Marangoni convection near a hydrogen bubble growing on a microelectrode

Aled M. Meulenbroek[a,*], Bas W.J. Bernts[a], Niels G. Deen[a,b], Albertus W. Vreman[a,b,c]
[a] Power & Flow group, Department of Mechanical Engineering, Eindhoven University of Technology, the Netherlands; [b] Eindhoven Institute of Renewable Energy Systems, Eindhoven University of Technology, the Netherlands; [c] Nobian Industrial Chemicals, the Netherlands
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Summary. In this work we investigate the growth of a hydrogen bubble on a microelectrode. Mass transfer effects of the hydrogen from electrode towards the bubble are elucidated, and special attention is given to the role of Marangoni convection around a bubble on the growth of the bubble.

Abstract. Efficient electrolysis is achieved by generating as much hydrogen gas with as little energy as possible. It is well known that bubbles have a negative influence on the efficiency, due to ohmic obstruction, electrode masking and local concentration effects [1]. Therefore, a more thorough understanding of the growth of bubbles on electrodes is required. Electrolysis starts by applying a potential difference between two electrodes. Resulting are two half reactions where hydroxide ions and water are depleted, at the anode and cathode respectively. While simultaneously water and oxygen gas are produced at the anode; hydroxide ions and hydrogen are produced at the cathode. The gasses dissolve into the liquid and once the concentration of the dissolved gasses exceeds the saturation concentration heterogeneous nucleation takes place at small defects in the electrode surface. A nucleated bubble on the electrode starts to grow by consuming the surrounding saturated gas concentration and thus influences the local concentration, posing mass transfer effects. The growth of a bubble and the rate of reaction at the electrode surface are therefore coupled phenomena [1].

Experimental observations of bubbles growing on electrodes are challenging because of the vigorous way in which typically thousands of bubbles are growing simultaneously on the electrode surface. On micro-electrodes we do not encounter such problems and therefore they are used in several experimental studies [2,3,4]. Yang et al.[2] found that the growth of a hydrogen bubble on such a micro-electrode was limited by the kinetics of the chemical reaction and the bubble radius would grow according to . This implied that at the microelectrode virtually all produced hydrogen is absorbed immediately into the bubble. Yang et al. [2] further state that this process is different from the diffusion limited growth often encountered in boiling liquids [2]. Although, Yang et al.[2,3] and Massing et al.[4] can experimentally observe the growth of a bubble and the corresponding current and potential applied to the cell, local and temporal information about the concentration of dissolved hydrogen was not obtained. Here simulations prove to be a valuable tool to uncover the mass transport phenomena that occur during electrolysis in the vicinity of bubbles. We also comment on the role that Marangoni convection plays in the bubble evolution, because based on previous quasi-steady-state simulations capillary effects drive strong convective flow near the bubble. This Marangoni flow could influence both detachment from the electrode but also the bubble growth due to mass transfer effects [3,4,5].

The growth of a bubble on a micro-electrode was implemented in COMSOL Multiphysics utilizing a moving mesh method. The advantage of this method is that it can reproduce the growth correlations reported in literature for both kinetics limited growth, as for diffusion limited growth, . In addition, COMSOL Multiphysics offers the opportunity to account for the concentration-dependent Butler-Volmer equation that describes the correlation between current density and overpotential. Moreover, the capillary-driven Marangoni convection is implemented. Thus, the numerical method can be benchmarked with the growth reported in [3,4] and we can comment on the influence the Marangoni convection has on the electrode kinetics and growth.

References

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[5] Aled Meulenbroek et al., Electrochimica Acta, 2021,Volume 385, 138298

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Monitoring of industrial water electrolysis systems for efficient and safe operation

Dr. Joonas Koponen[1], Dr. Anton Krimer[2]
[1]Neovolt, CTO, Finland, [2]Neovolt, COO, Finland
Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Monitoring of industrial water electrolysis systems for efficient and safe operation

Joonas Koponen[a], Anton Krimer[a]

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Summary. Estimation of energy losses in the entire energy supply and conversion chain of an industrial water electrolysis system requires comprehensive electrical measurements. Waveform information reveals the net transfer of electrical energy, and more numerous voltage measurements from the reactor improve the condition monitoring and system safety.

Abstract. The measurement capabilities in industrial water electrolyser systems can be insufficient to accurately determine the actual specific energy consumption (SEC) of hydrogen production (kWh/kg$_{H2}$) and allocate the losses in the overall energy supply and conversion chain. The number of electrical measurements from the system may be limited, which restricts online condition monitoring capabilities of the system. Furthermore, the measurement data may be aggregated in a way where, e.g., only mean DC voltage and mean DC current values are known during normal plant operation. As the DC current and DC voltage waveforms contain harmonic components in practical electrolyzer systems, the calculation of electric power requires waveform information on both voltage and current. Moreover, measurement of current and voltage waveforms as a function of time is also an additional tool for condition monitoring of the electrochemical reactor and the power supply. Thus, a properly designed electrical measurement system is crucial for continuous SEC optimization of the electrolysis plant, system safety, and condition monitoring.

The energy consumption to produce a kilogram of hydrogen by the means of water electrolysis varies as a function of the electrolyzer load and should, for industrial-scale systems, be determined based on the electrical energy transferred from the electricity grid side and hydrogen produced with specified characteristics (e.g. gas purity, pressure). Energy is lost from the main input from electricity grid in the grid transformer, power electronics and supply, water electrolysis (voltage efficiency, electric charge utilization efficiency, gas mixing), water production at DeOxo (if not recycled). Additionally, auxiliary power supply, e.g., to supply and circulate water and possible liquid electrolyte, generate heat for both the DeOxo catalyst and hydrogen drying unit are examples of energy consumption that will be included in the overall SEC value. This way to minimize SEC at all times, it is important to understand the losses of the hydrogen production line as a function of load, to record and analyse the changes to said function over time.

Thus, to conclude, industrial water electrolysers require properly designed intelligent electrical measurement and monitoring systems for efficient and safe operation.

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IrxNb1-xO2 Mixed Metal Oxides as Anode Catalyst for PEM Electrolysis: from Fundamentals to Application

MR. Matthias Kroschel[1], Mr. Malte Klingenhof[1], Dr. Camillo Spöri[1], Dr. Lorenz J. Falling[2], Dr. Travis E. Jones[2], Prof. Dr. Peter Strasser[1]

[1]Technical University Berlin, , Germany, [2]Fritz Harber Institute of the Max Planck Society, , Germany

Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

$Ir_xNb_{1-x}O_2$ Mixed Metal Oxides as Anode Catalyst for PEM Electrolysis: from Fundamentals to Application

Matthias Kroschel[a], Malte Klingenhof[a], Camillo Spöri[a], Lorenz J. Falling[b], Travis E. Jones[b], and Peter Strasser[a]

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[b]Fritz Harber Institute of the Max Planck Society, Germany

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Summary. Here we describe the synthesis of $Ir_xNb_{1-x}O_2$ (mixed) metal oxides powders with several compositions. The catalysts are characterized with a variety of techniques to achieve a structure – activity relation. Furthermore, the effect of annealing temperature is addressed. Promising catalysts were tested in a full electrolysis cell as well.

Abstract. Electrochemical water splitting will play a crucial role in future industries and will contribute to a more sustainable economy. Hydrogen produced by electrolysis is suitable to replace hydrogen produced by fossil fuels, enables the electrification of multiple sectors and can be used as long- and short-term chemical energy storage system [1].

Here we describe the synthesis of $Ir_xNb_{1-x}O_2$ (mixed) metal oxides powders by thermal decomposition. Several compositions regarding the Ir/Nb ration are synthesized and studied. The study is based on previous experimental and theoretical findings using model films of $Ir_xNb_{1-x}O_2$ [2]. The study addresses fundamental properties like crystal structure and oxidation state and the transfer to full electrolysis cell measurements. The synthesized materials are analysed using a variety of techniques, like XRF, XRD, RDE, XAS and TGA to determine the activity and stability, crystal structure, morphology, oxidation state and conductivity. Furthermore, the effect of the annealing temperature on the above mentioned properties was studied. The optimal composition was determined based on activity and stability measurements in a three-electrode setup and physical properties like the powder conductivity.

The synthesized catalysts could outperform commercial catalysts in terms of activity and stability measured in a three-electrode setup. According to recent publications the activity of amorphous, hydrous iridium oxide with an Ir oxidation state < 4 is greater than the one of crystalline IrO_2 [3]. XRD measurements reveals an IrO_2 rutile structure with very broad peaks, indicating an amorphous crystal structure. Furthermore, the absorption edges measured by x-ray absorption spectroscopy (XAS) of these catalysts is shifted to lower energies, indicating an oxidation state <4. Both, the XRD and XAS results confirm recent publications and theories.

The most promising catalysts were evaluated in a full electrolysis cell with different loadings.

[1] Getting Hydrogen to the Gigaton Scale; B. S. Pivovar, M. F. Ruth, A. Nakano, H. Furutani, C. Hebling, T. Smolinka; Electrochem. Soc. Interface. 2021, 30, 85.

[2] Molecular Analysis of the Unusual Stability of an IrNbOx Catalyst for the Electrochemical Water Oxidation to Molecular Oxygen (OER); C. Spöri, L. J. Falling, M. Kroschel, C. Brand, A. Bonakdarpour, S. Kuhl, D. Berger, M. Gliech, T. E. Jones, D. P. Wilkinson, P. Strasser

[3] Key role of chemistry versus bias in electrocatalytic oxygen evolution; H. N. Nong, L. J. Falling, A. Bergmann, M. Klingenhof, H. P. Tran, C. Spöri, R. Mom, J. Timoshenko, G. Zichittella, A. Knop-Gericke, S. Piccinin, J. Perez-Ramirez, B. R. Cuenya, R. Schlögl, P. Strasser, D. Teschner, T. E. Jones; Nature, 2020, 587, 408

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Critical Analysis of Published Physical Property Data and Collation into Detailed Models of Alkaline Electrolysis

Mr Aaron Hodges[1], Ms Stefanie Renz[2], Dr Felix Lohmann-Richters[3], Prof Werner Lehnert[6], Prof Gerhard Swiegers[4,7], Prof Gordon Wallace[5,7]

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Critical Analysis of Published Physical Property Data and Collation into Detailed Models of Alkaline Electrolysis

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Summary. We have critically analysed published data for a range of KOH properties and then collated the results into detailed excel models that predict crossover, purity, and the water vapour content of the gases produced in alkaline electrolysis as a function of temperature, pressure, KOH molarity, current density, and separator porosity and thickness.

Abstract. Physical properties of KOH are crucial to the design and operation of alkaline electrolysers but have been scarcely and sometimes unreliably reported. Obtaining published data for various properties presently requires time-consuming searches and subsequent interpretation, interpolation, and extrapolation. To simplify this situation, we have collected and critically analysed all the published data for a range of physical properties relevant to alkaline electrolysis, including the density, viscosity, conductivity, surface tension, O_2 / H_2 solubility, O_2 / H_2 diffusivity, and water vapour pressures of aqueous KOH solutions, as a function of temperature, KOH molarity, and pressure.

Our correlation functions, which are available in the form of excel spreadsheets, allow interpolation of the most reliable data and ready computation of desired quantities at specific temperatures, pressures, and KOH concentrations.

In addition, composite models incorporating these properties have been developed to provide automated computation of diffusive gas crossover and gas production volumes, including water vapour content, and associated dissolved gas concentrations in the liquid electrolyte, as a function of KOH concentration, temperature, pressure, current density, and separator thickness and porosity.

These spreadsheet models are provided as a tool and reference point for researchers and practitioners.

Investigation of the stability of air electrode in solid oxide electrolysis cells (SOEC) operated under high concentration of steam

Mr Michal Wierzbicki[1,2,3], Mr Stanisław Jagielski[1,2,3], Yevgeniy Naumovich[1,2], Anna Niemczyk[1,2], Magdalena Kosiorek[1,2,3], Agnieszka Żurawska[1,2], Kupecki Jakub[1,2,4]

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Solid Oxide Electrolysis 1, Metals Hall, June 21, 2022, 8:00 AM - 10:00 AM

Investigation of the stability of air electrode in solid oxide electrolysis cells (SOEC) operated under high concentration of steam

Michał Wierzbicki[a,b,c], Stanisław Jagielski[a,b,c], Yevgeniy Naumovich[a,b], Anna Niemczyk[a,b], Magdalena Kosiorek[a,b,c] ,
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Summary. Stability of the LSCF oxygen electrode operated with a steam as a sweep gas (for easy oxygen recovery) has been investigated in terms of long-term performance and microstructural evolution.

Abstract.

The rapid growth of penetration of renewable energy sources (RES) fallowed by continuously reduced costs of renewable energy during lastyears created the opportunity for significant progress in the development of so-called green hydrogen technologies. Rising number of newly installed RES capacity creates a demand for flexibility of the energy system and establishing sufficient energy storage capacities. That is why hydrogen is seen as a future energy carrier and is often described as a solution to the issues and problems related to the depletion of fossil fuels as well to concerns of the global warming. Green hydrogen can thus complement and take out some limitations of RES in the ongoing revolution in renewable electricity. Especially among many technologies for green hydrogen production, water electrolysis is considered as one of the most promising and with high potential for seamless integration in power and energy storage system. Electrolysers are complex electrochemical devices made of three basic functional layers – two electrodes separated by an electrolyte. In this electrochemical devices the water molecule is consumed and split into hydrogen and oxygen which are released on cathode and anode respectively. There are many electrolysers technologies but the high temperature solid oxide electrolysers (SOE) stand out as most efficient and with highest potential for thermal integration in industry processes.

In the conventional approach, operation of solid oxide electrolyser requires continuous feeding of steam to the cathodic compartments and air to the anodic side. However, the flow of O_2/N_2 mixture can be replaced also by the steam. Introduction of steam as a sweep gas in the anode offers the possibility for easy separation of oxygen (steam

condensation) and production of pure oxygen together with hydrogen. In this case, the by-product of the electrolysis process oxygen, that usually is discarded, could constitute additional value for the high temperature electrolysis. Such an approach might foster the integration of high temperature electrolysers with conventional power systems, enabling efficient transition to oxy-combustion.

The feasibility of this concept was experimentally verified and the behaviour of anode material, which usually is not subjected to the high steam content, was investigated. Complete comprehensive experimental analysis using advanced electrochemical methods to determine degradation rate and stability of the LSCF oxygen electrode in this conditions has been performed. The 50 mm x 50 mm cathode supported SOEC has been investigated in series of 1000 h long tests in order to determine the possible degradation phenomena. The cell voltage evolution has been measured and electrochemical impedance spectroscopy (EIS) has been performed during long-term testing. This allowed to investigate the changes of polarization (R_p) and ohmic (R_Ω) resistances during operation. The work was supported with microstructural analysis by means of SEM/EDS and XRD, which concluded the segregation of Sr at the GDC/LSCF interface that could be the reason of increase of the cell resistance.

Authors would like to acknowledge the National Science Centre of the Republic of Poland for financing this research under grant agreement UMO-2018/31/N/ST8/02491 and UMO-2021/42/E/ST8/00401.

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Design of Catalyst Layers for Fuel Cell and Electrolyzer Application

Dr Alexey Serov[1]
[1]*Oak Ridge National Laboratory, ,*

Polymer Electrolyte Membrane Electrolysis 2, Metals Hall, June 21, 2022, 10:30 AM - 12:15 PM

Design of Catalyst Layers for Fuel Cell and Electrolyzer Application

Alexey Serov[1*], Xiang Liu[1], Erin B. Creel[1], Haoran Yu[1], David A. Cullen[1], Nancy N. Kariuki[2], Jae Hyung Park[2], Deborah J. Myers[2], Timothy Van Cleve[3], KC Neyerlin[2], Jayson Foster[4], Svitlana Pylypenko[4], Kristianto Tjiptowidjojo[5], J. Alex Lee[6], Kelsey M. Livingston[1], P. Randall Schunk[5],[7] Nelson S. Bell[7], David L. Wood, III[1]

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Summary. Catalysts layers for fuel cell and electrolyzer applications were designed by controllable ink preparation followed by scalable coating methods. The presentation discussed on the different aspects of inks properties, their affect on the coating quality and final performance in Membrane Electrode Assembly evaluation.

Abstract. The methods of incorporation of different catalysts into the inks will be discussed. The focus will be given to Pt/C and unsupported IrO_x catalysts in the application to Proton Exchange Membrane (PEM) fuel cell (FC) and water electrolysis (WE) applications. Application of scalable methods of electrodes preparation such as Dr. Blade, Mayer Rod and other will be presented. An application of different mathematical models for estimation of the coating window for pilot scale usage of Roll-2-Roll coating will be correlated with experimental data.

The case studies based on a) single layers of Pt/C as a cathode for PEMFC b) single layer IrO_x as an anode for PEMWE and c) dual layers of Pt/C as cathodes for PEMFC will be presented and discussed.

Acknowledgements and Statements.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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Optimal design of a Pt recombination interlayer for the safe hydrogen production with PEM water electrolysers

Mrs. Agate Martin[1], Mrs. Dunia Abbas[2], Dr. Patrick Trinke[1], Dr. Thomas Böhm[2], Dr. Boris Bensmann[1], Prof. Dr. Simon Thiele[2], Prof. Dr. Richard Hanke-Rauschenbach[1]

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Polymer Electrolyte Membrane Electrolysis 4, Metals Hall, June 23, 2022, 8:00 AM - 10:00 AM

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Fabrication, Performance, and Durability of Roll-to-Roll Coated Iridium-Based Anodes

DR. Scott Mauger[1], Dr. Sanghun Lee[1], Dr. Elliot Padgett, Dr. Sunilkumar Khandavalli[1], Dr. Shaun Alia[1], Dr. Tobias Schuler[1], Genevieve Stelmacovich[2], Dr. Svitlana Pylypenko[2], Michael Ulsh[1]

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Polymer Electrolyte Membrane Electrolysis 3, Metals Hall, June 22, 2022, 8:00 AM - 10:00 AM

Fabrication, Performance, and Durability of Roll-to-Roll Coated Iridium-Based Anodes

Scott Mauger[a], Sanghun Lee[a], Elliot Padgett[a], Sunilkumar Khandavalli[a], Shaun Alia[a], Tobias Schuler[a], Genevieve Stelmacovich[b], Svitlana Pylypenko[b], Michael Ulsh[a]

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Summary. Slot-die and gravure coating were used to produce roll-to-roll coated IrOx anodes and explore the impacts of catalyst ink formulation and coating method on attainable loadings. Electrochemical testing of membrane electrode assemblies showed that at 0.4 mg_{Ir}/cm^2 roll-to-roll coated anodes performed the same as spray coated anodes.

Abstract. To reduce hydrogen production costs for low temperature water electrolysers to meet the Hydrogen Shot goal of $1/kg manufacturing methods need to be translated from batch to continuous processes. For production of IrO_2 anode layers, roll-to-roll (R2R) methods are well suited due to their potential for high throughput and uniformity. There are a variety of coating methods for R2R, each with their own operating limitations such as coating fluid viscosity and liquid film thickness. For any coating method there will be a region of operating conditions, known as the coating window, where stable coatings can be obtained. Related to this is the ink formulation and its solids (catalyst and ionomer) concentration which influences its viscosity and determines the required liquid film thickness to achieve a specified target loading. Increasing solids concentration is desirable to reduce solvent content enabling reduced dryer loads and/or increased line speeds. However, this reduces the liquid film thickness, potentially to values outside the coating window.

To better understand the relationship between coating method and formulation we conducted a study exploring the range of Ir loadings attainable with different formulations and coating methods. Catalyst inks were formulated with 10, 20, and 30 wt% IrO_2 with a fixed I:Cat ratio of 0.2. Slot die and gravure coating were used to coat the catalyst layers onto a decal substrate at a variety of loadings ranging from 0.06 mg_{Ir}/cm^2 to 0.65 mg_{Ir}/cm^2. Slot coating produced uniform coatings with 20 and 30 wt% IrO_2 inks but the low viscosity of the 10 wt% IrO_2 ink resulted in poor control of coating width and uniformity. In contrast gravure coating was able to produce uniform coatings with all formulations due to it being better suited for low viscosity fluids. For coatings within the coating window the catalyst layers had high uniformity with loading variations below 10%. However, optical and scanning electron microscopy revealed microscale heterogeneity of the catalyst layers with low loaded catalyst layers (< 0.2 mg_{Ir}/cm^2) appearing to have voids in the coating.

MEAs were fabricated from these R2R-coated catalyst layers for comparison to spray-coated catalyst layers. These MEAs were tested for both performance and durability. R2R-catalyst layers with 0.4 mg_{Ir}/cm^2 had identical initial performance compared to spray-coated catalyst layers. In contrast, R2R-coated CLs with 0.2 mg_{Ir}/cm^2 performed

significantly worse than spray-coated catalyst layers, likely due to the heterogeneities. These results illuminate the challenges in moving towards very low catalyst loadings. Results will also be presented on efforts to improve the homogeneity catalyst layers at 0.2 mg_{Ir}/cm^2 through changes in ink formulation and processing.

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Influence of the gas diffusion layer on the performance of a PEM water electrolyzer

Mr. Niklas van Treel[1], Mr. Edgar Cruz Ortiz[1,2], Dr. Severin Vierrath[1,2], Dr. Melanie Bühler[1,2]

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Influence of the gas diffusion layer on the performance of a PEM water electrolyzer

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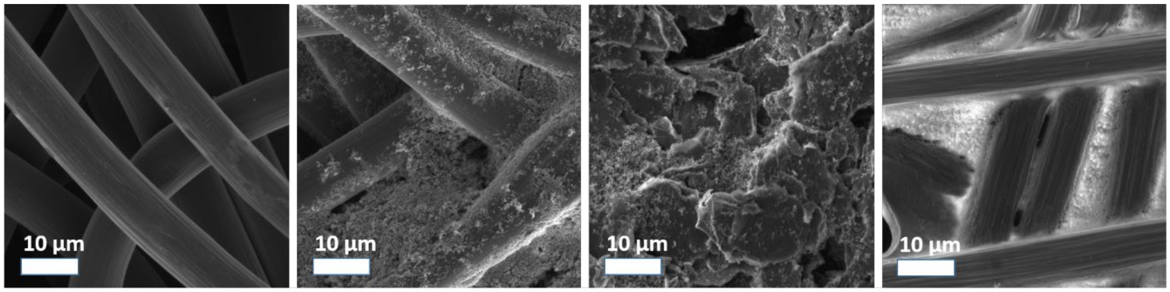
Summary. The influence of different gas diffusion layers (GDLs) on the performance of proton exchange membrane water electrolyzer (PEMWE) single cells is analysed. Differences in the recorded polarization data is correlated to the morphology and composition of the GDLs. Based on the drawn conclusions, an ideal GDL for the cathode hydrogen evolution side in PEMWE cells is suggested.

Abstract. At the cathode side of a PEMWE, produced hydrogen has to be transported via the GDL towards the outlet and – in case of water circulation at the cathode – a counter flow of water towards the catalyst layer has to be established. The bulk material influences the mass transport of hydrogen and water in the pores of the GDL. The surface of the GDL affects the electrical interfacial resistance to the cathode catalyst layer. Understanding the impact on cell performance of the GDL morphology and hydrophobicity is therefore essential to optimize the overall performance of a PEMWE. In this study, a PEMWE single cell setup with several commercial GDLs is characterized electrochemically. A loss-break-down analysis of the polarization data is correlated to structural differences imaged by SEM (Figure 1) along with contact angle measurements to study the wettability of the GDLs.



Freudenberg E15 Freudenberg E15H Freudenberg H24C5 Toray TP-120T

Figure 13: Top view SEM images of common commercial GDLs used in PEMWE. The materials show similar fiber diameters but a different porosity and surface roughness due to hydrophobic treatments or an additional microporous layer on top of the fibers.

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Solving the Mystery of Ohmic Resistance in Zero-gap Alkaline Water Electrolyzers

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Alkaline Electrolysis 1, Metals Hall, June 20, 2022, 3:40 PM - 5:30 PM

Solving the mystery of ohmic resistance in zero-gap alkaline water electrolyzers

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Summary. Existing alkaline water electrolyzers have a relatively high internal ohmic resistance compared to other technologies. The resistance is significantly higher than the ex-situ measured resistance of the diaphragm. Visualization of the diaphragm suggests that bubbles sticking to the diaphragm and inside the diaphragm could be responsible.

Abstract. Alkaline water electrolyzers are traditionally operated at low current densities due to a high internal ohmic resistance compared to other technologies. Even with a zero-gap configuration the ohmic resistance remains significantly higher than what one would expect based on the properties of the Zirfon diaphragm [1].

In this study we use Electrochemical Impedance Spectroscopy (EIS) in combination with polarization measurements (I-V curves) to further investigate the higher ohmic resistance for a zero-gap configuration [2]. Impedance data were fitted with an equivalent electric circuit, while the polarization measurements were fitted [1] as shown in Figure 1. It was found that the ohmic resistance determined with EIS (~0.48 Ω.cm²) is lower than the fitted area resistance from the polarization curve (~0.64 Ω.cm²), which seems to be related to a higher-than-expected charge transfer resistance at high current densities. Nevertheless, even the EIS resistance is still much higher than what would be expected for Zirfon UTP500 (~0.3 Ω.cm²) [2]. Visualization of the diaphragm during and after electrolysis shows that bubbles stick to the diaphragm and even originate from the diaphragm. Bubble formation inside the diaphragm might occur as a result of local supersaturation in combination with large pore sizes. Gas outside *and* inside the diaphragm is therefore expected to be a significant contributor to the increased ohmic resistance.

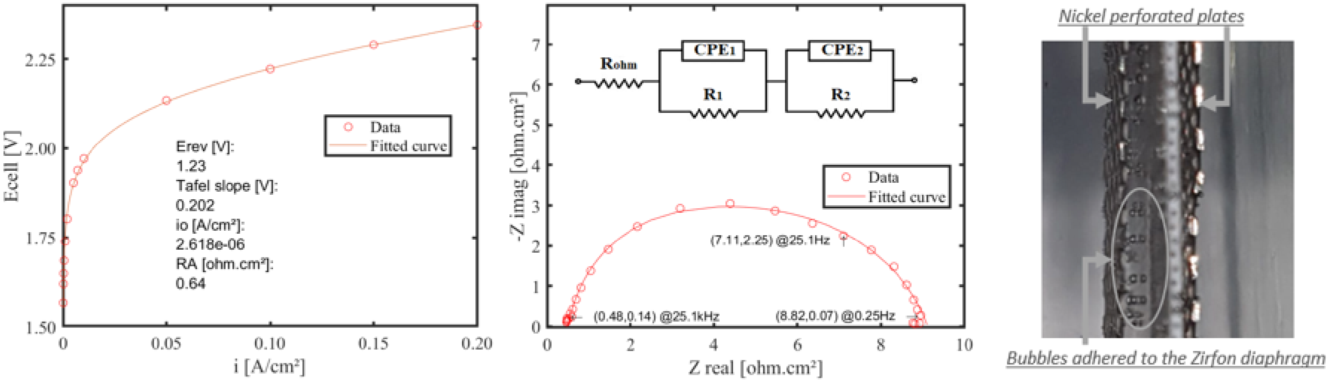

Figure 1: polarization curve (left) and Nyquist plot at 0.010 A/cm² (center) for a zero-gap cell with nickel perforated electrodes and Zirfon UTP500. Conditions: 28 wt% KOH at 0.3 L/min, 1 atm and 20 °C. Right: side view of a finite gap electrode-diaphragm assembly showing bubbles in the Zirfon diaphragm surface after electrolysis in an open beaker using KOH 28 wt% at 20 °C.

[1] M.T. de Groot, A.W. Vreman. **Ohmic resistance in zero gap alkaline electrolysis with a Zirfon diaphragm.** Electrochimica Acta, 2021, 369, 137684. https://doi.org/10.1016/j.electacta.2020.137684

[2] Rodríguez, J.; Palmas, S.; Sánchez-Molina, M.; Amores, E.; Mais, L.; Campana, R. **Simple and Precise Approach for Determination of Ohmic Contribution of Diaphragms in Alkaline Water Electrolysis.** Membranes, 2019, 9, 129. https://doi.org/10.3390/membranes9100129

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Effect of compression on the membrane electrode assembly of polymer electrolyte electrolyzers

MR. Edgar Cruz Ortiz[1,2], Dr. Melanie Bühler[1,2], Dr. Matthias Breitwieser[1,2], Dr. Severin Vierrath[1,2,3]

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Effect of compression on the membrane electrode assembly of polymer electrolyte electrolyzers

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Summary. The membrane deformation with increasing compression was quantified by segmenting cross-sections for the land and the channel region of the flow-field. The former presented clear trend of increased deformation as the assembly pressure was increased.

Abstract. Reliable operation of polymer electrolyte membrane electrolyzers requires a sound understanding of the effects surrounding the cell assembly, including flow-field architecture, operation conditions and membrane electrode assembly (MEA) compression. With membranes becoming thinner, too high compression easily leads to shunt currents, while too low compression can have a strong impact on cell performance. In this work, we analysed the effect of increasing MEA compression on membrane deformation in two regions; under the flow-field land and channel, as well as the changes to cell performance. To this end, a series of identical MEAs with 20% - 60% compression of the cathodic gas diffusion layer (H24C5 Freudenberg) was measured corresponding to 1.2-3.7 MPa and cryogenic cross-sections of each were imaged via SEM. The resulting polarization curves in Figure 1(a) show that compressions of 30 % and 40 % result in the lowest cell voltages. However, the membrane deformation increases along with the MEA compression, as seen in the membrane thickness standard deviation in Figure 1(b). This effect is considerably more pronounced for the land regions of the flow-field, which results in a higher local pressure and increased deformations caused by the porous transport layer.

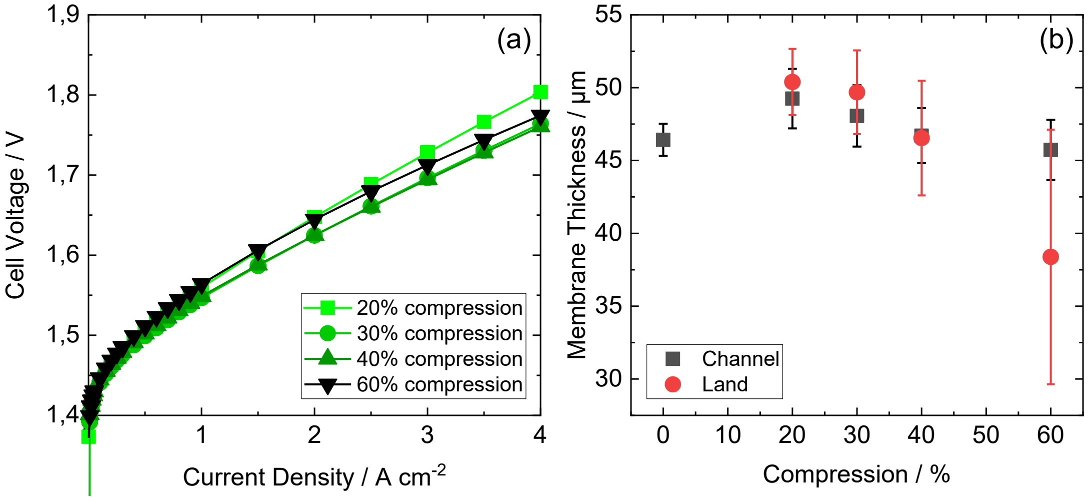

Figure 14 Polarization curves measured at different compression levels of the cathodic GDL, which results in a lower cell voltage for 30 % and 40 % compressions (a). Similarly, increased compression causes an increase in membrane deformation, particularly for areas below the land area of the flow field (b).

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The impact of the supporting electrolyte on alternative materials performance for anion exchange membrane electrolysis

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Alkaline Electrolysis 2, Metals Hall, June 21, 2022, 1:30 PM - 3:20 PM

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Solid Oxide Electrolysis Cell Performance & Durability – Past, Present and Future

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Plenary Session 2, Metals Hall, June 20, 2022, 10:15 AM - 12:15 PM

Solid Oxide Electrolysis Cell Performance & Durability – Past, Present and Future

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Summary. Solid Oxide Electrolysis cells (SOEC) have experienced a tremendous increase in initial performance and long-term durability which will be discussed this presentation followed by a view on the most critical degradation issues for state-of-the-art SOEC and a glance at our R&D focus for cells & stacks - here at the doorway to commercialization of SOECs at Topsøe.

Abstract. Figure 1 illustrates the different scales for SOEC from electrode micro-structures to commercial MW-scaled plants and these will be addressed in this review focusing on the past improvements of SOEC single cells over the last couple decades towards, present challenges and the future large-scale commercialization of the SOEC technology.

Firstly, the initial electrochemical performance of single cell SOEC has improved more than a factor of 2.5 over the last ~15 years and, in parallel, the long-term durability has increased, i.e. rate of degradation decreased, approximately an order of 100 [1]. Among other improvements, the increased SOEC performance relates to the shift in electro-catalytic material from the composite LSM/YSZ oxygen electrode to higher performing MIEC based electrode materials like LSCF and LSC; while significant performance increase for the Ni/YSZ based fuel electrode has been achieved through skilled manufacturing improvements leading to optimized fuel electrode structure. Furthermore, SOEC manufactures have over the last few years been able to increase the cell foot print from typically ~100 cm^2 to ~300-500 cm^2, enabling production of kW-scaled stacks and systems to produce e.g. 200 Nm^3/h H_2 (https://www.green-industrial-hydrogen.com/).

Secondly; considering the significant performance and durability improvements for the SOEC single cells – now what are the critical issues remaining to be addressed? In this presentation, we will touch upon following challenges: 1) The degradation caused by migration of nickel away from the active fuel electrode layer and how to hinder it [2], 2) Effect of impurities and how to tackle it [3], and 3) considerations regarding critical raw materials and consequences for future generation of SOEC.

Thirdly and last, this presentation will discuss the path to commercialization of SOECs with a focus on stack technology from Topsoe, including discussion on relevant end-of-life criteria, performance/degradation characteristics in terms of H_2 production rate and H_2 production capacity (total H_2 production over stack lifetime) and their relation to choice by optimization of operation strategy and operating conditions such as current density, inlet gas composition, temperature, and degree of steam conversion rate etc.

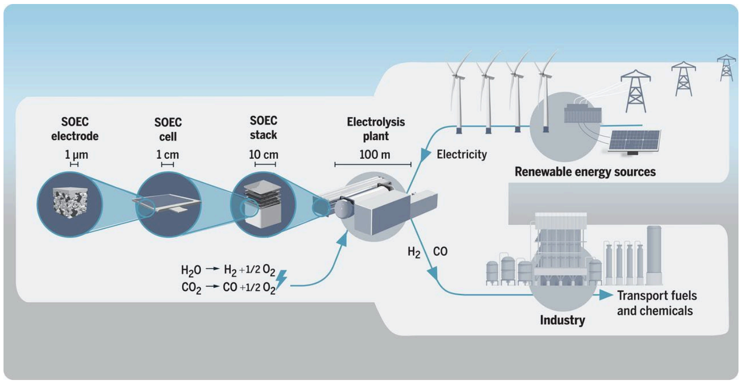

Figure 1: SOEC from µm-scaled electrodes to compact stacks bringing this technology to commercial MW-scaled plants [1].

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Simulative and experimental investigations of transient operating behaviour of SOEC reactors with multiple stacks for syngas production

Mr. Daniele Fortunati[1], Mr. Marius Tomberg[1], Ms. Diana-María Amaya-Dueñas[1], Dr. Marc P. Heddrich[1], Dr. Asif S. Ansar[1]

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Solid Oxide Electrolysis 3, Metals Hall, June 23, 2022, 10:30 AM - 11:50 AM

Simulative and experimental investigations of transient operating behaviour of SOEC reactors with multiple stacks for syngas production

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Summary.

Due to the high operating temperatures of SOCs (Solid Oxide Cell), complex test rig set-ups and SOC's high thermal masses, the experimental investigation of SOC reactors with multiple stacks is challenging. This study proposes a methodology to find optimal operating conditions of an SOC reactor with the use of a transient computational model, for syngas (H_2+CO) production.

Abstract.

Despite the increment in greenhouse gas emissions and global warming, current global energy demands are still relying on the usage of fossil fuels. Adopting hydrogen and syngas as a form of energy carrier can be leveraged as a major step towards defossilization of modern society, regardless of an increase in the current energy demands [1]. Electrochemical production of molecules using green electricity and co-electrolysis of steam and carbon dioxide could become a relevant path to obtain syngas, which is a key feedstock for several applications [2]. High temperature SOC systems can produce these gases with highest process efficiency. In order to play a significant role in the future energy system, green syngas production must be scaled into the multi MW range.

At the German Aerospace Center (DLR) a test environment for SOC reactors with multiple stack was built, for an electrolysis power of up to 150 kW. Additionally, an in-house simulation framework that allows to replicate the physical behavior of a SOC reactor was developed [3]. One of the challenges of co-electrolysis operation is to find optimal operating conditions at high reactant conversion. Such investigations require cost-intensive test rig set-ups and are time-consuming. In addition, commercially available reactors are not suitable for research, since the number of sensors installed is not sufficient to analyze operating conditions. In order to study and predict different operating conditions in a time efficient manner, the simulation framework can be utilized.

In this contribution, it is shown how a model of a SOC reactor with 24 stacks can be used to support the experimental investigation on that reactor. By using the simulation's thermoneutral and isothermal operating points, various syngas ratios are predicted. These are in turn used as inputs for the experimental investigation. Results from both simulation and experimental co-electrolysis operation are shown in detail, with a syngas ratio in the range of 2–4. During the experiment, the stack temperatures had a maximum offset of 5 K compared to the predicted values via the simulation, for the same operating conditions. This approach has led to a more efficient experimental investigation process, as well as to a significant amount of experimental time saved per each operating point. Analyses of operating behaviors and

strategies will be presented to showcase how the synergy between the simulation framework and experimental test protocols significantly contributes to the upscaling of SOC reactors.

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Three-dimensional analysis of morphological changes in anodic PEWE catalyst layers by X-ray ptychographic laminography

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Polymer Electrolyte Membrane Electrolysis 1, Metals Hall, June 20, 2022, 1:30 PM - 3:10 PM

Three-dimensional analysis of morphological changes in anodic PEWE catalyst layers by X-ray ptychographic laminography

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Summary

X-ray ptychographic laminography was used to characterize the morphological changes in PEWE catalyst layers that are induced by swelling of the ionomer when it is contacted with liquid water. From the acquired 3D data, we observed that the percolation network of the IrO_2 phase in the CL is affected significantly leading to detrimental losses in electrical conductivity.

Abstract

Minimizing the precious metal loading in the catalyst layers of polymer electrolyte water electrolyzers (PEWE) is essential for facilitating its commercial breakthrough. One of the main challenges lies in ensuring good electrical conductivity in the anodic catalyst layer (CL), particularly when poorly conductive catalyst support materials are used. Recently, it was shown that the electrical in-plane conductivities in the CL are strongly reduced when in contact with liquid water, which was hypothesized to be caused by ionomer swelling, leading to disruptions in the percolation network of the IrO_2 phase.[1] Here, we report a three-dimensional characterization of a typical sprayed anodic CL with commercial IrO_2 catalyst supported on TiO_2 (loading of 3 mg_{Ir}/cm^2) and three different ionomer loadings of 3, 11, and 18 wt%.[2] We performed an ex-situ hydration experiment on the sample series with the aim of characterizing the morphological changes in the structure caused by the swelling of the ionomer. The samples were scanned in the dry (as prepared) and in the fully wetted state (i.e. after immersion in liquid deionized water). We collected high-resolution 3D imaging data using X-ray ptychographic laminography, recently developed at the cSAXS beamline of the Swiss light source (SLS). The laminographic approach allows scanning of planar macroscopic samples (such as a CL) that are much larger than the field of view, which facilitates the possibility of handling samples and designing ex-situ or in-situ experiments.[3] The high data quality allowed us to separate and reconstruct both solid phases (IrO_2 and TiO_2) from the void/ionomer phase. We have estimated the bulk and transport characteristics of the different samples allowing us to compare the dry *vs* wet state of each phase. The results show that in the dry state, the IrO_2 phase exhibits good overall connectivity while in the wet state it is significantly reduced, resulting in a significant reduction of the computed in-plane and through-plane electrical conductivities. Furthermore, we observe a quantifiable increase in the average pore/ionomer phase fraction in the wet state, which reflects the swelling of the ionomer. This work sheds light on the morphology of CLs in conditions that are more representative of operating PEWE, guiding the understanding of the losses in CL utilization as well as paving the way for future *in-situ* or *operando* high-resolution 3D imaging in electrochemical applications.

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3 M. Holler, M. Odstrcil, M. Guizar-Sicairos, M. Lebugle, E. Müller, S. Finizio, G. Tinti, C. David, J. Zusman, W. Unglaub, O. Bunk, J. Raabe, A. F. J. Levi and G. Aeppli, *Nat. Electron.*, 2019, **2**, 464–470.

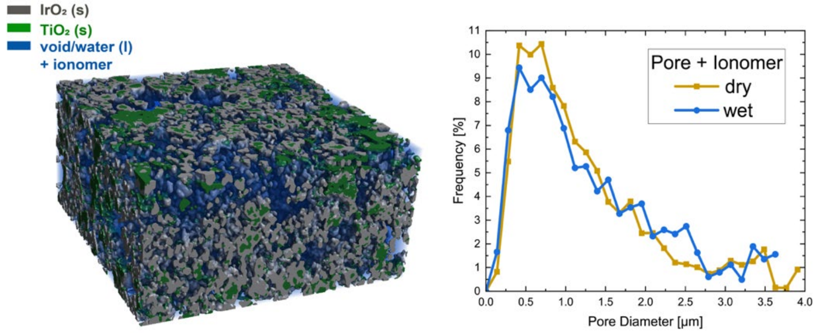

Figure 15. XTM surface rendering of the prepared CL with 11 wt% ionomer and respective pore size distribution in the dry vs wet state.

The role of surface area and stability-aspects of nickel-molybdenum HER electrocatalysts for the Alkaline Water Electrolysis

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

The role of surface area and stability-aspects of nickel-molybdenum HER electrocatalysts for the Alkaline Water Electrolysis

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Summary. Hydrogen by alkaline water electrolysis is gaining increasing interest due to favourable scalability [1]. In order to compete with the production rates of competing technologies, improving the electrocatalyst-activity is a commonly aspired approach. For this matter, the role of the surface area and electrocatalyst-stability aspects need to be addressed.

Abstract. In contrast to other technologies, a variety of non-noble electrocatalysts are suited for the alkaline water electrolysis. Among the electrocatalysts for the hydrogen evolution reaction (HER), nickel-molybdenum electrocatalysts are often reported to deliver high activities [2]. However, it is disputed whether the high activity of nickel-molybdenum electrocatalysts stems from intrinsic properties or from high surface areas. Moreover, the stability of these alloys remains uncertain [3,4].

The role of the surface area of nickel-molybdenum and nickel electrocatalysts is often disregarded. Furthermore, an agreement on the procedure to evaluate the electrochemical active surface area (ECSA) is not existent. Commonly applied methods to evaluate the ECSA include measurements of the double layer capacitance, either through non-faradaic cyclic voltammetry [1] or electrochemical impedance spectroscopy [5,6], or through the formation of α-nickelhydroxide for nickel electrocatalysts [6]. A comprehensive study on the correlation between different approaches to assess the ECSA, as well as the relation between the ECSA and the activity of nickel-molybdenum HER electrocatalysts is missing yet needed.

We investigated the outcome of the different procedures to evaluate the ECSA. The different methods correlate well if EIS is conducted at HER overpotentials (η_{HER}) greater than 200 mV. For $\eta_{HER} < 200$ mV, the results from EIS were influenced by a pseudocapacitive effect and thereby overestimated the ECSA. Lead by this observation, we present a relation between the overpotential at 10 mA/cm^2 and the ECSA for a variety of nickel and nickel-molybdenum electrocatalysts. We further included nickel and nickel-molybdenum electrocatalysts reported in the literature, which applied comparable procedures to evaluate the ECSA. We find that the overpotential generally decreases in a semi-logarithmic trend, indicating that the intrinsic activity of nickel and nickel-molybdenum HER electrocatalysts are not significantly different when compared to platinum. Nonetheless, the overpotential-ECSA relation of nickel-molybdenum electrocatalysts does not refute the theory about a higher intrinsic activity over nickel electrocatalysts. In addition and in order to address stability concerns, we investigated the stability of nickel-molybdenum during intermittent operation *in situ* by means of spectroelectrochemical Raman, using an in-house developed setup.

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Understanding The Effects of Different ECS Supports on the Sintering Processes of Pt Nanoparticles

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Understanding the Effects of Different ECS Supports on the Sintering Processes of Platinum Nanoparticles

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Summary. The main goal of this study is to understand the effects and the properties of Engineered Carbon Supports (ECS)™ having different degrees of porosity, on the stability of the Platinum nanoparticles (Pt NPs), and how different environments and temperatures affect the sintering processes taking place on the Pt NPs.

Abstract. The high emissions of pollutants that are mainly produced from fossil fuel-based energy generator has triggered not only a climate and an environmental existential crisis but also a growing demand for clean and efficient energy sources. Polymer Electrolyte Membrane Fuel Cell (PEMFC) technology is an advantageous solution for clean energy applications due to its zero-emission, high efficiency, low maintenance cost, and high energy density. The maturity of this technology has been the product of considerable scientific and industry efforts devoted to developing highly efficient and reliable systems increasingly adopted in the transportation and energy generation sectors. PEMFCs produce electricity by converting the electrochemical reactions of hydrogen oxidation and oxygen reduction into electrical energy. However, fabricating catalysts materials with high performance at scale is still a challenge that needs to be tackled to enable a marketable increase in the energy generated from this technology. For this reason, tunability of the catalyst materials at the core of this technology is more than essential to meet certain energy demands. Here, we investigate commercially available catalysts based on platinum nanoparticles (Pt NPs) supported on ECS™ produced by Pajarito Powder, LLC.

Heat treatments (HT) were performed on base catalyst materials containing 30 wt% Pt supported on two different types of ECS, labelled as 3701 and 4601 (both made with similar materials and fabrication procedures, 4601 has more pore formers). The treatments were performed at temperatures ranging from 400 to 1000 °C in 7% H_2/N_2, N_2, and Ar atmospheres for 1hr. Our preliminary results by X-ray diffraction (XRD) have shown an increase of the Pt crystallite size as temperature increases and 1000 °C in an atmosphere of 7% H_2/N_2 appears to have a stronger effect on Pt crystallite growth when compared to N_2 or Ar, while such growth seems to have the same trend in both N_2 and Ar atmosphere. Additionally, CO chemisorption showed a reduction of the active metallic surface area with increasing temperature, verifying the trend measured by XRD. For every treated sample, Raman characterization did not show a dramatic change in the ratios between the G-mode peak (representing crystalline sp^2 hybridized carbon), and the D-mode peak (attributed to disordered sp^3 amorphous-like carbon). This can shed a light on the amorphization or graphitization processes taking place under these conditions and the degree of graphitization of the carbon support. Transmission Electron Microscopy (TEM) will be performed to further clarify any structure related conclusion. X-ray Photoelectron Spectroscopy (XPS) surface characterization revealed that there is a reduction in the Pt NPs oxidation from 600 to 1000 °C. Treatments in N_2, the O 1s spectra were different than the other conditions possibly due to the lower presence of atmospheric oxygen

during this treatment. On the other hand, the C 1s spectra show a minor shift to higher binding energy in the main peak as a result of the treatments, indicating a slight increment in the amount of sp^3 and a decrease in the amount of sp^2 carbon nature. Additionally, this research will be expanded with TEM imaging and physisorption data to get a more quantitative and qualitative interpretation of the phenomena taking place in the mobility and sintering processes of Pt NPs on the ECS surfaces and the role of the porosity and carbon morphology.

Review of morphology and synthesis of Pt-based micro-particles in PEM WE for hydrogen cross-over reduction

Prof Dmitri Bessarabov[1]

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Polymer Electrolyte Membrane Electrolysis 4, Metals Hall, June 23, 2022, 8:00 AM - 10:00 AM

Review of morphology and synthesis of Pt-based micro-particles in PEM WE for hydrogen cross-over reduction

Dmitri Bessarabov[a]

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Summary. Platinum-based catalytic microparticles in the PEM membranes can reduce hydrogen gas cross-over from cathode to anode in water electrolysis cells. Platinum-based microparticles act as hydrogen-oxygen recombination catalyst. Morphology and methods of synthesis will be reviewed in great details in this talk.

Abstract. Of the several factors which influence catalytic activity and morphology of Pt-based microparticles for hydrogen/oxygen recombination in PEM water electrolysis cells, particle size, location in PEM, structural morphology and syntheses methods, are of crucial importance. Pt/PFSA composites are of interest not only for WE or FC applications, but also for other applications such as sensor devices, actuators, electrochemical applications, etc. Various methods of microparticle depositions will be reviewed, including chemical depositions. Various modifications of a chemical reduction route will be also reviewed. These modifications of both PFSA members and a process result in various morphological features of the microparticles. Results on the mathematical modelling of Pt-based catalysts towards hydrogen oxygen recombination will also be presented as well as attributes describing the physical growth of micro- and nanoparticles will be reviewed.

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Tuning the Rheology of Anode Inks with Aging for Low-Temperature Polymer Electrolyte Membrane Water Electrolyzers

Dr. Sunilkumar Khandavalli[1], Dr. Jae-Hyung Park[2], Robin Rice[1], Dr. Guido Bender[1], Dr. Deborah J. Myers[2], Mr. Michael Ulsh[1], Dr. Scott A. Mauger[1]

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Polymer Electrolyte Membrane Electrolysis 3, Metals Hall, June 22, 2022, 8:00 AM - 10:00 AM

Tuning the rheology of anode inks with aging for low-temperature polymer electrolyte membrane water electrolyzers

Sunilkumar Khandavalli,[a] Jae Hyung Park,[b] Robin Rice,[a] Guido Bender,[a] Deborah J. Myers,[b] Michael Ulsh,[a] and Scott A. Mauger[a]

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Summary. We report a dramatic effect of aging on the rheological properties of low-temperature polymer electrolyte membrane water electrolyzers, as well as the effects on ink stability and MEA performance.

Abstract. Low-temperature polymer electrolyte membrane water electrolyzers (PEMWE) are an attractive clean energy technology to produce hydrogen (H2), which is an energy carrier for several applications such as transportation and grid-scale energy storage and distribution (as supported by the US Department of Energy's H2@Scale initiative). The catalyst layers -- composed of catalyst particles and ionomer, which acts as a binder for the catalyst and a proton conducting medium -- are key components of the PEMWE membrane electrode assembly (MEA). The catalyst layers are commonly fabricated by solution-processing an ink, which is a mixture of catalyst and ionomer often dispersed in a water-alcohol solvent mixture. Tuning the rheological properties of the anode inks (typically composed of iridium oxide catalyst, IrOx), particularly increasing their viscosity without significantly increasing the solids loading, to suit various scalable coating methods, is generally a challenge due to relatively low porosity and high density of the IrOx catalysts compared to the carbon-supported cathode catalysts. The typically low viscosities of the anode inks combined with high particle densities often cause stability/settling issues and challenges obtaining unform coatings, leading to inhomogeneous distribution of the catalyst that may have a negative effect on electrode performance. In this presentation we report on a dramatic enhancement in the viscoelasticity of the anode inks with aging, where the ink transitions from a liquid-like to a weak gel-like structure. The steady-shear and oscillatory shear rheology characterizations of the inks as a function of aging/time, the impact of formulation conditions (ionomer-to-catalyst ratio and dispersion media composition) on the viscoelastic enhancement with aging, and possible mechanisms for the observed behavior will be discussed. In addition

to the rheological measurements, X-ray scattering characterization of the ink structure will be presented. The implications of the rheological changes on ink stability and processing will also be discussed. Additionally, the impact of ink age on MEA performance will be presented.

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Sensitivity analysis of the effects of microstructure of the performance of solid oxide electrolyzer operated at elevated pressure

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Sensitivity analysis of the effects of microstructure of the performance of solid oxide electrolyzer operated at elevated pressure

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Summary. Model of solid oxide electrolyzer (SOE) was developed for numerical analysis of off-design operation of SOE at elevated pressure. The study included sensitivity analysis of the performance of SOE with modified electrodes to qualitatively and quantitatively assess the effects of fine tuning of microstructure of SOE to boost performance.

Abstract.

The installed capacity of intermittent energy sources such as wind and solar is growing worldwide. These sources are predictable to a given extent, however annual production is limited to certain value, depending of the location and season. At the same time, due to the insufficient capacities of energy storage systems (ESS) curtailment of renewables is observed. For that reason new technologies for large-scale storage of energy are sought. Electrolyzers and often listed among potential options which can be deployed in centralized and distributed ESS units.

Three generic types of electrolyzers exist in the market: (i) alkaline water electrolysis (AWE), (ii) proton exchange membrane water electrolyzers (PEMWE), and (iii) solid oxide electrolyzers (SOE). While the first type is available at the largest scale as fully-commercial products, the last one offers outstanding performance with the lowest energy demand for production of hydrogen. Solid oxide electrolyzers still remain at the phase of subsidized development, still being subject of numerous R&D activities globally. Early-stage demonstrators are now deployed in various industries which can benefit from high temperature electrolysis which can be thermally integrated with downstream processes as well with external sources of heat either in a form of steam or hot gases. Currently SOE is mostly investigated at the atmospheric conditions, with limited number of reports on the pressurized operation. Elevating the pressure adds to the performance of solid oxide electrolyzer and can potentially reduce the energy demand for pressurizing generated hydrogen and oxygen. This makes it possible to increase the system-level performance of electrolysis systems. At the same time, pressurized electrolyzer can be coupled with downstream processes such as Sabatier or Fischer-Tropsch reactor which operate above the atmospheric conditions.

In the study, the assessment of the performance of SOE operated at the pressure of up to 8 bar(g) is presented. The numerical model with was built for the study includes the parameters of microstructure of interlayers of SOE. This made it possible to assess the performance gain when hydrogen and oxygen are produced in electrolyzer operated both in the design point and in off-design. Reference cells fabricated in house in the Institute of Power Engineering were used in the study. Their material and geometrical properties were included in the model which was later used for predictive modelling of the performance. Current-voltage (j-V) curves were compared in order to determine the effect of microstructural modification of the electrode on the energy consumption for generation of hydrogen in a pressurized solid oxide electrolyzer.

Authors would like to acknowledge the National Science Centre of the Republic of Poland for financing this research under grant agreement UMO-2021/42/E/ST8/00401.

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Parametric impedance spectroscopy study on nickel based alkaline electrolysis cells

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Parametric impedance spectroscopy study on nickel based alkaline electrolysis cells

Mikkel R. Kraglund[a], Anna Winiwarter[a,b], Tobias Holt Nørby[b], Peter Blennow[b], Poul Georg Moses[b], Johan Hjelm[a], Jens Oluf Jensen[a]

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Summary. Electrochemical impedance spectroscopy (EIS) has been used to characterize alkaline electrolysis cells, using low and high surface area nickel electrodes. The EIS response was systematically probed as function of temperature and current density, and different equivalent circuit models were investigated for their applicability for the system.

Abstract. The cell voltage from conventional two-electrode alkaline electrolysis cells does not always provide sufficient information to properly characterize a system. For instance, if the anode and cathode activate and deactivate respectively, it will not necessarily show clearly in a simple 2-point voltage measurement as the effects might cancel out. One tool to address this deficiency is electrochemical impedance spectroscopy (EIS), which has been applied previously to great success in other electrochemical systems. Nonetheless, detailed studies on a cell level for alkaline cells are scarce in literature.

We have explored a simple system with both low and high surface area (HSA) nickel electrodes. Plain nickel mesh was used as low surface area electrodes, whereas a HSA nickel coating was applied to nickel foam to represent high surface area electrodes. The EIS response was investigated across parametric variations of temperature (30-80°C) and current density (1-200 mA cm^{-2}). To quantify the results different equivalent circuit models were applied to fit the data.

In most cases, a simple L-R-RQ-RQ-RQ equivalent circuit model fit the data well. Variations in current density show that the two dominant arcs are kinetic of nature. By individually switching electrodes it is shown that, for electrodes with similar surface area, the high frequency kinetic arc can be ascribed to the cathode, whereas the low frequency kinetic arc relate to the anode.

A third arc at frequencies higher than those of the cathode displays an apparent independence on the current density and appears to contribute to the cell voltage with an ohmic-like behaviour. While the contribution can be mathematically handled as an RQ element, direct interpretation of such an element is difficult. To explore this further, a porous electrode framework was adopted, and transmission line equivalent circuit models were explored as a way to fit the EIS data.

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Advanced Materials for Efficient and Durable Water Electrolysers

DR David Hodgson[1], Mr Ben Johnson

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Advanced Materials for Efficient and Durable Water Electrolysers

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Summary. This paper will review existing and developmental materials that TFP Hydrogen offers to the water electrolyser market. The materials span PEM, alkaline and AEM technologies, including the option to repurpose materials at end of life.

Abstract.

TFP Hydrogen is at the forefront of electrochemical materials technology to lower the cost of producing electrolytic hydrogen and to extend the life of electrolysers.

In PEM we have demonstrated the capability of our corrosion-resistant coatings for titanium components at multi-MW scale and over years of operation. These Pt-based coatings have been specifically formulated for use in PEM water electrolysers and can be applied to PTLs, meshes, flow fields, cell separators and bipolar plates. The coatings and deposition methodology have been developed in-house to combine material and process efficiencies to provide a highly cost-effective solution. More recent innovations, that are now ready for commercial trials, have further improved the value proposition.

We have already established the feasibility of re-processing coated components for re-introduction into the supply chain, decreasing

Again in the PEM technology space, our catalysts have been demonstrated over 1000s h to provide low and stable overpotential. With IrO_2 and $IrRuO_2$ options, customer are able to select their preferred material

At an earlier stage of development are our catalysts for AEM technology, developed under the EU Anione programme.

The paper will illustrate the role we play providing materials, with a flexible supply chain, to enable low-cost green hydrogen technologies for now and in the future. An overview of material performance and manufacturing capability will be provided.

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Novel approaches in automatic microscopy and spectroscopy data analysis for fuel cells and electrolyzers

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Novel approaches in automatic microscopy and spectroscopy data analysis for fuel cells and electrolyzers

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Summary. Exclusive implementation of automatic data and image processing approach for the calculation of particle/agglomerate and pore size distribution as well as interfacial contact percentage between catalyst particles and ionomer in fuel cells and electrolyzers.

Abstract. Advanced characterization techniques with their specialized and remarkable capabilities deliver comprehensive micro or nanometric scale information which is essential for uncovering various aspects of microstructural processes for performance evaluation of fuel cells and electrolyzers as for other clean energy technologies. However, the huge dataset offered by the characterization methods entails a difficult, extended, and subjective manual analysis, often resulting in less than statistically acceptable results. Implementation of automated procedures based on digital image and data processing coupled with the latest artificial intelligence-based models can offer a fast, user-independent, and accurate data analysis of large data sets in a fraction of time, resulting in a statistically representative outcome. The current study thereby aims to introduce a set of such unique automatic techniques for quantifying particle/agglomerate and pore sizes as well as interfacial contact percentage between different components in the cathode catalyst layer (CCL) of fuel cells and electrolyzers. The techniques use microscopy and spectroscopy data acquired from transmission electron microscope (TEM), scanning transmission electron microscopy, and energy dispersive spectroscopy (STEM/EDS) which are then processed via a custom-developed python code and open-source ImageJ plugins i.e., Trainable Segmentation and Local Thickness. The results indicate that the introduced automated techniques provide rapid, detailed, and consistent post-analysis of the microscopy and spectroscopy data vital for CCLs prototyping, optimization, and scale-up, as well as for predicting the electrochemical performance of the fuel cells and electrolyzers.

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Model Based Analysis of Proton-Exchange-Membrane (PEM) Water Electrolyzer Parameters' Ageing

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Model Based Analysis of Proton-Exchange-Membrane (PEM) Water Electrolyzer Parameters' Ageing

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Summary. In this contribution, a model-based analysis has been performed to understand the behavior of water electrolysis cells and stacks under stress caused by fluctuating loads. Thereby, significant changes in electrochemical cell parameters were observed. This knowledge allows the development of a reliable electrochemical model that can be used to design, optimize, and control the water splitting reaction in PEM electrolyzers.

Abstract. A model-based approach has been used to improve the measurement plan and to develop an analytic sequence of the electrolyzer states. To get a reliable database, measured operation-data were collected and statistically analyzed. Based on the information gained from the test-stack and recent literature, a stochastic stationary model was deduced. This model was then parameterized by nonlinear regression and probabilistic analyses. Based on information provided by the operation-data, different model approaches with budding complexity were used for the parameter identification. Thereby uncorrelated, significant, and precise estimations were ensured.

1. Model level:
    - Ohmic resistance, charge-transfer resistance, and thermodynamic equilibrium resistance
2. Model level (budding):
    - Charge-transfer resistance, and exchange current density
3. Model level (budding):
    - Further breakdown of ohmic and charge-transfer resistance utilizing the Arrhenius equation

At the end a sensitivity study was performed to inspect the propagation from the parameter results' uncertainty to the voltage output uncertainty of the different model levels.

The evaluation of electrical impedance and galvanostatic (polarisation curve) data led to consistent electrochemical and kinetic parameter estimations and offered a statistical understanding of parameter correlations and model boundaries. The main achievements were:

1. Model discrimination based on measured variables (voltage, current, impedance, temperature, pressure)
2. Comparable states (Begin of Life, End of Life)
3. Parameter changes due to accelerated stress tests (significant compared to parameter uncertainty)

The analytic approach gives insight into parameters that are not recorded by measurement directly. It allows the deduction of parameter variations over time and current and enables refining the measurement and the model used for the analysis.

Thermal management of H2/H2O based reversible solid oxide cell (ReSOC) system for electrical energy storage (EES) applications

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Thermal management of H2/H2O based reversible solid oxide cell (ReSOC) system for electrical energy storage (EES) applications

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Summary. A system analysis of hydrogen production and storage via high temperature solid oxide electrolysis cell is provided. It is shown that H_2/H_2O based electrolysis system performance is improved by employing suitable thermal energy storage measures that can be charged during fuel cell mode. In particular, a steam accumulator is introduced as an appropriate option to raise the system efficiency.

Abstract. Hydrogen storage via solid oxide electrolysis offers numerous advantages over other means of electrical energy storage systems due to its superior thermodynamics and favourable kinetics both of which serve to lower the needed operating cell voltage. Furthermore, solid oxide cells can operate reversibly to generate electricity or fuel depending on the electrical energy demand and pricing. Therefore, power generation and hydrogen production and storage systems can coupled into a single integrated system which can lower the capital expenditures and improve the overall economics of energy production and storage. Depending on the working fluid chemistries, H2/H2O vs. CH4/H2O-CO2, different scenarios in terms of system round-trip efficiency (RTE) and thermal management are expected. H2/H2O systems offer simpler system configurations, but they can suffer from lower RTE due to the highly endothermic nature of electrolysis mode or require external thermal sources to lower parasitic energy requirements. Surplus thermal energy of the cell-stack exhaust in fuel cell mode can be leveraged vis a suitable thermal energy storage system (TES) to then be employed to help alleviate external thermal load requirements in electrolysis mode. A detailed study of incorporating several TES systems with ReSOC is performed through modelling and simulation of state-of-the-art SOEC technology and is presented with the aim of improving the system RTE. The system is designed to operate at 100 kW/800 kWh capacity rating. The effects on the system performance are studied of employing several TES systems including two tank energy storage, high temperature packed bed storage and steam accumulator. Steam accumulator is a pressurized vessel that stores the exhaust thermal load in fuel cell mode as a saturated liquid. The

results indicate that system RTE above 50% and levelized cost of storage of ~30 ¢/kWh are achievable with relatively simple BOP configurations.

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Operando measurement of hydrogen crossover in proton exchange membrane electrolysis cells at differential pressures

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Operando measurement of hydrogen crossover in proton exchange membrane electrolysis cells at differential pressures

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Summary. We will present a measurement technique for quantifying the *operando* H_2 crossover rate of low temperature electrolysis cells, including the effect of differential pressure operation.

Abstract. Low temperature water electrolysis (LTE) using proton exchange membrane electrolysis cells (PEMECs) is a commercially viable approach for producing green H_2 that can use electricity from renewable sources. PEMECs can be operated at high differential pressures, e.g., >30bar on the cathode side, to increase the energy density of the produced H_2 and to reduce the amount of required downstream compression. However, high differential pressure operation can result in undesirable H_2 crossover to the anode (O_2) side. This not only reduces the capturable H_2 efficiency of the cell, but also can result in flammability hazards.

In this talk we will present an *operando* crossover measurement technique that can be applied to PEMECs employing a variety of membrane materials. Figure 1 shows a schematic of the measurement technique. A series of components were added downstream of the anode outlet to remove liquid water and water vapor from the exhaust, and a N_2 blanket was added to mitigate potential flammability hazards. The resulting dry gas is fed into a GC to analyze the H_2:O_2 ratio. Data from multiple membrane materials, temperatures, differential pressures, and current densities will be presented. The results will elucidate the tradeoff between performance and capturable H_2 production that occurs when thinner membranes are used, and how this effect responds to differential pressure operation.

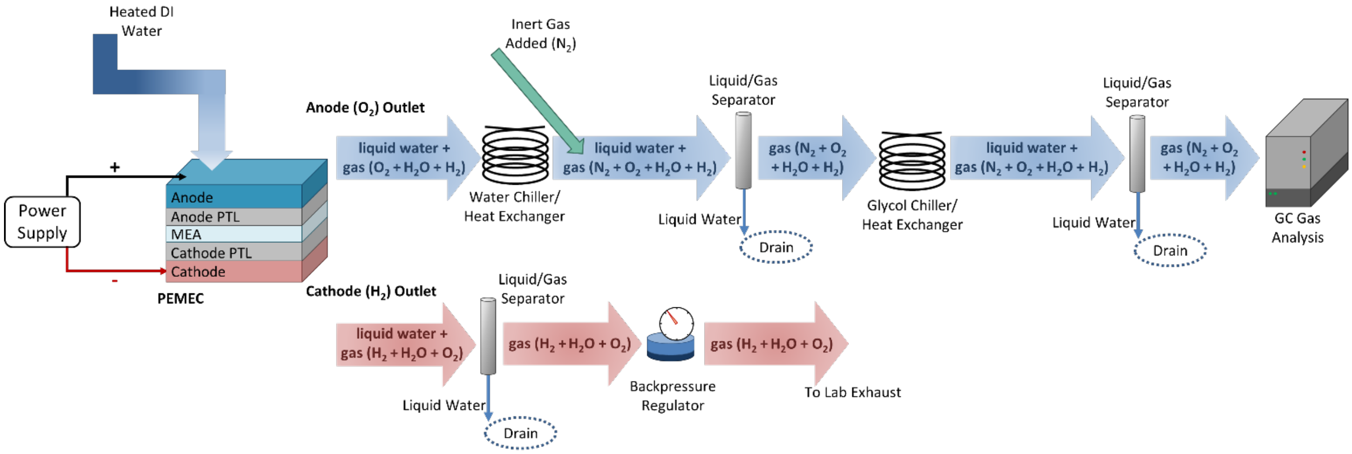

Figure 1 – Schematic of operando crossover testing setup.

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The impact of porous transport layer/anode contact on inhomogeneous degradation of membrane electrode assembly

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The impact of porous transport layer/anode contact on inhomogeneous degradation of membrane electrode assembly

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Summary. The inhomogeneous degradation of PEM water electrolyzer MEAs is examined using STEM-EDS with respect to the contact between the porous transport layer (PTL) and anode catalyst layer.

Abstract. Proton exchange membrane (PEM) water electrolyzers plays an integral role toward zero carbon emission and the hydrogen economy. Successful deployment of PEM water electrolyzers requires long lifetimes and high efficiency of hydrogen production. Thus, research into the degradation of electrolyzer components is crucial to achieve long-term durability. Components for the anode electrode suffer significant degradation due to the high potential for the oxygen evolution reaction (OER) and the strong acidic environment during operation. In this work, we investigate the impact of the PTL/anode contact on inhomogeneous degradation observed in MEA.

The PTL is a multi-functional component in PEM electrolyzers providing electrical conductivity between the anode and the flow field, water transport to the anode, and oxygen transport to the flow field. State-of-the-art PTLs are composed of sintered titanium particles or titanium fiber, which sustain porosity for mass transport. However, such porous structures have non-continuous surfaces which results in inhomogeneous contact with the anode catalyst layer. Observations of MEA cross sections using scanning transmission electron microscopy (STEM) suggest that the catalyst degradation is different between areas of anode which are in direct contact with PTL and other areas lying in the gaps of titanium particles or fibers, especially at lower catalyst loadings. Here, we study the anode catalyst degradation in MEAs using both sintered Ti particles and Ti fiber PTLs, with accelerated stress tests (AST) of either potential hold or cycling. MEA specimens are prepared via ultramicrotome and examined with STEM and X-ray energy-dispersive spectroscopy (EDS). The degradation of Ir-based anodes is investigated in terms of the Ir dissolution from the anode, the chemical composition of metal particles in the membrane, and the crossover of Ir to the cathode. These findings will help elucidate the performance loss mechanism of PEM water electrolyzers during long-term operation.

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Deep integration of solid oxide electrolyzers with steam cycles – towards repurposing conventional power plants

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Deep integration of solid oxide electrolyzers with steam cycles – towards repurposing conventional power plants

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Summary. The development of hydrogen economy stimulates the penetration of renewable energy sources. While electrolysis is under rapid development and the installed capacity doubles every year, numerous potential alternative applications are still under consideration. The primary focus is currently on zero-emission hydrogen, integrating hydrogen production systems with conventional power plant still remains a technically and economically viable option. The work present the preliminary findings of HYDROGIN project which is focused on a highly integrated electrolyzer which can convert fossil fuel-based steam cycle into a hydrogen production plant.

Abstract.

Hydrogen is an increasingly important medium for large energy producers in Poland. The development of this technology is slowly becoming a key element in the strategy of the energy sector in Europe and worldwide. The installed capacity of electrolysis is on average doubling every year. Low-temperature hydrogen generators, namely alkaline water electrolyzers (AWE) and PEM electrolyzers and currently deployed at the multi-megawatt scale, including systems with capacity of 100 MW and beyond. At the same time, market is expecting improved technologies as well alternatives which can provide cost-effective solutions of generating hydrogen in various industrial processes. Additionally, power-to-X systems (P2X) which are under consideration for generation of gaseous synthetic fuels (power-to-gas or P2G), liquid synthetic fuels (power-to-liquid or P2L) or ammonia (power-to-ammonia or P2A) are at the phase of early commercialization as subsidized demonstrators. This stimulates the development of highly-efficient technologies for hydrogen production using alternative paths. Solid oxide electrolyzers (SOE) which operated at elevated temperature, typically in the range from 550 to 750°C are one of the options. SOE offers an outstanding performance which is quantified by the lowest energy demand for producing hydrogen when compared to low-temperature electrolyzers.

Solid oxide electrolyzer are the only technology which can be directly fed by steam. Such a solution results in reduced demand for electricity to electrochemically split water into hydrogen and oxygen. External sources of steam are numerous, including industrial processes, by-product steam, steam generated using high-grade waste heat, geothermal sources and other. One of additional options is to couple SOE with steam cycles which can supply steam at various conditions.

HYDROGIN system which is discussed in the work integrates solid oxide electrolyzer with steam cycle which is generating up to 80 tonnes of steam per hour using biomass as a fuel. This unit was retrofitted to accommodate the electrolysis island which draws the steam from the turbine and feeds it directly to the cathodic compartments of SOE. At the same time, renewable electricity is powering the electrolyzer. This results in a hybrid system which can produce hydrogen which is stored on-site. Moreover, the unit can be operated interchangeably in the fuel cell mode (SOFC) making the system a true power-to-gas-to-power or P2P installation. Such a concept adds to the resilience of the grid by making the power plant more flexible, repurposes fossil fuel-based cycle, increase the penetration of renewable in the electrical grid and provides energy storage capacities. Most importantly, the concept elevates the annually averaged efficiency of the steam cycle by reducing the number of shutdowns when the power plant cannot operate due to reduction of the load below the technical minimum. Despite the large potential of the technology, there are several limitations to fully realize the concept of deep integration of solid oxide electrolyzers. These are related both to the functionality and the design of solid oxide electrolysis stacks and the design of the turbine. The work presents the outline of the system and discusses the results of the numerical analysis of the steam turbine-SOE couple which was investigated under steady-state conditions in the design point and in off-design.

Authors would like to acknowledge the National Centre for Research and Development of the Republic of Poland for financing this research under grant agreement POIR.01.01.01-00-0335/19.

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Sensitivity analysis of the effects of microstructure of the performance of solid oxide electrolyzer operated at elevated pressure

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Solid Oxide Electrolysis 1, Metals Hall, June 21, 2022, 8:00 AM - 10:00 AM

Sensitivity analysis of the effects of microstructure of the performance of solid oxide electrolyzer operated at elevated pressure

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Summary. Model of solid oxide electrolyzer (SOE) was developed for numerical analysis of off-design operation of SOE at elevated pressure. The study included sensitivity analysis of the performance of SOE with modified electrodes to qualitatively and quantitatively assess the effects of fine tuning of microstructure of SOE to boost performance.

Abstract.

The installed capacity of intermittent energy sources such as wind and solar is growing worldwide. These sources are predictable to a given extent, however annual production is limited to certain value, depending of the location and season. At the same time, due to the insufficient capacities of energy storage systems (ESS) curtailment of renewables is observed. For that reason new technologies for large-scale storage of energy are sought. Electrolyzers and often listed among potential options which can be deployed in centralized and distributed ESS units.

Three generic types of electrolyzers exist in the market: (i) alkaline water electrolysis (AWE), (ii) proton exchange membrane water electrolyzers (PEMWE), and (iii) solid oxide electrolyzers (SOE). While the first type is available at the largest scale as fully-commercial products, the last one offers outstanding performance with the lowest energy demand for production of hydrogen. Solid oxide electrolyzers still remain at the phase of subsidized development, still being subject of numerous R&D activities globally. Early-stage demonstrators are now deployed in various industries which can benefit from high temperature electrolysis which can be thermally integrated with downstream processes as well with external sources of heat either in a form of steam or hot gases. Currently SOE is mostly investigated at the atmospheric conditions, with limited number of reports on the pressurized operation. Elevating the pressure adds to the performance of solid oxide electrolyzer and can potentially reduce the energy demand for pressurizing generated hydrogen and oxygen. This makes it possible to increase the system-level performance of electrolysis systems. At the same time, pressurized electrolyzer can be coupled with downstream processes such as Sabatier or Fischer-Tropsch reactor which operate above the atmospheric conditions.

In the study, the assessment of the performance of SOE operated at the pressure of up to 8 bar(g) is presented. The numerical model with was built for the study includes the parameters of microstructure of interlayers of SOE. This made it possible to assess the performance gain when hydrogen and oxygen are produced in electrolyzer operated both in the design point and in off-design. Reference cells fabricated in house in the Institute of Power Engineering were used in the study. Their material and geometrical properties were included in the model which was later used for predictive modelling of the performance. Current-voltage (j-V) curves were compared in order to determine the effect of microstructural modification of the electrode on the energy consumption for generation of hydrogen in a pressurized solid oxide electrolyzer.

Authors would like to acknowledge the National Science Centre of the Republic of Poland for financing this research under grant agreement UMO-2021/42/E/ST8/00401.

Electron microscopy investigation of porous transport layer surface structures and coatings

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Electron microscopy investigation of porous transport layer surface structures and coatings

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Summary. The impact of various coatings and treatments on the nanoscale morphology and composition of the surfaces of porous transport layers used in proton exchange membrane water electrolyzers is examined using analytical electron microscopy.

Abstract. The high potential experienced at the anode in polymer electrolyte membrane (PEM) water electrolyzers requires titanium-based porous transport layers (PTL) to control the flow of reactants and biproducts of the oxygen evolution reaction and provide thermal and electronic conduction pathways. While reasonably corrosion resistant, Ti-based PTLs still suffer from high interface resistance between the PTL and anode due to the formation of a native oxide layer that passivates the fiber or sinter surfaces. Various etching and coating approaches have been used to reduce the overall ohmic resistance of the PTL/anode interface. Understanding the morphology of the structures and interfaces that result from these treatments is paramount to optimizing their effectiveness. Here, we will present analytical electron microscopy methods for investigating these PTL surfaces with sub-nanometer resolution.

A combination of scanning electron microscopy (SEM), focused ion beam (FIB), aberration-corrected scanning transmission electron microscopy (STEM), and energy dispersive X-ray spectroscopy (EDS) was used to investigate the homogeneity of platinum coatings applied to PTLs by physical vapor deposition. In addition, the effectiveness of acid treatments to remove Ti-oxide passivation layers or generate unique nanostructured surfaces was studied. The application of FIB-SEM to prepare thin cross sections of the PTL surfaces for STEM-EDS analysis will be presented, along with methods for reducing damage and redeposition layers arising from this site-specific sample preparation method. High-resolution STEM images and quantitative elemental maps will be presented of the PTL/coating interface and correlated with performance data. Overall, these findings will help steer the development of PTL treatments and coatings for highly durable and efficient PEM water electrolyzers.

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X-ray photoelectron spectroscopy characterization of IrO2 electrodes coated from aged ink

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X-ray photoelectron spectroscopy characterization of IrO_2 electrodes coated from aged ink

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Summary. Investigation of CLs using ex-situ and in-situ X-ray Photoelectron Spectroscopy with focus on CLs homogeneity, ink aging and catalyst-ionomer interface through careful analysis of the O 1s and Ir 4f core levels providing key insights.

Abstract. Proton exchange membrane water (PEMW) electrolyzers are an advanced and effective solution to producing hydrogen from water for hydrogen energy technologies. To improve PEMW electrolyzer operation, it is necessary to analyze the PEMW electrolyzer catalyst layer (CL) surface as it relates to processing, performance, and degradation. However, understanding the CL composition, structure, and morphology at all relevant scales is difficult. X-ray photoelectron spectroscopy (XPS) is a surface-sensitive technique that is capable of measuring subtle interfacial interactions and chemistries of a sample's surface within 3-10 nm, enabling better understanding of surfaces in CLs. However, there are additional challenges associated with limited information that has been reported in the literature thus far.

This study focuses on investigating the CLs made with IrO_2 catalysts using Mayer Bar coating method that enables scale up production of electrodes. Surface information was acquired using *ex situ and in situ* XPS using a recently developed approach that mitigates issues with degradation of ionomer possible from XPS conditions. Firstly, *ex situ* XPS was used to probe variations between different areas of the CLs. Secondly, *ex situ* XPS was employed to investigate CLs made with inks aged for different amount of time. And lastly, *in situ* XPS was used to probe CLs in the presence of humidification. Results from this study will discuss surface differences due to ink age, as well as address specific challenges in fitting the O 1s and Ir 4f core level spectra which are inherently challenging to curve fit. This initial work motivates further studies investigating other aspects related to ink and CL stability.

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Catalyst Layer Resistance, Utilization, and Degradation in PEM Electrolysis

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Catalyst Layer Resistance, Utilization, and Degradation in PEM Electrolysis

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Summary. Internal resistance within the catalyst layer of PEM electrolyzers causes lower catalyst utilization and cell performance, and can also accelerate degradation. We present methods for measuring catalyst layer resistance in-situ and determining the associated voltage losses, analysing both nanoparticle IrO_2 and Ir-NSTF catalyst systems.

Abstract. Proton exchange membrane (PEM) electrolysis is a promising route for renewable hydrogen production. However, to enable widespread, low-cost hydrogen generation, PEM electrolyzers must make advances in performance and durability with greatly decreased loadings of iridium as the anode oxygen evolution catalyst. The ionic and electronic resistance of the anode catalyst layer is an important consideration, as high internal resistance lowers catalyst utilization and cell performance, while accelerating degradation. Catalyst layer resistance (CLR) is relatively well-understood in fuel cells and other porous electrode systems. However, characterization of CLR is not routinely used in the PEM electrolysis community, and the impacts of CLR for PEM electrolysis are not widely understood.

Here we will present in-situ impedance methods for measuring CLR in electrolysis cells using a non-faradaic H2/H2O condition as well as methods for calculating the associated voltage losses. These methods are applied to anode catalyst layers based on IrO2 nanoparticles as well as dispersed nano-structured thin film (NSTF) Ir catalysts. Trends of CLR, performance, and durability with electrode properties such as loading and interactions between the porous transport layer and catalyst layer will be discussed. We will also present investigation of characteristic uneven degradation of the catalyst layer caused by CLR and strategies for mitigating this degradation mechanism.

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Time of Flight Secondary Ion Mass Spectrometry (ToF-SIMS) as a novel approach for characterization of Porous Transport Layers

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

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Summary. Time of Flight Secondary Ion Mass Spectrometry (ToF-SIMS) is introduced as a complimentary technique to characterize the surfaces and interfaces of Porous Transport Layers. ToF-SIMS initial results will be compared to STEM-EDS data and benefits of introducing this technique as an additional analytical tool for these materials will be highlighted.

Abstract. The United States energy infrastructure aims to move towards the integration of hydrogen energy. As such, the production of reliable hydrogen generation through the optimization of water electrolyzers is imperative. In proton exchange membrane water electrolyzers (PEMWE's), the porous transport layer (PTL) plays an important role. Due to the harsh conditions of the cell, titanium is the current state-of-the-art anode PTL material. However, titanium quickly forms a layer of titanium oxide which significantly reduces conductivity of the PTL and respectively decreases the overall efficiency of the PEMWE system. To mitigate oxide effects, coatings are commonly applied to the PTL. Detailed physicochemical characterization of PTLs and PTL coatings is needed to complement electrochemical testing.

Focused Ion Beam Scanning Electron Microscopy (FIB-SEM), in conjugation with Scanning Transmission Electron Microscopy Energy-dispersive X-ray Spectroscopy (STEM-EDS) analysis, is a commonly used technique to characterize PTL materials and PTL coatings; specifically to look at coating homogeneity and unfavorable oxide layer formation. Unfortunately, this approach is both time-consuming and labor intensive. Additionally, STEM-EDS analysis only provides elemental information, so if several oxide layers are present, it can be difficult to differentiate them, and thus lead to a lack of understanding fundamental degradation mechanisms. These technique deficiencies have motivated the development of alternative approach that utilizes Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) for more efficient characterization of these materials. ToF-SIMS is a valuable technique that is commonly used to characterize thin films and buried interfaces. ToF-SIMS can be performed relatively quickly in relation to commonly used techniques, provides chemical information, and is sensitive to trace elements. This technique also enables visualization of elemental distribution, which provides more detailed surface and interface information. This presentation will demonstrate capabilities of ToF-SIMS for characterization of PTLs, along with challenges in optimization. ToF-SIMS results will be compared to TEM analysis of cross-sections obtained with FIB-SEM. This study will highlight similarities and differences

between the techniques, expand on technique optimization for these morphologically challenging samples, and suggest paths for future investigation moving forward.

Investigations of SOEC Degradation Using Electron and Ion Microscopy

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Investigations of SOEC Degradation Using Electron and Ion Microscopy

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Summary: Many of the theories surrounding SOEC degradation during elevated temperature testing requires sub-micron spatial resolution elemental mapping along with crystallographic determination to determine the phases of reaction products. Using a combination of Focused Ion Beam, Scanning Electron, and Transmission Electron Microscopy along with energy dispersive X-ray spectral imaging, we illustrate sub-micron scale diffusion of Sr and Ag after 1000 hrs of high temperature testing. Secondary phases are determined using Raman spectral imaging at sub-micron scales and 4-D STEM diffraction at sub-nm scales.

Abstract.

Determining sources of degradation in SOEC using electron microscopy first requires sectioning the cells in cross section without damaging the porous structure. This led to the development of new sample preparation techniques to produce the cross section and smooth the exposed edge. Mechanical fracturing was found to be the most effective cross sectioning technique, followed by mechanical polishing to produce clean interfaces.

Electron microscopy and EDS data revealed microstructural changes in the LSCF layer. Interfacial roughness increases with increasing testing time and also included migration of Sr to the ceria barrier layer (Figure 1). The migration of strontium is a previously known cause of the degradation as the Sr forms $SrZrO_3$ at the electrolyte interface and prevents oxygen ion conduction through the cell. Additionally, migration of silver from the current collectors was observed to pile up at the ceria / YSZ interface.

Limitations in the spatial resolution of SEM-EDS mapping prefaces the need for more precise morphological analysis and elemental analysis to confirm the mechanisms behind cation migration. For instance, previous studies have shown Sr diffusion occurs after transition metal cations diffuse from the anode and concentrate on the YSZ electrolyte grain boundaries. Future analyses will include 3-D FIB / SEM imaging, 4-D STEM diffraction mapping, STEM-EDS spectral imaging, as well as confocal Raman spectral imaging to give sub-micron information about secondary phase formation. These methods require further FIB preparation which is also favoured in its ability to create smooth surfaces to properly conduct Raman spectra on each of the layers. These studies are complementary to X-ray based studies being conducted by our group. Ideally, more precise forms of data collection will present the proper morphological information to determine the exact mechanisms behind SOEC degradation.

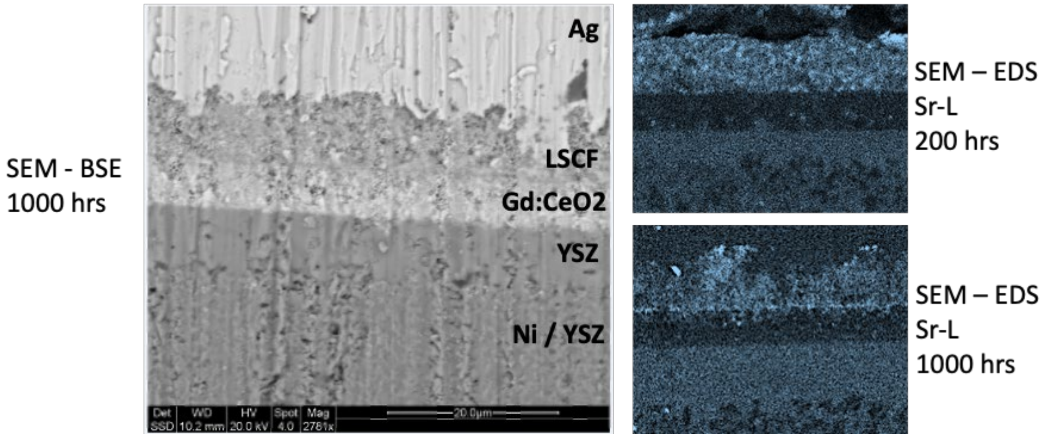

Figure 1. SEM-BSE image of a SOEC stack in cross section. On the right are SEM-EDS maps illustrating changes in the Sr distributions between 200 hrs (top) and 1000 hrs (bottom) of testing.

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X-ray photoelectron spectroscopy characterization of catalyst-ionomer interactions for polymer electrolyte membrane fuel cells

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X-ray photoelectron spectroscopy characterization of catalyst-ionomer interactions for polymer electrolyte membrane fuel cells

Jayson Foster[a], Sarah F. Zaccarine[a], Carlos Baez-Cotto[b], Sara Kim[a], Michael J. Dzara[a], Mariah Batool[c], Jasna Jankovic[b], Scott Mauger[b], Michael Ulsh[b], Svitlana Pylypenko[a]

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Summary. Surface catalyst-ionomer interfacial interactions probed using *ex situ* and *in situ* X-ray photoelectron spectroscopy on Pt/Carbon electrodes with varied support materials, Pt catalyst loading, and ionomer loading. Complementary electron microscopy techniques are used to visualize distribution of platinum, carbon, and ionomer.

Abstract. Proton exchange membrane fuel cells (PEMFCs) are a progressive technology capable of providing on-demand energy without contributing to greenhouse gases. Scaled-up fabrication of PEMFC catalyst layers (CLs) motivates studies that relate catalyst chemistry and morphology to processing parameters and performance characteristics. A common issue within the cathode CL is non-uniform distribution of the ionomer within the catalyst layer. Additionally, interfacial interactions between catalyst and ionomer are not well understood.

X-ray photoelectron spectroscopy (XPS) is a highly surface-sensitive technique primed to provide information into the surface properties of CLs, including relative amount of surface ionomer, and further improve understanding of interfacial interactions among the catalyst, support, and ionomer. Although Nafion is inherently susceptible to X-ray degradation, XPS can be used effectively through a modified acquisition strategy developed previously in our group. In this work, XPS has been used to probe CLs with focus on the catalyst-ionomer interface and interactions using a series of electrodes prepared by a Mayer rod coating method. The catalyst-ionomer interface was investigated as a function of support material in the catalyst, Pt loading on the support, and ionomer loading. Surface information was acquired using *ex situ* and *in situ* XPS to emphasize this technique's capabilities at probing ionomer interactions. Scanning transmission electron microscopy (STEM) catalysts is used to visualize distribution of Pt nanoparticles on support, relating catalyst and support properties to their surface behaviour while integrated with ionomer. Furthermore, scanning electron microscopy (SEM) and STEM scanning in combination with energy-dispersive X-ray spectroscopy (EDS) mapping of electrode cross-sections were utilized to visualize distribution of ionomer and Pt in the CL to further assist with interpretation of XPS data. Results from this dataset emphasize the strength of this technique to study complex interfaces in PEM catalyst layers motivating further work expanding to other catalysts and ionomers.

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Catalyst Development and Electrode Fabrication for Low-Temperature Water Electrolyzer Operating with Anion Exchange Membrane

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Catalyst Development and Electrode Fabrication for Low-Temperature Water Electrolyzer Operating with Anion Exchange Membrane

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Summary. Anion exchange membrane water electrolysis is a promising technology for the sustainable hydrogen production. We summarize our recent research progress in the development of high-performance electrocatalysts, fabrication of membrane-electrode assemblies, and electrolyzer testing under different operating conditions.

Abstract. Hydrogen is considered a promising energy source owing to its high energy density and CO_2-free emission. Anion exchange membrane-based low-temperature (< 100 °C) water electrolyzers (AEM-LTWEs) can compete with state-of-the-art proton exchange membrane (PEM) electrolysis systems to produce "green" hydrogen.[1, 2] AEM-LTWEs can potentially operate on pure water feed and use less expensive platinum group metal-free (PGM-free) electrocatalysts.[3] The key to realizing this technology is the development of PGM-free catalysts for hydrogen and oxygen evolution reactions, (HER and OER, respectively) in alkaline media, provided they can be successfully integrated into the electrodes and achieve satisfactory cell performance.[4, 5]

In this work, we investigated different classes of OER catalysts: commercial IrO_2 (a PGM OER benchmark), $La_xSr_{1-x}CoO_{3-\delta}$ oxides, Ni-Fe nanofoam oxides, Ni-Fe aerogel-derived oxides, and MOF-derived Co oxides; and HER catalysts: commercial PtRu/C (a PGM HER benchmark) and aerogel NiMo/C catalyst in both three-electrode electrochemical system and AEM water electrolyzer. To enhance cell performance, effects of the membrane-electrode assembly (MEA) fabrication, *e.g.*, ink deposition method, amount of ionomer, incorporation of a binding agent, and the type of anode porous transport layer on performance were examined. AEM-LTWEs were operated in three modes: on pure-water feed, using 0.1 M KOH electrolyte, and 1 wt% K_2CO_3 electrolyte. Catalysts and electrodes before and after testing were characterized by XRD, SEM, EDS, and XPS. The results suggest that the primary factor limiting the AEM-LTWE performance may be effective transport of OH^- ions within the catalyst layer, especially in the pure water-fed operation mode.

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Benchmarking efforts for the PEM electrolysis community – a reference protocol

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Polymer Electrolyte Membrane Electrolysis 4, Metals Hall, June 23, 2022, 8:00 AM - 10:00 AM

Benchmarking efforts for the PEM electrolysis community – a reference protocol

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Summary. In the present contribution, the benchmarking efforts from a group of three leading institutions (out of a working group of the Annex 30 within the International Energy Agency (IEA)) towards a thoroughly tested reference hardware and measurement protocol is presented.

Abstract.

The number of publications in the PEM electrolysis community constantly increase each year. But so far, no common ground, concerning reference hardware and testing protocols could be established which is necessary for the comparability of experimental results. First attempts for such reference hardware and procedures were published by an international group of institutes, working together in the framework of the Annex 30 within the international energy agency (IEA) [1]. As improvements of both the test hardware (test cell and components) as well as the measurement protocol were identified since the first publication, the group of institutions (reduced number of members for higher flexibility in adjustments) will present the revised methodology and key results out of a comprehensive measurement series. A detailed protocol for testing commercial reference components (PTL: Ti Fibre material, Beakert, Belgium; MEA: E400, N115 based, Greenerity GmbH, Germany) with a reference laboratory test cell developed in-house by Fraunhofer ISE (see figure 1) is presented. For evaluation of the protocol and the hardware, it was tested at three different institutes at the same time. Impedance spectroscopic and polarisation data (see figure 2) was acquired and analysed. Differences in performance were calculated to give the community an expectation window to compare own data to.

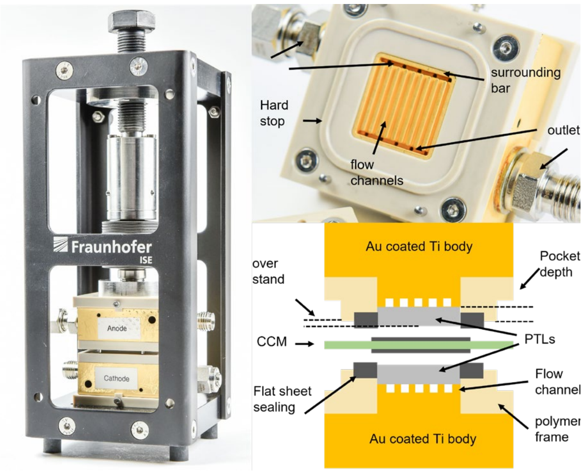

Figure 16: Picture and sketch of test cell and half-cell

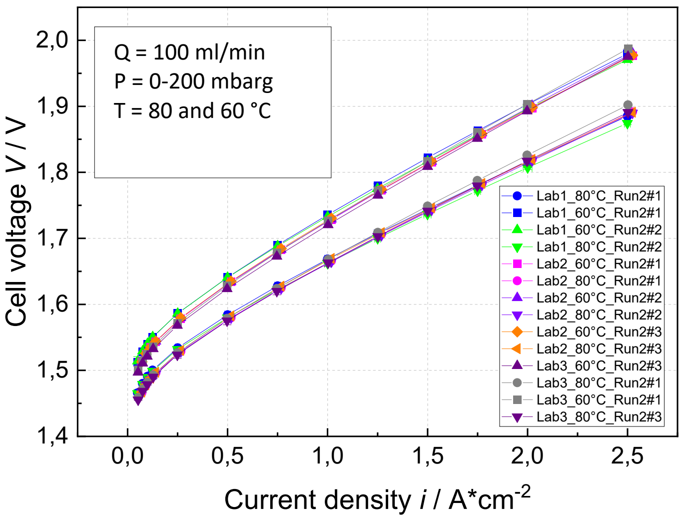

Figure 17: Polarization data from three institutes

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Understanding Durability of PEM Water Electrolyzers

Dr. Siddharth Komini Babu[1], Dr. Xiaoxiao Qiao[1], Mr. Fausto N. Pasmay[2], Dr. Haoran Yu[3], Mr. Abdurrahman Yilmaz[1,5], Dr. Jacob S. Spendelow[1], Dr. Shawn Litster[2], Dr. David Cullen[3], Dr. Deborah Myers[4], Dr. Rangachary Mukundan[1]

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Polymer Electrolyte Membrane Electrolysis 1, Metals Hall, June 20, 2022, 1:30 PM - 3:10 PM

Understanding Durability of PEM Water Electrolyzers

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Summary. Degradation of catalyst layer and membrane in PEMWE during accelerated stress tests under different operating conditions is studied to determine the degradation mechanism.

Abstract. Generation of clean hydrogen needs to be significantly increased to meet the carbon neutral goals. Polymer electrolyte membrane water electrolyzers (PEMWE) for hydrogen production will be critical in hydrogen generation as well as efficiently incorporating intermittent renewable energy sources. To meet the recent DOE's hydrogen earth shot target of $1/kg of hydrogen in a decade, improved understanding of the durability of PEMWE with low loading of iridium is required for developing mitigation strategies. This work will present the effect of different operating conditions including voltage cycling on the degradation of the anode catalyst layer and the membrane.

Accelerated stress tests (AST) development and the effect of certain stressors on the degradation rates will be presented. Degradation of PEMWE was monitored through various operando, in-situ and ex-situ characterization techniques. In specific, various electrochemical characterization techniques including cyclic voltammograms, and impedance spectroscopy can be used to highlight changes in the polarization behaviour of electrolyzers. The cathode potential during the potential cycling is measured using a reference electrode. We will also present the fluoride emission rate of the effluent water in both anode and cathode in tracking membrane degradation. The changes in electrode morphology and the catalyst composition during the AST will be elucidated using microscopy and X-ray analysis techniques.

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Physicochemical Evolution of SOECs as a Function of Accelerated Ageing: A Multi-Scale X-ray Characterization Approach

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Physicochemical Evolution of SOECs as a Function of Accelerated Ageing: A Multi-Scale X-ray Characterization Approach

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Summary. Correlating performance loss to physicochemical changes within an SOEC is of great interest, yet the variety of possible degradation phenomena presents a challenge that necessitates a multi-faceted characterization approach. Herein we present a study featuring several X-ray characterization techniques to reveal SOEC evolution during accelerated ageing.

Abstract. The high efficiency and the potential to avoid the use of expensive and scarce metals make solid oxide electrolysis cells (SOECs) an attractive technology to generate hydrogen renewably. However, the harsh environment (high temperature, oxidizing environments, and high current density) that SOECs are operated in presents a challenge in device performance loss over time. Indeed, to reach relevant SOEC durability goals of less than 0.5%/1,000 hours performance loss, and lifetimes on the order of tens of thousands of hours of operation, improvements in cell durability must be made to further reduce the rate of SOEC degradation in concert with efficiency improvements and cost reduction.[1,2] Accelerated ageing protocols have been developed to quickly induce physicochemical changes in the SOE cell, enabling comparison of different materials and fabrication methods. Comprehensive physicochemical characterization studies are needed to identify degradation factors and correlate these to cell properties and processing history.

A number of possible degradation pathways for SOECs have been hypothesized and identified, including cation migration into/across the electrolyte, particle coarsening in the electrodes, change in porosity of the electrodes or the support, undesired phase formation, and others.[1,3] These can lead to increased electrical resistance, decreased mass transport rate of gaseous reactants or products, and deactivation through formation of inactive species. Due to the number of different layers within an SOEC, the variety of elements, phases, and morphologies, and the different scales at which the aforementioned degradation processes can occur at, performing comprehensive physicochemical characterization is a challenge, and a multi-faceted approach is a must. A combination of X-ray spectroscopy and microscopy, electron microscopy, electrochemical characterization, and other techniques are employed, while the focus of this work is solely on X-ray spectroscopy and microscopy. X-ray fluorescence (XRF) mapping was performed in order to investigate chemical distribution at the micro/macro scale, evaluating cell heterogeneity and enabling tracking of large-scale cation migration. This was complemented by X-ray absorption near-edge spectroscopy (XANES) 2D-mapping, which is used to track Ni, Fe, and Gd distribution at a spatial resolution on the order of tens of nanometers. Depth-resolved X-ray diffraction (XRD) was performed by changing the incident angle of the SOE cell to investigate crystalline phase evolution within the various layers of the cell. Finally, Transmission X-ray microscopy (TXM) is used to investigate changes in 3D morphology, enabling evaluation of porosity, and distribution of elements of interest in 3D.

As a case study, a set of oxygen conducting, Ni-YSZ steam-electrode supported SOECs with a YSZ electrolyte, GDC barrier layer, and GDC-LSCF composite oxygen-electrode were characterized as a function of time subjected to accelerated ageing protocols. Several key material changes were identified, including segregation of Sr within the oxygen-electrode. Such results confirm that physicochemical changes can be tracked within the various layers of the SOE cell at multiple scales, and the information gained can be used to inform the manufacture of SOECs with improved durability, as well as supporting modelling studies. These efforts will drive SOEC technology advances towards longer operating lifetimes, enabling cheaper hydrogen production.

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Understanding the transport properties of PTL on the anode side and GDL on the cathode side for water electrolyzers

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Understanding the transport properties of PTL on the anode side and GDL on the cathode side for water electrolyzers

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Summary. Storing the electricity from intermittent renewable sources as hydrogen can be effective due to its lightweight and compressibility. However, the efficiency of water electrolysis needs to be improved and the costs need to be lowered. Therefore, understanding the transport properties of the anode PTL and cathode GDL is essential to improving the efficiency of the water electrolysis reaction.

Abstract. Polymer electrolyte water electrolyzers (PEMWEs) are a promising technology for energy storage from intermittent renewable sources such as wind and solar. Porous transport layers (PTLs) and gas diffusion layers (GDLs) play a crucial role in catalyst utilization, gas bubble removal, and membrane expansion/contraction. Therefore, understanding the transport properties of the PTL on the anode side and GDL on the cathode side is critical for improving the overall performance of the PEMWEs.

In this study, we elucidate how mass transport properties are affected by the structure of anode PTLs. The PTLs morphology (sinter, felts, etc), thickness and porosity were studied on the anode side of PEMWEs. The hierarchical porosity graded PTLs were studied by stacking different PTLs to guide the development of the microporous layers for PTLs. Hierarchical PTL with corrosion resistant microporous layers were fabricated from corrosion-resistant powders and binder. We will present the effect of the thickness, porosity, and wettability of the MPL on the performance and durability of PEMWE. Very limited research has focused on understanding cathode GDLs. Our study shows significant performance improvements by changing the thickness and compression of the cathode GDLs.

Acknowledgment. Financial support from the US Department of Energy through the Office of Energy Efficiency and Renewable Energy, Hydrogen and Fuel Cells Technology Office is gratefully acknowledged.

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Instrumental insights into faradaic efficiency measurements of electrocatalytic CO2 reduction and water splitting

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Instrumental insights into faradaic efficiency measurements of electrocatalytic CO_2 reduction and water splitting

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Summary. Faradaic Efficiency (FE) is a key figure of merit of electrocatalyst performance in laboratory-scale CO_2 reduction (CO2RR). We showcase results of an organic polymer plus CO2RR electrocatalyst cathode measured in a membrane separated H-type cell, to exemplify our instrumental approach to quantify FE dynamically and versatilely.

Abstract.

Energy conversion to chemicals like H_2 is technically and economically crucial to reach the milestones set for reducing CO_2 emissions. Water electrolysis is the workhorse technology for industrial H_2 production from renewable electricity, but its current limitations for scalability remain at the anode electrocatalyst. At the anode, the oxygen evolution reaction (OER) takes place, whose sluggish kinetics related to the 4-electron transfer involved requires a compromise between the working overpotential and electrocatalyst durability.[1] CO2RR instead of HER at the cathode is an even more rewarding process since it has the additional asset of recycling CO_2 into useful chemicals with higher volumetric energy density than H_2 (i.e., syngas). Yet, CO2RR is also kinetically taxing on the cathode electrocatalyst, and it adds the catalytic challenge of selectivity toward carbon products (i.e., CO and higher hydrocarbons) over HER.[2,3] Electrocatalyst development at laboratory scale to achieve better OER or CO_2RR electrocatalytic performance is then in the spotlight of material research. Electrocatalyst performance scrutiny is multidimensional and is approached holistically by assessing multiple figures of merits, like chronoamperometry and faradaic efficiency (FE).[3,4] FE judges primarily catalyst selectivity and stability. Experimentally, FE measurements rely on the proper quantification of product formation rates, which is the technical challenge we highlight in this presentation.[3]

We show our instrumental approach to obtain facile and reliable FE measurements, which is primarily focused on *operando* conditions of conventional three-electrode (photo)electrochemical cells at the laboratory scale. Although our presentation focuses on a membrane separated H-type cell example, our approach remains general to the myriad of other more specialized (photo)electrochemical cell designs. Our FE quantification method benefits from flow-reactor engineering concepts discussed in our previous photocatalysis works, like mass transfer and leakage control, and trace product detection.[5,6] The resulting dynamic FE analysis can be coupled modularly to multiple (photo)electrochemical cell modes (alkaline-membraned, electro-photoelectro, OER-HER- CO2RR, etc), with more versatility than actual real time reaction tracking techniques (i.e., DEMS), and more robustness and sensitivity than conventional high throughput electrolyte product detection techniques (i.e., RRDE).[3] The detection hardware design allows detection of gas (i.e., H_2, O_2, CO) and liquid products (i.e., CH_3OH), with a time resolution of 10 min. Our headspace detection based on gas chromatography (GC) differs from the commercial version found in the literature, mainly in terms of the universal *all-in-one* analyte detection and the wide linear range of the former. Upon mass transfer and signal-to-noise considerations, this method guarantees FE measurements approximately in the range of 10^{-6} to 10^{0} (A) of applied current and the possibility of alternative GC-mass spectrometry analysis. As an example of the fine capabilities of our method, we present the FE quantitative trends of a series of covalent organic frameworks (COF), modified from COF-366, as electrocatalysts for the CO2RR (i.e., for CO production).

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Developing high efficiency high rate alkaline water electrolyzers

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Alkaline Electrolysis 3, Metals Hall, June 22, 2022, 10:30 AM - 12:20 PM

Developing high efficiency high rate alkaline water electrolyzers

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Summary. Alkaline electrolyser was developed having highly active Raney nickel type electrodes and advanced membranes reaching at 70°C a current density of 1.04 A cm^{-2} and 1.56 A cm^{-2} at 1.8 V respectively with Zirfon and with developed membranes. The results were reproducible in 100 cm^2 stack of 7 cells. A complete AEL system testrig was developed and the stack was operated for more than 1000 hours without a measurable degradation. Moreover, transient models are developed to predict and improve the operation strategies under dynamic operations.

Abstract. Alkaline water electrolysis presents an economical technology for generation of sustainable hydrogen. However, the production rate of H_2 and the energy consumption per kg of produced hydrogen needs improvement. This should be achieved without incorporating noble metals. Moreover, for coupling with intermittent renewable power, AEL needs an enhanced capability of operating at part loads while maintaining a minimum gas purity and faster response to the load changes.

Developing these aspects in AEL require innovation in the stack components and improving the operational strategies. From the material point of view, three components were developed including i) highly active electrodes, ii) new types of membranes and iii) well-tune substrate/transport layers.

Highly active Raney Nickel type electrodes were developed which resulted in increasing the AWE operational current densities while maintaining the high efficiency. Using Zirfon diaphragm, the cell with developed activated electrodes delivered the current density of 1.04 A cm^{-2} at 1.8 V in 6M KOH at 70°C. The performance and durability of non-precious Raney Nickel type electrodes in combination with commercial diaphragm is validated in a the short AEL stack attaining these current and voltage values. Furthermore, no measurable degradation in the performance was recorded during continuous operation for more than 1000 hours of the stack. In the second step, the commercial Zirfon is replaced by specialty functionalized membrane reinforced by woven fiber. With thinner and more conductive functionalized alkaline membrane, the current density of 1.56 A cm^{-2} at 1.8 V could be attained. Tests in a full stack are pending. There is still a room to improve the overall stack efficiency and production rate by adapting a more tuned substrates and porous transport layer. So far, the electrodes have been fabricated on 2D supports. By replacing these with 3D substrates, and by implementing suitable gas diffusion layers with hierarchical structure for a better bubble management, further improvements are expected.

From the operational strategy point of view, the effect of electrolyte concentration, electrolyte flow rate and temperature have been investigated on the AEL performance. Although expanding the operational parameters can increase the system flexibility, the gas purity in AEL is still a challenge. This is addressed using the system approach by optimization of balance of plant layout and components such as decoupling of anode- and cathode KOH circuit to lower the gas impurity specifically in the part-load range.

In terms of degradation, a negative influence on the long-term performance of catalytic electrodes for AEL system was reported due to the dissolution of stainless-steel system-based components. Therefore, the AEL system has been modified and adapted accordingly. Contact of KOH with stainless steel is avoided wherever possible in the system. Piping was done by using PTFE hoses and PP Fittings. Suitable material selection was done for the separators, the circulation pumps, the filters and the sensors.

Lastly, transient modelling of AEL is under development using simulation framework of DLR called TEMPEST employing Modelica. Using 1D+1D models for mass and energy flow, the behaviour of stack and system under dynamic operation is investigated numerically.

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A more efficient design philosophy for PEM fuel cell electrodes

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

A more efficient design philosophy for PEM fuel cell electrodes

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Summary. Evidence will be provided to suggest (1) prioritization of both efficiency and durability and (2) allowance of higher stack & system costs if these lower H_2 usage. Electrode material and structure design philosophies will be proposed consistent with the two aforementioned overarching principles in combination with fundamental electrode obstacles.

Abstract. Total cost of ownership (TCO) analyses performed by U. Oregon[1], the National Renewable Energy Lab[2] and Argonne National Lab[3] are shown in Figure 1. Research efforts should focus on improving efficiency, if significant durability trade-offs are not in introduced due to the initial costs of stack & system components being small relative to the cost of fuel & maintenance (Figure 1). The conclusions of these analyses are that even multiple-times more costly stacks are acceptable if that facilitates the 2030 efficiency and durability targets.

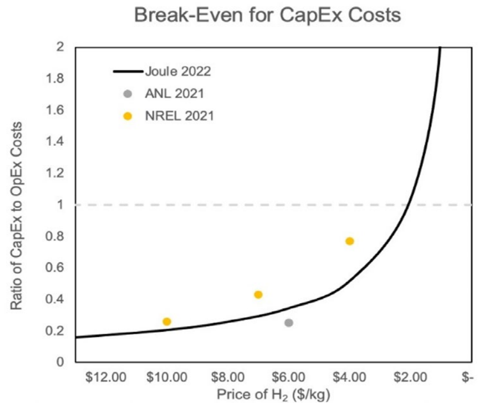

Figure 1. Comparison of capital expense vs operating expense (predominantly fuel costs) of a state-of-the-art stack with respect to a kg of H_2.

Electrode Materials

Consistent with the philosophy of minimizing fuel costs, the cost of the electrode in a stack for heavy-duty applications should not be prioritized over its efficiency and durability. Carbon is electrochemically unstable at all voltages & the low pH environment present in a PEM fuel cell, and thus could contribute to ultimate failure over the expected 25-to-30,000-hour heavy duty fuel cell lifetimes. Metal-oxide supports may be attractive only if low surface area and conductivity issues can be solved. Interactions between the electrode and the membrane are of high interest and will be discussed.

Electrode Structure

To achieve the highest volumetric power density in a stack, other than simply decreasing the pitch of the bipolar plates, one route is to minimize the number of cells required to produce a nominal power. This may be done by increasing individual cell performance and/or increasing the size of an individual cell. Homogeneity of certain parameters within the electrode and purposeful heterogeneity of others may be of use to tune both mechanical and hygrothermal properties.

While great advancements in catalysts have been made, little of that progress has translated to improvements in the MEA. The interactions within the catalyst layer, including minimizing the adsorption of ionomer sulfonates on catalyst surfaces, are currently being investigated as possible routes to bridge the gap between ex-situ and in-operando fuel cell tests.

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Investigation of power electronics as interface between power grid and electrolyser

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Polymer Electrolyte Membrane Electrolysis 4, Metals Hall, June 23, 2022, 8:00 AM - 10:00 AM

Investigation of power electronics as interface between power grid and electrolyser

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Summary. A reliable large-scale production of green hydrogen via electrolysis could transform the hard-to-abate industry and heat sector. However, the adverse effects for power grids and electrolyser stacks deriving from the systems power electronics need to be minimized. The Hydrogen Lab Bremerhaven enables tests and model validation at MW-scale.

Abstract. Hydrogen units such as electrolysers, fuel cells, and combined heat and power (CHP) stations will play a decisive role in the energy transition towards climate neutrality. The importance of hydrogen is shown by the current plans of various governments. The EU Hydrogen Strategy targets 6 GW of installed electrolysis capacity until 2024 and 40 GW until 2030. Moreover, many EU member states have included ambitious plans for hydrogen production in their national energy and climate plans. Thus, the new German government recently increased the previous plans of 5 GW installed electrolysis capacity to 10 GW until 2030.

However, the fulfilment of these ambitions is threatened if green hydrogen production technology does not enhance regarding fundamental technical challenges. Electrolysers are currently to be installed in modules in the low MW range up to 10 MW per plant. Considering the current plant size, but also taking future plant capacities of 100 MW and more into account the electrical characteristics of such systems in terms of grid compatibility need to be fully understood. Since electrolysers are nonlinear, dynamic loads connected to the grid via power electronics it should be assumed that grid perturbations such as harmonics can be emitted and even the stack performance can be affected by rectifiers with insufficient filtering of high-current ripples. Thus, an in-depth analysis and controller design is required.

At the Hydrogen Lab Bremerhaven (HLB) a PEM electrolyser with 1.4 MW nominal power and an alkaline electrolyser with 1.3 MW nominal power are installed using different rectifier and step-down converter technologies. A full downstream hydrogen infrastructure with gas compression and storage on the one side and the coupling to the 44 MVA Power Electronics Grid Simulator (PEGS) on the other side enable systemic research on the electrical characteristics of electrolyser units (Figure 1). The PEGS is a voltage controlled high performance converter system which can be connected to the different units of the HLB. It is used to emulate an artificial medium voltage grid to enable the possibility to perform static and dynamic tests. Within the static tests, the determination of the injected active and reactive power can be examined for various grid conditions. Furthermore, performing dynamic tests, transient grid events like voltage dips, frequency changes and phase angle jumps can be examined.

The lab's device under test (DUT) pads are designed as an open platform for electrolysers, fuel cells, CHP units as well as other electrical components. Several DUTs can be tested simultaneously on the test field. The nominal power of a single DUT pad is up to 5 MW. The installation can easily be done via an ISO container base, which allows a quick assembly and disassembly. Every DUT pad can be directly connected to the electrical power system. The pads are available for manufacturers and operators to validate and assess their equipment (Figure 2).

With more than five years of experience with wind energy testing methods, Fraunhofer IWES is looking forward transferring this knowledge to green hydrogen technology.

Figure 1: Overview of the test facilities in Bremerhaven with the HLB layout (bottom) and the DyNaLab with PEGS

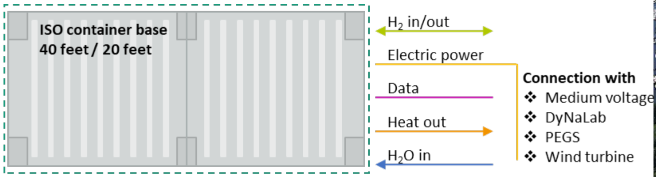

Figure 2: Design and concept of the DUT pad

Understanding the Potential Dependence of Ir Dissolution from IrO2 PEM Electrolyzer Anode Catalysts Through Modeling of Time-Resolved Measurements

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Polymer Electrolyte Membrane Electrolysis 3, Metals Hall, June 22, 2022, 8:00 AM - 10:00 AM

Understanding the Potential Dependence of Ir Dissolution from IrO_2 PEM Electrolyzer Anode Catalysts Through Modeling of Time-Resolved Measurements

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Summary. A significant degradation mechanism of PEM electrolyzer Ir-based anode catalysts is the dissolution of Ir during electrolyzer operation and loss of this dissolved Ir into the membrane. The potential and time dependence of Ir dissolution from a commercial IrO_2 anode catalyst was studied using an electrochemical flow cell system connected to an inductively-coupled plasma-mass spectrometer (ICP-MS). Fundamental models have been developed to explain the mechanisms of the dissolution process under various potential conditions.

Abstract. A carbon neutral energy economy must draw on renewable, energy sources such as solar and wind power. Due to the intermittent availability of these sources, energy storage and conversion systems, such as electrolyzers and fuel cells have become a crucial topic of research and development. Electrocatalysis efforts in low temperature, PEM-based water electrolyzers (PEMWE) tend to focus on the oxygen evolution reaction (OER) since it is several orders of magnitude kinetically slower than the hydrogen evolution reaction (HER). Iridium-based metal oxides (IrOx) are regarded as the best PEM electrolyzer electrocatalysts as they are both active and relatively stable. However, even Ir-based electrocatalysts undergo dissolution under the operating conditions of the PEMWE anode. Considering the need for thrifting of Ir to meet system cost targets and the required system lifetime of 80,000 operating hours, understanding the kinetics and mechanism of Ir electrochemical dissolution is of vital importance to develop strategies to enable both high OER activity and long-term stability of the PEMWE anode catalyst. This presentation describes the potential dependence of the dissolution of a commercial IrO_2 OER catalyst. The amount of dissolved Ir during potentiodynamic conditions was determined using an electrochemical flow cell system connected to an inductively-coupled plasma-mass spectrometer (ICP-MS) capable of detecting trace concentrations (<ppb) of dissolved elements in solution. The electrochemical data combined with the ICP-MS data are used to evaluate the influence of various factors such as potential, potentiodynamic profile parameters (e.g., scan rate, upper and lower potential limits) on the dissolution processes in acidic aqueous electrolyte at room temperature. Fundamental models developed to explain the mechanisms of the observed potential and time dependence of Ir dissolution will be described.

Acknowledgements

This work was supported by the U.S. Department of Energy, Energy Efficiency and Renewable Energy, Hydrogen and Fuel Cell Technologies Office (HFTO) under the H2NEW Consortium. This work was authored in part by Argonne National

Laboratory, a U.S. Department of Energy (DOE) Office of Science laboratory operated for DOE by UChicago Argonne, LLC under contract no. DE-AC02-06CH11357.

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Scaling proton-conducting ceramic fuel cells and electrolyzers from the laboratory to the marketplace

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Solid Oxide Electrolysis 2, Metals Hall, June 21, 2022, 4:00 PM - 5:30 PM

Scaling proton-conducting ceramic fuel cells and electrolyzers from the laboratory to the marketplace

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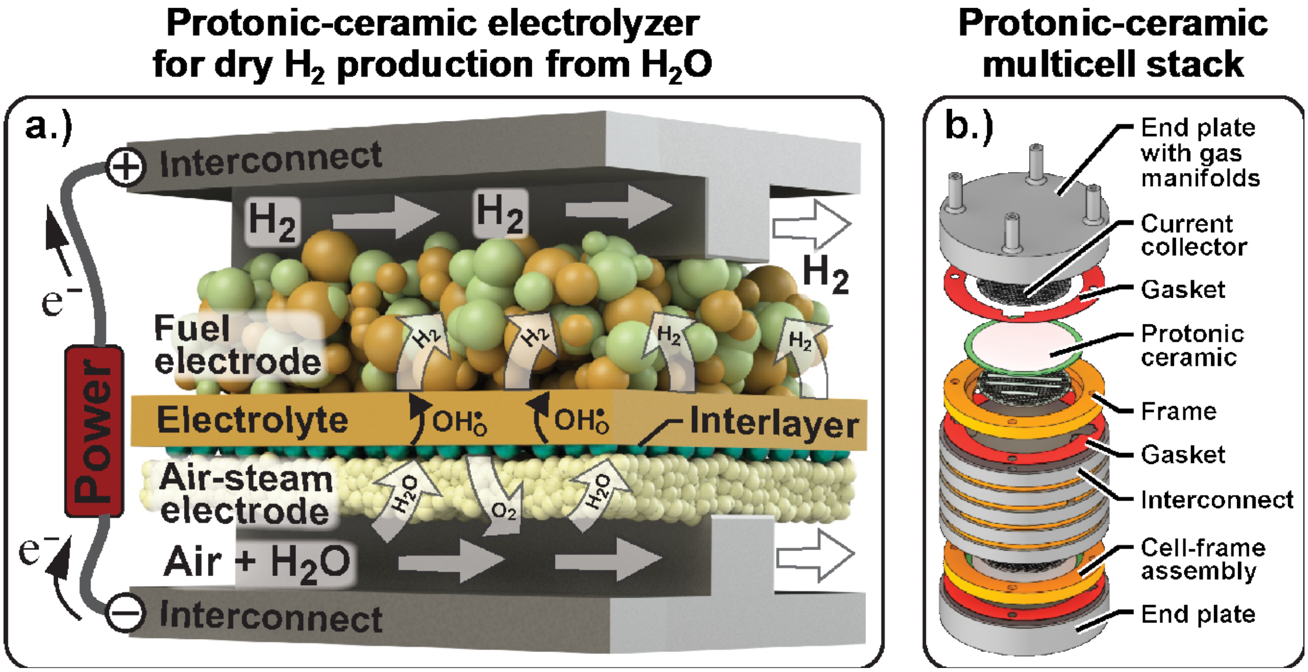
Summary. We present results from our university-industrial collaboration to scale up proton-conducting electroceramics from small "button cells" to larger-area, multi-cell stacks. Scale-up successes and challenges will be presented, along with results from our follow-on studies to move protonic ceramics closer to the commercial marketplace.

Abstract. Proton-conducting electroceramics offer great promise for "green" hydrogen production. Commercial development of protonic ceramics remains at an early stage in comparison to that of more well-established oxygen-ion-conducting solid-oxide devices. That said, lab-scale demonstrations of protonic-ceramic electrolyzers boast encouraging performance, including high current density at modest overpotentials and lower operating temperatures, low degradation rates, and high Faradaic efficiency. Through Department of Energy support, the Colorado School of Mines has partnered with commercial developer FuelCell Energy to scale up protonic ceramics into 100-cm^2 devices and multi-cell stacks. This presentation will review the technical progress, some of the challenges revealed through the scale-up program, and efforts to move forward.

The high ionic conductivity of protonic ceramics enables strong performance at lower operating temperatures (~ 500 ºC). However, our larger-area cells demonstrated high rates of voltage degradation at these lower temperatures. Higher operating temperatures were necessary to drive degradation rates below 1% khr^{-1}, a counter-intuitive result. The source of this degradation was traced to the interface between the $BaCe_{0.4}Zr_{0.4}Y_{0.1}Yb_{0.1}O_{3-d}$ (BCZYYb) electrolyte and the $BaCo_{0.4}Fe_{0.4}Zr_{0.1}Y_{0.1}O_{3-d}$ (BCFZY) air-steam electrode. Inclusion of a 10%-Gd-doped ceria interlayer at this interface greatly reduced degradation rates, enabling robust device performance at the target operating temperatures (550 ºC). Further, protonic-ceramics degradation was found to be significantly higher in fuel-cell / electricity-production mode in comparison to electrolysis / energy-storage mode. This is counter to degradation in O^{2-}-ion-conducting electroceramics. The root cause of this performance improvement remains an active area of study, as does the field of degradation in protonic ceramics.


Protonic-ceramic electrolyzer for dry H_2 production from H_2O

Protonic-ceramic multicell stack

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Towards better understanding of the Transport-/Catalyst layer Interface

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Polymer Electrolyte Membrane Electrolysis 2, Metals Hall, June 21, 2022, 10:30 AM - 12:15 PM

Towards better understanding of the Transport-/Catalyst layer Interface

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Summary. High anode catalyst utilization is a critical parameter for PEM water electrolysis. The interface is governed by the structural properties of the catalyst and transport layers. For optimization the understanding of the interrelation of the two components is the critical parameter.

Abstract.

The structure of the interface between the anodic porous transport layer (PTL) and the catalyst layer (CL) is a crucial factor limiting cell efficiency. Today's PEWE technology relies on porous, Ti particle or fibre based, transport layer materials. The lack of understanding of the decisive interface properties of both layers and the commercial availability of PTL materials with suitable surface characteristics, tailored for this application is critical for the improvement of catalyst utilization and cell efficiency.

The structural characterization of the surface of porous transport layer and the catalyst layer, using X-ray imaging and model experiments with a matrix of regular PTL structures allow for identification of limiting processes and the design of improved PTL structures. Multi-layer PTLs with a smooth MPL surface allow for a significant increase of the catalyst utilization (shown in Figure 1) for a particle sintered base material (SL) and different double layer materials with smooth surfaces. The smooth surface also allows for the use of thinner membranes, reducing the ohmic losses and increasing cell efficiency.

The structural properties of PTL and CLK are discussed and limiting processes identified. And the characteristics and performance of cells with improved CL/PTL interface presented.

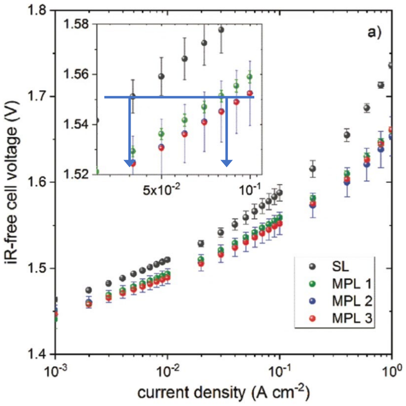

Figure 1: IR-free polarization curves (1 bar, 50 °C, N115) showing the improvement of catalyst utilization. Figure adapted from [1].

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Understanding Structure and Catalyst Distribution of Anodic Porous Transport Electrodes in Proton Exchange Membrane Water Electrolyzers

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Polymer Electrolyte Membrane Electrolysis 2, Metals Hall, June 21, 2022, 10:30 AM - 12:15 PM

Understanding Structure and Catalyst Distribution of Anodic Porous Transport Electrodes in Proton Exchange Membrane Water Electrolyzers

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Summary. This study provides a deeper understanding of the structure of porous transport electrodes and their catalyst distribution. Advanced tomography methods are applied to the anode electrode of a PEMWE to cover the different scales present in this system.

Abstract. The transition to a carbon-neutral energy sector is linked with the implementation of energy storage solutions. This is due to the natural fluctuation and intermittency of renewable energy sources. Hydrogen as a primary energy carrier could be a promising candidate as a storage solution. Thereby, green hydrogen is produced by electrochemical water splitting. So-called proton exchange membrane water electrolyzers (PEMWEs) are suited to a renewable energy based energy infrastructure due to their flexibility, rapid system response and scalability ease. [1, 2]

Nowadays, state-of-the-art PEMWEs consist of a catalyst coated membrane (CCM) sandwiched between two porous transport layers (PTLs). A different approach of the manufacturing of PEMWEs is the direct coating of the catalyst ink onto the PTL. These porous transport electrodes (PTEs) would allow a wider variety of membranes because the glass-transition temperature of the polymer is no longer of concern.[3] Bühler et al. [4] showed that PTE-based PEMWEs could perform similarly to CCM configurations. Kulkarni et al. [5] analysed the morphology and performance of several PTL and PTE-based PEMWEs. Overall, the PTE configurations had a worse performance due to a lower connection between catalyst particles and membrane. This results from the deep penetration of the catalyst ink into the titanium PTL.

The above studies pointed out that further improvements of PTEs are necessary to make them competitive against CCMs. One essential point is to get a deeper understanding of the structure of PTEs. Therefore, we used a combination of different tomography methods to image the structure of the titanium fibre substrate, the IrO_2 catalyst layer and its catalyst distribution. X-ray tomography and focused ion beam scanning electron microscopy (FIB-SEM) measurements were capable of representing the system in the µm- and nm-scale. The structural analysis could reveal morphological properties, like catalyst layer thickness and surface roughness. Together with a modelling approach these findings can help to design future PTE configurations and improve their performance.

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A hybrid measurement technique for rapid insight into electrochemical performance

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Solid Oxide Electrolysis 1, Metals Hall, June 21, 2022, 8:00 AM - 10:00 AM

A hybrid measurement technique for rapid insight into electrochemical performance

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Summary. A hybrid measurement technique provides rapid access to the distribution of relaxation times, enabling new types of experiments and analysis.

Abstract. The distribution of relaxation times (DRT) has been established as a versatile tool for analysis of electrochemical impedance spectroscopy (EIS) data, providing insight into the relevant electrochemical processes of fuel cells, batteries, and other devices without the constraints of an *a priori* model. However, the measurement time required to obtain suitable EIS spectra can limit the practicality of detailed impedance studies, especially when a large number of evaluation conditions and/or low-frequency relaxations are of interest. Here, we present a hybrid characterization technique coupling rapid frequency-domain and time-domain measurements that provides direct access to the DRT in a fraction of the time, which opens new avenues for characterization and analysis that are inaccessible and/or impractical with conventional EIS. A hierarchical Bayesian model is applied to robustly obtain the DRT from the hybrid dataset. We demonstrate how this technique can be used to quickly map the DRT as a function of additional variables such as applied bias or external gas conditions, producing multidimensional DRT maps that yield new insight. The capability of this method to quickly resolve the DRT along additional dimensions promises to enhance the interpretability of the DRT, providing new insight to guide materials and device optimization.

A Comparative Analysis of Conventional Ammonia Production with that based on High Temperature Solid Oxide Electrolysis Technology

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

A Comparative Analysis of Conventional Ammonia Production with that based on High Temperature Solid Oxide Electrolysis Technology

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Summary: A numerical analysis for an ammonia production plant incorporating solid oxide electrolysis is conducted. Conventional solid oxide electrolysis for ammonia is compared to a novel concept that eliminates the air separation unit by combusting a part of the hydrogen.

Abstract: Ammonia is the world's second most commonly produced chemical [1]. It provides a medium for carbon-free energy storage which is rapidly increasing the scope of its application. On a volumetric basis, ammonia is an effective hydrogen carrier and contains 75% more energy as compared to hydrogen (16 MJ/L for ammonia vs 9 MJ/L for hydrogen) which makes it easier to store and transport [2], [3]. Most of ammonia gas produced today is generated with hydrogen obtained from steam reforming of natural gas and nitrogen obtained from air separation. Steam reforming of natural gas leads to the emission of carbon dioxide whereas air separation into nitrogen and oxygen is a highly energy intensive process. Solid oxide electrolysis of water to produce hydrogen, coupled with the Haber-Bosch process offers a potentially attractive pathway to reduce carbon emissions.

This study aims to numerically explore an electrified ammonia plant that incorporates hydrogen production using solid oxide electrolysis. The operating temperature and pressure space, along with viable current densities of solid oxide electrolysis technologies will be examined for optimal integration with downstream ammonia synthesis using a novel idea proposed by the SOC4NH3 project [4]. In this concept, the air separation unit can be eliminated by adding auxiliary air to hydrogen downstream of the stack. A fraction of the product hydrogen exiting the stack is combusted to form water whereas the remaining exhaust stream which consists of hydrogen and nitrogen can be utilized to form ammonia. Incorporating such a process would eliminate the electricity required to separate air into nitrogen and oxygen at the expense of reducing the efficiency of hydrogen production. The process energetics of this concept are explored to evaluate the feasibility in terms of thermodynamic efficiency and performance characteristics of the given system. The results will be compared to conventional ammonia production plants.

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Fluidized bed processing for scaled-up production of Pt/C catalysts for fuel cell applications

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Fluidized bed processing for scaled-up production of Pt/C catalysts for fuel cell applications

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Summary.

The preparation of platinum on carbon fuel cell catalyst powders was scaled up in fluidized beds to the 10-30 g (75-250 ml powder) scale. Fluidization aids were developed to improve the processing of the substrate, allowing for the deposition of high Pt content catalysts (20-70 wt% Pt) with high catalytic activity. Further scaling to larger batches is very feasible.

Abstract.

As potential applications for atomic layer deposition (ALD) expand beyond the nano-scale devices of the semiconductor industry, development of larger-scale processes on high surface area substrates include many challenges that must be solved. This is especially true for catalyst applications, where literature reports performed at the small scale (~1 g) have shown that ALD can improve stability, selectivity, and lifetime of catalyst materials. Typical catalyst supports have very high surface area (>100 m^2/g), meaning that to scale the deposition up to larger quantities, transport of the ALD precursors to the support surface is a driver for production scalability. Powder handling of the support materials, specifically the carbons used as catalyst supports often used in fuel cell applications, can also be a challenge, as they can have a tendency to agglomerate during processing.

Forge Nano scaled the deposition of platinum onto carbon supports in fluidized bed reactors, with the goal of ultimately producing catalysts for automotive and other fuel cell applications. We studied the deposition of Pt by ALD on EC-300J ketjenblack carbon at the 10-30 g scale (75-250 ml powder volume) in fluidized bed reactors at rough vacuum (~10 torr). Initially, the catalyst deposition suffered from many of the same processing challenges commonly seen with carbon black substrates: poor fluidization and agglomeration into large-scale aggregates. This would lead to inhomogeneous dispersion of the catalyst across the substrate surface, a problem magnified by the high target loadings (~50wt% Pt) used in fuel cell applications.

Implementation of fluidization aids, including microjets and powder surface treatments, aided in preventing the agglomeration of the substrate during processing and improved the fluidization behavior. This allowed us to deposit the Pt onto the carbon using both thermal oxygen- and ozone-based ALD chemistries, achieving loadings ranging from 20-70wt% Pt. Process monitoring and product mass balances indicated that the oxygen and ozone used in the ALD chemistry had the potential to combust measurable fractions of the substrate powder over the course of the depositions. Product powders showed high catalytic oxidation activity for the deposited platinum. Proper choice of the deposition conditions could be used to limit this activity for the product upon removal from the reactor. We will discuss strategies for continuing to scale these processes to 100-1000 g batches and beyond for commercial fuel cell applications.

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Low Temperature Electrolysis Catalyst Development, and Giga-manufacturing.

Dr Barr Zulevi[1]

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Polymer Electrolyte Membrane Electrolysis 3, Metals Hall, June 22, 2022, 8:00 AM - 10:00 AM

Low Temperature Electrolysis Catalyst Development, and Giga-manufacturing.

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Pajarito Powder, LLC 3600 Osuna Rd NE, Albuquerque, NM 87109 (USA)[1]
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Summary. The rapid increase in Low Temperature Electrolysis system deployment have created great needs in the associated supply chain needs in scale, improved quality control, and of course improved PGM utilization and performance. The needs, challenges, and successes in LTWE catalyst and QA development and manufacturing will be discussed.

Abstract.

Catalysts for LTWE have until recently been mostly multipurpose catalysts adapted or simply used in LTWE. To improve performance , stability, and utilization as well as mass deployment better quality control, analytical methods, and purposes designed catalysts are needed. These, the potential for improvement, and challenges will be outlined and discussed. Improvements and the potential for further improvement will be presented.

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Characterization of surfaces and interfaces in polymer electrolyte membrane electrolyzers

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Polymer Electrolyte Membrane Electrolysis 2, Metals Hall, June 21, 2022, 10:30 AM - 12:15 PM

Characterization of surfaces and interfaces in polymer electrolyte membrane electrolyzers

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Summary. Characterization of surfaces and interfaces in polymer electrolyte membrane water electrolyzers using electron and X-ray microscopy and spectroscopy methods with a focus on catalyst and porous transport layers.

Abstract. Polymer electrolyte membrane water electrolyzers (PEMWEs) are of significant importance towards enabling the large-scale utilization of renewable hydrogen. Fabrication and integration of components, advancement of scalable manufacturing techniques, elucidation of degradation mechanisms, and development of degradation mitigation strategies all require extensive characterization of materials, components, and devices. The complexity of the systems and problems combined with the multitude of relevant scales require multi-technique characterization and motivate further developments of characterization methods and novel approaches. This talk will discuss some of our recent studies on both catalyst layers (CLs) and porous transport layers (PTLs) for application in PEMWEs. Specifically, this presentation will highlight the complementary nature of electron and X-ray microscopy and spectroscopy methods for investigation of surfaces, interfaces, and interactions within the CLs comparing results for Ir and IrO_2-based CLs, and fresh and aged or tested CLs. Similarly, characterization of PTLs requires advanced characterization to properly assess elemental distribution and chemical speciation of PTLs and protective coatings.

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Anode Catalyst Durability in Low Temperature Electrolysis

Dr Shaun Alia[1], Kimberly Reeves[3], Haoran Yu[3], A. Jeremy Kropf[2], Nancy Kariuki[2], Jaehyung Park[2], Deborah Myers[2], David Cullen[3]

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Polymer Electrolyte Membrane Electrolysis 1, Metals Hall, June 20, 2022, 1:30 PM - 3:10 PM

Anode Catalyst Durability in Low Temperature Electrolysis

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Summary. Studies related to anode catalyst layer durability will be discussed and include the development of catalyst-specific accelerated stress tests. Testing has been applied to several advanced material approaches, which tend to produce higher performances and degradation rates, and speaks to catalyst development needs and perspectives.

Abstract. Hydrogen has unique advantages as an energy carrier, with a high energy density and abilities for long term storage and conversion between electricity and chemical bonds. Although hydrogen currently has a significant role in transportation and agriculture, its use in energy consumption overall has been limited, particularly in the case of electrochemical water splitting. With decreasing electricity prices, electrolysis cost reductions can be achieved and allow for an opportunity for greater use.(1) While load-following renewable power sources can reduce feedstock cost, further cost reductions can be achieved by reducing the platinum group metal (PGM) content.(2) Efforts are needed to understand and mitigate electrolyzer degradation, particularly when accounting for lower PGM loadings and intermittent operation.

In this presentation, studies related to anode catalyst durability will be discussed and include the impact of individual stressors, observed degradation mechanisms, and the development of catalyst-specific accelerated stress tests. Membrane thickness and ohmic losses were deconvoluted from catalyst layer durability experiments, allowing for a transition from potential-driven parametric observations to current-driven stress tests for advanced materials and coating processes. Expanded studies have incorporated advanced materials, including higher surface areas, different oxide compositions, supports, and multicomponents. Kinetic improvements were found to lessen load requirements and can mitigate catalyst loss. Cell performance loss during extended operation, however, tended to qualitatively correspond to ex-situ dissolution rates and less stable materials accelerated catalyst layer thinning, migration into the membrane, and interfacial tearing. Perspectives on anode catalyst development will be discussed and increasing site-access and utilization further into the catalyst layer is needed to better understand the role of advancements in mitigating electrolyzer durability losses.

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Coupling electrolysers to renewable energy sources – status, challenges, and pathways for reaching MAWP 2023 targets

Dr. Belma Talic[1], Ms. Sara Andrenacci[1], Dr. Yash Raka[1], Dr. Thulile Khoza[1], Dr. Luis Colmenares-Rausseo[1]

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Coupling electrolysers to renewable energy sources
– status, challenges, and pathways for reaching MAWP 2023 targets

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Summary. We provide an overview of key challenges to be solved for reaching performance targets for PEM electrolysers, alkaline electrolysers and solid oxide electrolysers with regards to integration with renewable energy sources.

Abstract.

The increasing share of intermittent renewable energy sources raises the need for grid balancing and energy storage. Producing hydrogen by electrolysis is an excellent way to store excess renewable energy that can be used in the chemical industry, in the transport sector or later re-electrified. Direct coupling of electrolysers to renewable energy sources offers opportunity to quickly absorb dynamic generation peaks but puts demanding requirements on the load following capability of the electrolyser.

The multi-annual work plan (MAWP) for the European Fuel Cell and Hydrogen Joint Undertaking defined in 2014 three key performance indicators (KPIs) concerning flexibility of electrolysers[1], shown in Table 1. In the framework of the EU-project HAEOLUS, a review has been made of the PEM, AEL and SOEL electrolyser technologies to evaluate the status of commercial systems relative to MAWP 2023 targets. In this presentation, we will provide an overview of the key challenges and most promising pathways for reaching the targets regarding operational flexibility based on literature review and experience from the HAEOLUS project.

Table 1. Key performance indicator (KPI) targets for hydrogen production from renewable electricity for energy storage and grid balancing.[1]

KPI	Target 2023
1. H_2 production electrolysis, flexibility with a degradation < 2 %/year	0-300% of nominal power
2. H_2 production electrolysis, hot start from min to max power	< 1 sec
3. H_2 production electrolysis, cold start	10 sec

Acknowledgement

The HAEOLUS project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement № 779469.

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Alkaline water electrolysis powered by fluctuating renewable energies

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[1]TU Clausthal, , Germany

Alkaline Electrolysis 2, Metals Hall, June 21, 2022, 1:30 PM - 3:20 PM

Alkaline water electrolysis powered by fluctuating renewable energies

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Summary. The dynamic operation of alkaline water electrolysis powered by fluctuating renewable energies is analyzed. The main problem is the foreign gas contamination during part-load operation, which can be successfully resolved by process strategies such as adapting the electrolyte flow rate or the temporary separation of the two electrolyte cycles.

Abstract. Water electrolysis will be the most important technology for the large-scale production of green hydrogen powered by renewable energies. Among the available processes, alkaline water electrolysis (AEL) is currently the most advanced technology. AEL is also very cost-effective because it does not rely on precious metal electrocatalysts [1]. With a rising share of fluctuating and intermittent wind and solar energy systems, the dynamic operation of water electrolyzers is becoming increasingly attractive to avoid additional storage technologies. However, this poses considerable challenges due to the increased degradation of materials and safety aspects. During part-load operation of electrolyzers, enhanced contamination of the product gases occurs, which is mainly caused by the mixing of the two electrolyte cycles in AEL [2], whereas permeation through the membrane is the main contamination mechanism in PEM electrolysis [3]. A mathematical model including both mechanisms was developed with which the measured foreign gas concentrations could be accurately described [4]. The permeability of both porous separators and membrane materials was determined as a function of temperature and electrolyte concentration [5].

These insights opened up ways to improve the gas purity during dynamic AEL operation through adapting the electrolyte flow rate or the temporary separation of the two electrolyte cycles. Synthetic current density profiles with wind and photovoltaic power characteristics were calculated by autoregressive-moving-average models as a basis for the evaluation of dynamic operating concepts for AEL [6]. Experiments and simulations revealed that the developed strategies could be successfully used to maintain the hydrogen-in-oxygen content well below the safety limit at 50% of the lower explosion limit. In the case of water electrolysis systems driven by photovoltaics only, a combination with a battery can reduce the required power of an AEL system resulting in improved energy and time usage. On the other hand, the additional investment has to be taken into account. Analysis of two different locations (Germany and Morocco) showed that a further reduction of the battery costs is necessary for the economical operation of such a hybrid system [7].

With a novel cell concept, the foreign gas contamination in AEL could be reduced even further. We proposed to combine a conventional cathode and a state-of-the-art Zirfon separator with a gas-diffusion electrode (GDE) for the oxygen evolution [8]. The electrolyte is transported through the separator and reaches the GDE, where oxygen evolution occurs. In principle, this configuration requires only one cathodic electrolyte cycle, which should improve the gas purity. First experimental results show that almost the same performance as in conventional cells can be achieved with this new setup.

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PANI/Zeolite-13X based Electrocatalyst for Hydrogen and Oxygen Evolution Reaction

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

PANI/13X Zeolite based Electrocatalyst for Hydrogen and Oxygen Evolution Reaction

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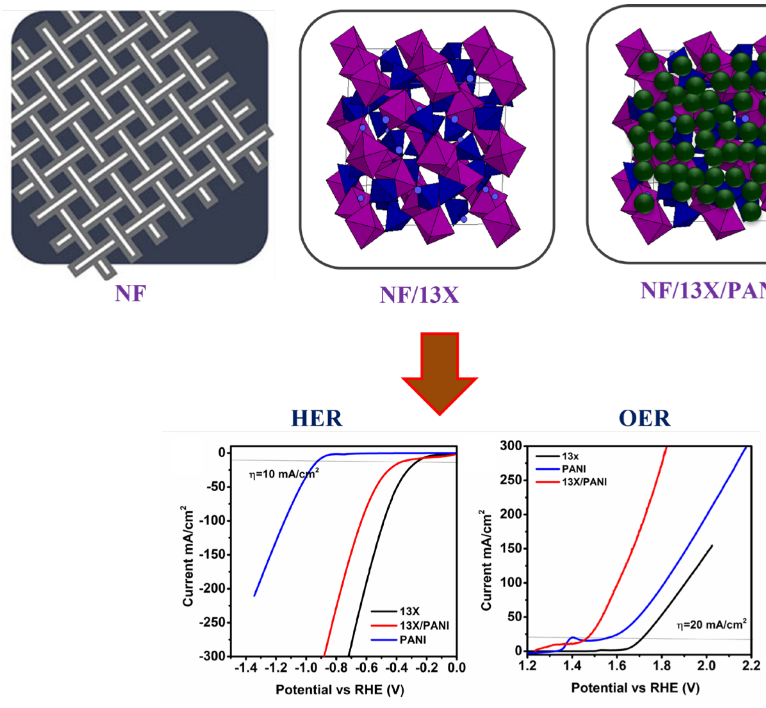
Summary. This work offers new research venues for designing efficient bifunctional electrocatalysts to improve the overall performance of alkaline water electrolysis.

Abstract. Herein, 13X zeolite was first synthesized by hydrothermal method. Then, the composite electrode was constructed by employing 13X zeolite and aniline monomer in nickel foam by electropolymerization method (PANI/13X). The catalytic behavior of the prepared 13X, PANI and PANI/13X composite electrodes was evaluated in oxygen evolution reaction (OER) and hydrogen evolution reaction (HER) by using linear square voltammetry (LSV) and Tafel slope method. The Tafel slopes of HER were found to be 203 mV dec^{-1}, 440 mV dec^{-1} and 282 mV dec^{-1} for 13X, PANI and 13X/PANI-15 electrodes respectively. While the OER Tafel slopes were found to be 423 mV dec^{-1}, 310 mV dec^{-1} and 168 mV dec^{-1} for 13X, PANI and 13X/PANI-15, respectively. 13X/PANI-15 electrodes show excellent catalytic performance about the overpotential at 10 mA cm^{-2} for HER and the overpotential at 20 mA cm^{-2} for OER. The attained outcomes illustrate a constructed PANI/13X composite electrode are an efficient bifunctional catalyst for water electrolysis.


NF
NF/13X
NF/13X/PANI
HER
OER
η=10 mA/cm^2
Current mA/cm^2
0
-50
-100
-150
-200
-250
-300
13X
13X/PANI
PANI
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
Potential vs RHE (V)
300
250
200
150
100
50
0
13x
PANI
13X/PANI
η=20 mA/cm^2
1.2
1.4
1.6
1.8
2.0
2.2
Potential vs RHE (V)

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Perspectives of ion-solvating membranes for alkaline electrolysis

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Alkaline Electrolysis 2, Metals Hall, June 21, 2022, 1:30 PM - 3:20 PM

Perspectives of ion-solvating membranes for alkaline electrolysis

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Summary. The interest in alkaline electrolyzer technologies is growing. A significant boost in performance is expected in alkaline electrolyzer cells built around an ion-conducting membrane. The paper will discuss perspectives of using ion-solvating membranes (ISM) as an alternative to anion-exchange membranes (AEM).

Abstract. The mainstream trend in alkaline membrane development is that of the anion-exchange membrane (AEM), the alkaline counterpart to the acidic cation-exchange membrane (CEM). The AEM has cationic sidechains with OH^- as counter ions (the exchangeable anions), just as the CEM has anionic sidechains with H^+ as counter ions. While CEM's have been around since the 1960's in fuel cells and recently marketed in electrolyzers too, the AEM's are still under development. The main challenges have been conductivity and chemical stability. The conductivity has improved remarkably in recent years, and today one can say that the main problem to address is long-term stability, often particularity related to the hydrophilic side chains with the immobilized ions.

The alternative solution, the ion-solvating membrane (ISM), does not necessarily involve side chains or even immobilized ions. The guiding principle is to use a polymeric material that is imbibed with a solution of ions - can be aqueous KOH. High conductivities have been demonstrated this way [1-3] along with lab-scale electrolyzers capable of several amperes per cm square at less than 2 V [4].

The ion-solvating concept allows for a different set of functional groups than ionic side chains to make the membrane conductive. A variety of hydrophilic moieties can be used, but the question is of course if they are long-term stable. However, the bottom line is that new degrees of design freedom come with the ISM.

In contrast to the ultimate AEM used with only pure water, the ISM still depends on an electrolyte with very high pH. This naturally challenges chemical stability, but it also eliminates the need for an ionomer in the catalyst layer. High pH moreover reduces the solubility of gasses and consequently the hydrogen crossover rate in pressurize cells.

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High Temperature Electrolysis Technology Demonstration at Idaho National Laboratory

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

High Temperature Electrolysis Technology Demonstration at Idaho National Laboratory

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Summary. Scaling up hydrogen electrolysis systems requires commercial acceptance and commercial acceptance requires third party validation. To support the high temperature electrolysis industry Idaho National Laboratory has developed open access solid oxide test facilities capable of testing single cells through sub megawatt systems.

Abstract. In order to scale electrolysis technology it is necessary to achieve commercial acceptance which in turn drives demand which allows manufacturers to traverse the valley of death into a cost effective production scale. However, historically, scale up of industrial equipment has often required decades to build up an adequate installed system base and real-world operations data to reduce risk. Given the rapidity of the changing grid environment and push for accelerated decarbonization, electrolysis offers a tremendous opportunity to address these issues if it can scale quickly enough.

To address the dearth of industrial validation data Idaho National Lab has developed a suite of test facilities designed to evaluate solid oxide electrolysis technology across the entire TRL scale – from single cells through pre-commercial sub megawatt systems. These test facilities are available to the industry as a third-party validation testing service through a variety of private and publicly funded demonstration projects.

Test facilities are broken into four length scales – single cell, small stack, large stack/hot module, and system testing. Single cell test facilities are utilized chiefly for materials development and degradation studies from button cell up to several hundred square centimeters with tightly controlled conditions. Stack test facilities allow for similar test environments with the addition of muti-stack capabilities up to 25kW electrolysis while adding recycle flow capability and more realistic reactant flows. The large stack and hot module testing facilities move away from the tightly control test stand environment and support testing up to 50kW electrolysis in more system like conditions utilizing realistic heat exchangers, process heaters, boiler supplied steam, and reversible commercial inverters. Finally, several system test facilities bays have been developed to enable testing of fully integrated pre-commercial systems up to 500 kW with simulated plant steam and grid based electrical connections.

All of these test facilities have been developed so that they can be adapted to any manufacturer’s high temperature electrolysis technology for validation testing. Furthermore, these test facilities have been developed with the direct intention of integration into the larger Energy Systems Laboratory at INL which allows hardware in the loop integration with real-time grid simulation, thermal energy distribution loops, and even automotive charging systems. These capabilities allow INL to support the industry to rapidly gather necessary validation data to accelerate the adoption of high temperature electrolysis.

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Challenges of MEA production for PEM electrolysis and fuel cell application by decal transfer process

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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Challenges of MEA production for PEM electrolysis and fuel cell application by decal transfer process

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Summary. Screen printing of electrodes for electrolysis and fuel cell application gives high process flexibility and comparability to other scientific institutions. Within this contribution, we present key learning from MEA production from the entire production chain, starting form ink preparation to in situ performance testing.

Abstract.

The catalyst coated membrane (CCM) or membrane electrode assembly (MEA) for both fuel cell and electrolyzer application is responsible for a large fraction of the costs of the stacks (Quelle 1). And as these are in turn responsible for a large fraction of the system costs, the production process of MEAs/CCMs need to be developed towards a high throughput process to be able to decrease costs of the entire hydrogen production system and fuel cell system significantly (Quelle 2).Different ways of producing an MEA/CCM are known in the scientific communities and industry (Quelle?). In the case of the herein presented results, the indirect process of the so-called decal transfer is used to investigate the production process (see **Error! Reference source not found.**). One of the major advantages is, that the decal process gives some degree of freedom in terms of choosing the coating process of the electrode onto the decal transfer material. For fuel cell application, a comparison of slot dye coating and screen printing of supported Pt/C electrodes will be presented. (Kurzer Abschnitt, Input Linda?) For the electrolysis side, screen printed unsupported iridium oxide-based electrodes with different loadings will be presented. A comprehensive study on transfer parameters will be shown as wells as results from ex situ analysis (e.g. XPS analysis on loading homogeneity, see Figure 18) and corresponding in situ polarization data.

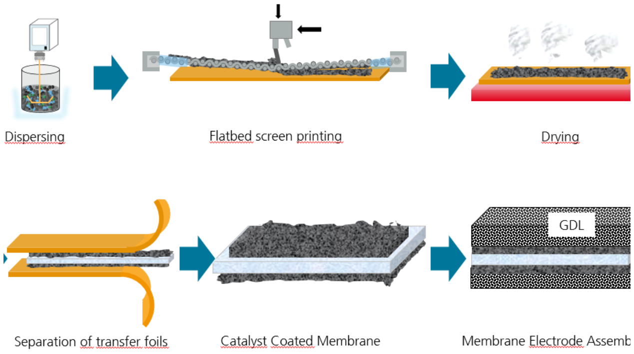
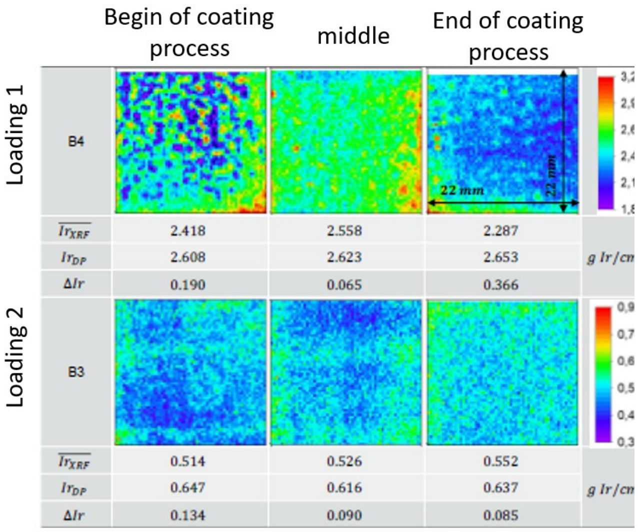


Figure 1: Schematic MEA production process by screen printing and decal transfer



		Begin of coating process	middle	End of coating process	
Loading 1	B4				
	$\overline{Ir_{XRF}}$	2.418	2.558	2.287	
	Ir_{DP}	2.608	2.623	2.653	$g\ Ir/cm$
	ΔIr	0.190	0.065	0.366	
Loading 2	B3				
	$\overline{Ir_{XRF}}$	0.514	0.526	0.552	
	Ir_{DP}	0.647	0.616	0.637	$g\ Ir/cm$
	ΔIr	0.134	0.090	0.085	

Figure 18: XPS results for different point in time during coating process for high and low loading electrolysis anodes.

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Understanding Performance and Durability of Solid Oxide Electroyzers

Dr. Olga Marina[1]

[1]*Pacific Northwest National Laboratory, , United States*

Solid Oxide Electrolysis 1, Metals Hall, June 21, 2022, 8:00 AM - 10:00 AM

Understanding Performance and Durability of Solid Oxide Electrolyzers

Olga A. Marina, Kerry Meinhardt, Long Le, Nathanael Royer, Chris Coyle, Lorraine Seymour, John Zaengle,
Dan Edwards, Matthew Olszta, Jie Bao, Yunxiang Chen, and Dewei Wang

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Summary. A significant multi-tactical effort towards understanding the performance limitations and durability of solid oxide electrolysis cells (SOEC) has been undertaken at the Pacific Northwest National Laboratory. Multiple cells of varied sized were tested in electrolysis mode in long term experiments followed by extensive post-test microscopical characterization to identify the favourable operating conditions for hydrogen production and elucidate potential degradation mechanisms. In addition, advanced modelling tools and machine learning were applied to assist the experimental approach.

Abstract. Solid oxide Ni-YSZ electrode-supported cells were produced using state-of the-art materials. Cell size varied from small 1 inch button cells to intermediate planar cells with an active area of 13 cm^2 to much larger 300 cm^2 planar cells used in a SOEC stack. All tests were performed in a potentiostatic mode at a fixed voltage while monitoring current. Most of the experiments were performed near the thermo neutral voltage at 1.3 Volt, yet some were performed at either lower or higher voltages, 1.2-1.6 Volt, to assess the effect of operating conditions on overall cell stability. Temperature varied from 700 to 800^{o}C and steam concentration varied from 10 to 95%. Repeat cells were tested for performance validation and to eliminate an occasional “bad” cell with poor contacts or other atypical trends. Tests were conducted for at least 1,000 hours with the maximum test duration of 6,000 hours. Electrochemical characteristics, such as current-voltage dependences, area specific resistances, ohmic and polarization resistances were obtained in each test to establish the baseline degradation rates. Relatively high degradation (10%/1000 hrs) was observed during the initial 500 hours on button cells, followed by very low (<0.4%/1000 hrs) to no degradation in the following 1,000+ hours of testing. The changes were electrodic in nature, as confirmed by an increase in the polarization resistance. Ohmic losses remained constant over time. Extensive high resolution, large-area microscopic analyses of cells were performed following the test termination.

For simulating stack conditions, intermediate-sized cells without real interconnects were tested. Planar cells exhibited much more stable performance during the initial conditioning steps and showed similarly low degradation over the following 1,000 hours. The performance of planar cells was validated in 20, 50, 80, and 90% steam and compared to that of button cells.

Large area cells were tested as single-unit short stacks in 50-80% steam and stack operation at up to 80% steam utilization was demonstrated.

Advanced 3D deep-convolution GAN modelling tools and machine learning were applied to provide the quantitative estimation on the probability of electrode microstructure variation under different operating conditions. Properties that

are only available in 3-D, such as triple phase boundary, tortuosity, and particle/pore sizes were calculated and related to test time.

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Emergent Nanomaterials for Solid Oxide Electrolysis

Prof John Irvine[1]
[1]*University of St Andrews, Professor, United Kingdom*

Solid Oxide Electrolysis 1, Metals Hall, June 21, 2022, 8:00 AM - 10:00 AM

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The history of water electrolysis - what can we learn from the past?

Dr. Tom Smolinka[1], Prof. Henry Bergmann[2], Prof. Jürgen Garche[3], Dr. Mihails Kusnezoff[4]
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Plenary Session 1, Metals Hall, June 20, 2022, 8:00 AM - 9:45 AM

The history of water electrolysis - what can we learn from the past?

Tom Smolinka[a], Henry Bergmann[b], Jürgen Garche[c], Mihails Kusnezoff[d]

[a] Fraunhofer Institute for Solar Energy Systems ISE, Germany; [b] Anhalt University of Applied Sciences, Germany; [c] Ulm University, Germany; [d] Fraunhofer Institute for Ceramic Technologies and Systems IKTS, Germany
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Summary. The principle of the electrochemical decomposition of water in an electrolysis cell has already been known for more than 230 years. Nevertheless, it took decades before the processes were used in first technical applications. This presentation provides an overview about the greatest milestones of electrolysis and places the historical developments in the context of current efforts to establish water electrolysis as one of the pillars of the energy transition [1].

Abstract. The first generation of hydrogen by electricity was done as early as 1789 by van Troostwijk and Deiman using an electrostatic generator as DC source. Shortly after Volta invented the voltaic pile in 1800, Carlisle and Nicholson used such a device to decompose water into hydrogen and oxygen. In the same year, Ritter performed comparable experiments in Jena, Germany. Moreover, Cruickshank used a voltaic pile for the electrochemical decomposition of NaCl to hydrogen and chlorine at the beginning of the 19th century. Only decades later - around 1890 - Charles Renard constructed a water electrolysis unit to generate hydrogen for French military airships. It is estimated that around 1900 more than 400 industrial alkaline water electrolyzers were in operation worldwide and large-scale deployment of the chlor-alkali process started. Later, different types of commercial alkaline water electrolyzers were developed in the 20th century to generate hydrogen needed to produce ammonia fertilizers based on low-cost hydroelectricity. As the 20th century progressed, the more cost-effective production of hydrogen by steam reforming of methane increasingly replaced water electrolysis, and by the end of the 20th century the process was only used in niche applications. In the late 1960s the development of Proton exchange membrane electrolysis began at General Electric using an acidic fluorinated ionomer as solid electrolyte. But the technology became established in the following decades only in laboratory, military, and space applications due to the high material costs. At about the same time, General Electric and the Brookhaven National Laboratory also started to develop high-temperature electrolysis with solid oxide cells. In Germany, Dornier followed in the HOT ELLY project this technology until the mid-1980s. But despite of all technical progress made commercialization of the membrane and solid oxide electrolysis could not be launched. But new interest in water electrolysis was stimulated already in the 1990s as hydrogen was regarded as green energy carrier for renewable energy sources like wind and solar power and to power fuel cells e.g. in automotive applications. However, it is only in the last 10 years that we have seen a significant increase in global interest for water electrolysis, with the adoption of ambitious national climate protection programs. Water electrolysis is regarded as the central element for sector coupling and is expected to make an important contribution to reducing GHG emissions close to net zero by 2050.

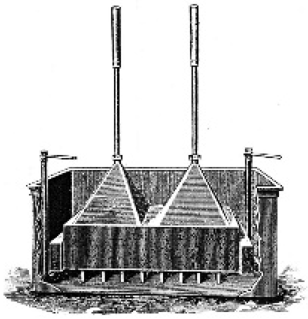

Figure: The Garuti electrolyzer from the late 19th century (courtesy of La Cour Museum Askov)

[1] Smolinka, T., Bergmann, H., Garche, J., Kusnezoff, M.: Chapter 4 - The history of water electrolysis from its beginnings to the present, in Editor(s): Smolinka, T., Garche, J., Electrochemical Power Sources: Fundamentals, Systems, and Applications - Hydrogen Production by Water Electrolysis, Elsevier, 2022, Pages 83-164, ISBN 9780128194249.

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AEM Electrolyzer Development at Hanwha Solutions

Dr Hoon Chung[1]

[1]*Hydrogen Technology R&D Center, Hanwha Solutions , Directer, South Korea*

Alkaline Electrolysis 3, Metals Hall, June 22, 2022, 10:30 AM - 12:20 PM

AEM Electrolyzer Development at Hanwha Solutions

Hoon Tack Chung

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Summary. Hanwha Solutions Company (HSC) has been at the forefront of Korea's advancements in the chemical industry. HSC is now searching for new growth engines through R&D. One of such efforts is the development of anion exchange membrane water electrolyzers (AEMWEs). In this presentation, we will introduce current status of AEM electrolyzer development at HSC.

Abstract. Since establishment in 1965, Hanwha Solutions Company (HSC) has been at the forefront of Korea's advancements in the chemical industry. Starting with Korea's first production of PVC (Polyvinyl Chloride), we began producing a full array of basic petrochemical products including LLDPE (Linear Low-Density Polyethylene), CA (Chlor-Alkali), ASR(Alkali Water Soluble Resin), and TDI(Toluene Diisocyanate), all of which has since served as base products across an wide range of industries.

HSC is now searching for new growth engines through R&D. One of such efforts is the development of anion exchange membrane water electrolyzers (AEMWEs). AEMWEs are considered one of the most promising sustainable hydrogen production technologies because of their ability to split water using platinum group metal-free catalysts, less expensive porous transport layers (PTLs), and bipolar plates, while their performances are expected very similar to those of PEM electrolyzers. There are several technical challenges in the development of AEMWEs such as (i) choice of materials including AEM and anion exchange ionomers (AEIs), OER/HER catalysts, anode/cathode PTLs, (ii) MEA fabrication technology, (iii) design and fabrication of bipolar plates, and (iv) design and fabrication balance of plant (BoP), and (v) operating technologies particularly in conjunction with renewable energies. In this presentation, we will introduce how HSC is developing AEM electrolyzers handling such challenges and current status of AEM electrolyzer development at HSC.

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The Renewable Energy-Electrolysis Nexus

Dr Bill Tumas[1]

[1]*National Renewable Energy Lab, Associate Lab Director, United States*

Plenary Session 1, Metals Hall, June 20, 2022, 8:00 AM - 9:45 AM

The Renewable Energy-Electrolysis Nexus

Bill Tumas

Associate Lab Director, National Renewable Energy Laboratory
bill.tumas@nrel.gov

Summary. Electrochemically-driven processes along with massive amounts of readily available renewable energy are at the forefront for decarbonizing all energy sectors required for our clean energy transformation and to address energy, environment, economy, and equity.

Abstract. This lecture will discuss the opportunities and challenges at the nexus of renewable energy and electrolysis that must be addressed to accelerate the innovation and technology development needed for energy conversion, delivery, storage, and use. For example, hydrogen will play a central role in stabilizing the electricity grid, delivering low-carbon energy dense fuels, providing feedstocks and reducing equivalents for chemicals, materials and products, and enabling cross-sector coupling and enabling deep electrification through efficiency interconversion of electrical and chemical energy. An overview of the National Renewable Energy Laboratory's strategy for a clean energy future through our three critical objectives: Integrated Energy Pathways, Electrons to Molecules, and Circular Economy for Energy Materials (https://www.nrel.gov/about/vision.html) will be provided. Advances in materials discovery, photovoltaics, solar fuels, hydrogen generation, storage, and utilization, electrochemical conversions, and carbon dioxide utilization/removal will be presented to illustrate how science and engineering can and must play a critical role in our energy transformation.

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Industrializing alkaline electrolysis production at Stiesdal A/S

DR. Harish Lakhotiya[1], Dr. Niels Vinter Voigt[2], Mr. Anders Vangsgård Nielsen[3], Mr. Henrik Stiesdal[4]

[1]Stiesdal Hydrogen A/S, Engineer Electrolyzer, Denmark, [2]Stiesdal Hydrogen A/S, Senior Engineer , Denmark, [3]Stiesdal Hydrogen A/S, Head of Technology, Denmark, [4]Stiesdal A/S, Founder / CEO, Denmark

Alkaline Electrolysis 3, Metals Hall, June 22, 2022, 10:30 AM - 12:20 PM

Industrializing alkaline electrolysis production at Stiesdal A/S

Harish Lakhotiya[a], Niels Vinter Voigt[a], Anders Vansgård Nielsen[a], Henrik Stiesdal[b]

[a]Stiesdal Hydrogen A/S and [b]Stiesdal A/S, Vejlevej 270, Give (7323), Denmark
Corresponding author email: hla@stiesdal.com

Summary. At Stiesdal Hydrogen we have taken up the challenge of producing green hydrogen at the low costs necessary for replacing fossil fuels in the industrial sector and heavy transport. By designing for manufacturing in already established high-throughput industries, we expect to scale the production to GW with small barriers and in a short timeframe.

Abstract. With the recent decade's strong reduction in the cost of renewable power, large scale roll-out of electrolysers can displace the current use of fossil fuels in large parts of heavy industry. Alkaline electrolysers are efficient, proven, durable and can be manufactured from readily available materials, which make them ideal for industrial scale production of green hydrogen. Alkaline electrolysis technology is a century old, but so far, the production has been laborious and costly. At Stiesdal Hydrogen, we design and manufacture industrial scale commercial systems. The team at Stiesdal has been rethinking the design of alkaline electrolyzers from the bottom up to leverage on already existing and well proven high throughput manufacturing processes, supply chains and low-cost yet efficient materials, whereby we can cut the unit costs drastically. We focus our cell level R&D activities towards activation of readily available materials for alkaline electrolysis with least compromise in its lifespan. At the stack- and system-level we reduce or possibly eliminate all sorts of losses associated with the conventional design of alkaline electrolyzers (i.e., power, electrolyte, materials, etc.). This presentation will introduce our low-cost alkaline electrolyzer, the HydroGen electrolyzer, for mass production and outline how this unit paves the way for low-cost green hydrogen enabling swift scaling into the GWs.

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Low Cost Coating Technology for PEM Water Electrolyzer Metallic Bipolar Plates

Conghua Wang[1]
[1] *TreadStone Technologies, Inc., ,*

Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

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Breaking the hydrogen crossover limitations for PEM electrolysers - Hystar's next generation PEM electrolysers

Dr Magnus Thomassen[1]
[1]Hystar AS, , Norway

Polymer Electrolyte Membrane Electrolysis 4, Metals Hall, June 23, 2022, 8:00 AM - 10:00 AM

Breaking the hydrogen crossover limitations for PEM electrolysers – Hystar's next generation PEM electrolysers

Magnus Thomassen[a], Alejandro Oyarce Barnett, Eddy Van Oort

[a]Hystar AS, Norway
Corresponding author email: magnus.thomassen@hystar.com

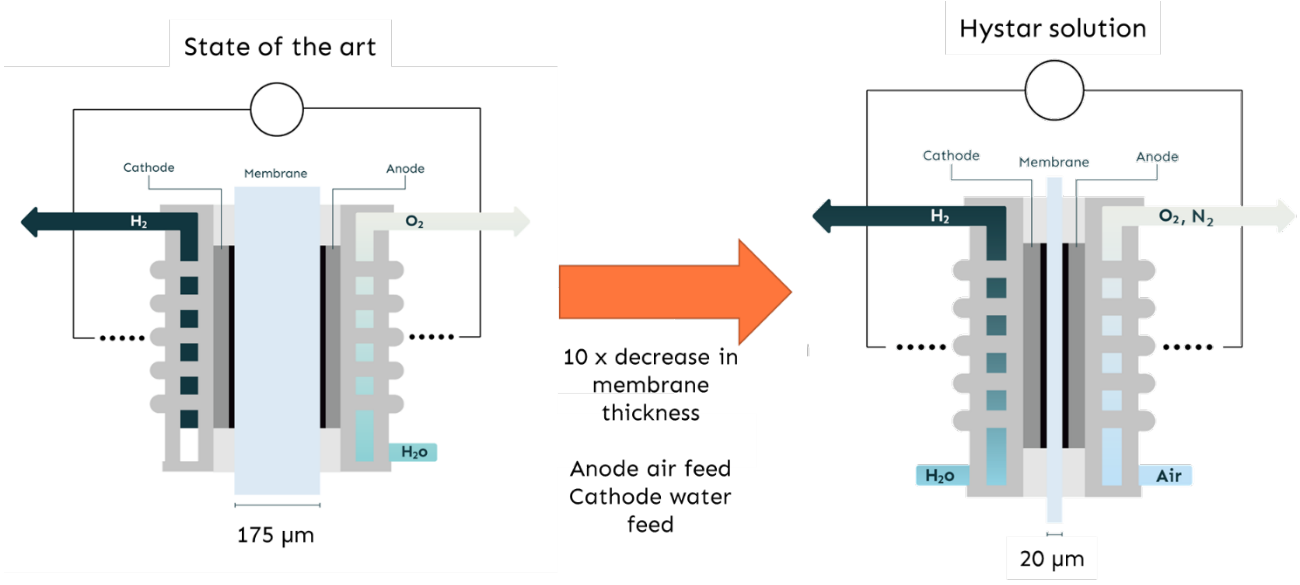
Summary. This presentation will give an overview of the patented Hystar solution for mitigation of hydrogen crossover in PEM electrolysers using thin membranes and the effect on overall electrolyser performance.

Abstract.

Proton exchange membrane (PEM) water electrolysers for hydrogen generation have several benefits such as high current densities; rapid system response (suitable for intermittent and fluctuating renewable energy sources); high gas purity; and good partial load range. One major challenge in PEM electrolysis is gas permeation through the electrolyte membrane, also known as gas crossover, which is limiting the use of thinner membranes and higher operating pressures.

Especially, the hydrogen crossover can cause Faradaic losses and can be a significant safety concern as only small amounts of H2 in O2 will lead to combustible gas mixtures. Several strategies to mitigate hydrogen crossover are currently used today; Using thick membranes will efficiently reduce the flux of hydrogen, but also leads to a significant ohmic resistance and a reduction of the cell efficiency. Recombination catalysts, either inside the cell or by using a separate recombiner after the electrolyser unit can be introduced but increase the use of PGMs.

In this presentation, Hystars patented solution for mitigation of the effects of hydrogen crossover and the resulting performance increase of Hystars PEM electrolysers compared to state-of-the-art systems will be presented.



State of the art

Hystar solution

10 x decrease in membrane thickness

Anode air feed
Cathode water feed

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Challenges in Scaling PEM Fuel Cells, Electrolyzers and Systems

Cortney Mittelsteadt[1]

[1]*Plug, , United States*

Plenary Session 2, Metals Hall, June 20, 2022, 10:15 AM - 12:15 PM

Challenges in Scaling PEM Fuel Cells, Electrolyzers and Systems

Cortney Mittelsteadt

Plug, USA
cmittelsteadt@plugpower.com

Summary. Previously the greatest challenge for PEM devices was securing PEM contracts! Plug has been a leading in developing, manufacturing, and deploying PEM devices from the MW to now GW scale levels. Challenges have mounted in securing supply chain for the building block stack materials as well as the balance of plants to operate them in. Deployment has its own challenges which varies with geography and finally consideration is needed to be given for end of life of these components and systems.

Abstract. PEM devices are rapidly moving from niche applications to projects beyond the 100 MW scale. Europe alone is looking to add 40 GW of renewable hydrogen by 2030. This brings with it several challenges. First, there is not currently the supply chain set up for these materials. In many cases this is trivial, stamped metal, end plates and piping can readily be diverted from other uses, in others new capacity will have to be built, and raw material capacity, specifically PGMs are a major concern. Once a supply chain is in place, manufacturing capacity needs to come online with challenges, particularly in QA/QC that are unique to these devices. Educated and trained labor to support these activities is generally done at the corporate level at this stage. Once supply of stack materials and construction are secured one needs to consider the balance of plant to support them. Again, training and education leaves large gaps as there are very few personnel with knowledge of the safe handling of hydrogen and operation of hydrogen systems. Certifications and guidance from regulating bodies is still in process, particularly on the electrolyzer side, which has borrowed more from fuel cells to this date. Engineering, procurement, and construction of the hubs is a tremendous challenge as compliance is almost always done at the local level. Once the system is up and running and fully commissioned, operation and service have their own challenges, mostly again by lack of an existing workforce or infrastructure to generated new trained workers. Both first most and finally, one needs to consider the end of life of these systems. We cannot wait 10-20 years from now to determine how to collect, repurpose and dispose of the materials that were utilized.

This talk will show how Plug is going to market with PEM fuel cells, electrolyzers, liquefiers, transport, and full systems. It will give a broad look at how we are addressing these concerns, and what are the most challenging.

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Hydrogen Program and Electrolyzer Activities at the U.S. Department of Energy

Dave Peterson[1]

[1]*U.S. Department of Energy, ,*

Plenary Session 1, Metals Hall, June 20, 2022, 8:00 AM - 9:45 AM

Hydrogen Program and Electrolyzer Activities at the U.S. Department of Energy

Dave Peterson, Ned Stetson, Sunita Satyapal, Hydrogen and Fuel Cell Technologies Office, U.S. Department of Energy

Today the technology around generating efficient and sustainable energy is rapidly evolving and hydrogen and fuel cells are emerging as versatile examples within a portfolio of options to meet our national climate goals. The U.S. Department of Energy's (DOE) is funding a comprehensive research, development, demonstration, and deployment (RDD&D) effort to address the challenges to achieving largescale commercial viability of hydrogen and related technologies across sectors and applications. This presentation will cover an overview DOE's Hydrogen Program and outline key priorities within the Bipartisan Infrastructure Law, also known as the Infrastructure Investment and Jobs Act, which includes $9.5 billion for hydrogen technologies, including $1 billion for electrolysis, $0.5 billion for clean hydrogen technology manufacturing and recycling, and $8 billion for at least four clean regional hydrogen hubs in the United States.

To unlock the market potential for clean hydrogen, DOE launched the Hydrogen Energy Earthshot (Hydrogen Shot) in June 2021, to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade ("1 1 1"). The Hydrogen Shot is the first of the DOE's Energy Earthshots, which aim to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade while creating good-paying union jobs and growing the economy. The presentation will focus on electrolysis activities funded through DOE's Hydrogen and Fuel Cell Technologies Office and discuss current status, key targets, and remaining challenges that need to be addressed to meet Hydrogen Shot goals. DOE will discuss the various consortia and priorities through national laboratory, university and industry projects. Preliminary feedback from stakeholder feedback and DOE workshops will also be presented.

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Understanding Effect of Porous Transport Layer Morphologies and Catalyst Layer Structure on Oxygen Transport in Polymer Electrolyte Membrane Water Electrolyzer

Iryna Zenyuk[1]
[1]*University of California Irvine, , United States*

Polymer Electrolyte Membrane Electrolysis 2, Metals Hall, June 21, 2022, 10:30 AM - 12:15 PM

Understanding Effect of Porous Transport Layer Morphologies and Catalyst Layer Structure on Oxygen Transport in Polymer Electrolyte Membrane Water Electrolyzer

Devashish Kulkarni[a], Nemanja Danilovic[b], Katherine E Ayers[c], Christopher Capuano[c], Iryna V. Zenyuk[a]

[a]University of California Irvine, USA; [b]Lawrence Berkeley National Laboratory, USA; [c]Nel Hydrogen, USA
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Summary. This study aims to understand the fundamental processes that affect catalyst utilization and gas transport through the porous media in polymer electrolyte water electrolyzers (PEWEs) to optimize interfaces between the catalyst layer, porous transport layer (PTL) and membrane by using imaging techniques, simulations and characterization.

Abstract. PEWEs is a promising technology to produce green hydrogen with high efficiencies at low temperature. The widespread deployment of this technology is stifled today by high catalyst cost, high catalyst loadings and material properties that affect the complex two-phase transport processes consequently resulting in lower voltage efficiency. Currently, two major types of PTLs of varying morphologies (sintered Ti and fiber Ti) are commercially available but the correlation of their bulk properties and the effects of catalyst distribution that affect the gas transport and the cell performance are still topics of dispute. This study aims to bridge the gap between the catalyst loadings and its effect on gas transport in two different types of commercially available PTLs (sintered Ti and fiber Ti). For a given catalyst loading, two different electrode configurations have been compared namely catalyst coated membrane (CCM) and gas diffusion electrode (GDE) up to current densities of 5 A cm^{-2}. In this study, we present detailed investigation of the effect of loadings on the performance of PEWEs with these two different electrode configurations. We used x-ray computed tomography (CT) to quantify the interfaces and observe oxygen transport in the channels. Furthermore, we used Lattice Boltzmann method (LBM) modeling to predict the oxygen transport pathways in the PTLs as influenced by the interfacial catalyst layer PTL contact. Finally, we address the question of how PTL morphologies can be tuned with respect to Ir loadings to utilize maximum gas transport pathways at high current densities.

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Large scale deployment of modular pressurised alkaline electrolysers

Kasper Therkildsen[1]

[1]Green Hydrogen Systems A/S, , Denmark

Plenary Session 2, Metals Hall, June 20, 2022, 10:15 AM - 12:15 PM

Large scale deployment of modular pressurised alkaline electrolysers

Kasper Tipsmark Therkildsen

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Corresponding author email: KTT@greenhydrogen.dk

Summary. Green Hydrogen Systems develops modular alkaline electrolyzers to accelerate the electrolyzer deployment to the multi-MW-range anticipated in the hydrogen strategies.

Abstract. Electrolysers is a novel component in the energy system and is expected to play a key role in the transition to a fossil free energy system.

Modularity is a key parameter is a key factor for the large scale deployment of electrolysis as envisioned in both the EU Hydrogen Strategy and national Hydrogen Strategies

This talk focuses on electrolysis, electrolysers and the development of a novel multi-MW-range alkaline electrolyser platform with factory assembled and pre-tested modules allowing rapid on-site installation in order to keep up with the pace needed to reach EU targets.

A multi-MW module will be demonstrated in a large scale industrial Power-to-X project capable of replicating across Europe with associated green growth and job creation benefits. Electricity can be supplied from both on-site renewables or grid connection and the utilisation of waste heat can also been utilised to increase the total energy efficiency. Electrolysis plants can also provide grid balancing services in order to reduce the cost of hydrogen.

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Progress in Power-to-X with Protonic-Ceramics

Ryan O'Hayre[1]

[1]*Colorado School of Mines, , United States*

Solid Oxide Electrolysis 2, Metals Hall, June 21, 2022, 4:00 PM - 5:30 PM

Progress in Power-to-X with Protonic-Ceramics

Ryan O'Hayre[a*], Neal Sullivan[b], Rob Braun[b], Bob Kee[b], Long Le[b], Carolina Herradon Hernandez[b], Huayang Zhu[b], Sandrine Ricote[b], Amogh Thatte[b], Jake Huang[a], Yewon Shin[a], Meagan Papac[a], Charlie Meisel[a], Youdong Kim[a], Michael Walkter[a], Steven Harvey[c], Andriy Zakutayev[c], Hossein Ghezel-Ayagh[d], Tony Wood[d], Michael Pastula[d], and Eric Tang[d]

[a] Department of Metallurgical and Materials Engineering, Colorado School of Mines, Golden, CO USA
[b] Department of Mechanical Engineering, Colorado School of Mines, Golden, CO. USA
[c] National Renewable Energy Laboratory, Golden, CO. USA
[d] Versa Power Systems/Fuel Cell Energy, Calgary, Canada/Danbury CT. USA
*Corresponding author, e-mail: rohayre@mines.edu

Summary. Proton conducting ceramic electrolyzers operate in a thermochemical "sweet spot" of 400-600 ^oC, thereby enabling a number of reversible "power-to-x" applications including reversible H_2 fuel cell/electrolysis cells, reversible NH_3 fuel cell/synthesis cells and reversible CH_4 fuel cells/synthesis cells. Are they ready for prime time? Learn more in this talk!

Abstract. Because they can enable proton-mediated electrochemistry under both dry and wet environments at moderate temperatures, protonic ceramic electrosynthesis cells provide unique opportunities to enhance or synergize a diverse range of complementary electrochemical and thermochemical processes. Because of this potential, significant efforts have been devoted to advancing a variety of "power-to-x" applications using these materials. Here, we will provide an overview of recent research efforts at the Colorado School of Mines focused on developing protonic ceramics for several electrolysis/electrosynthesis applications, including reversible protonic ceramic electrolyzers (RePCECs) and protonic-ceramic electrosynthesis devices where electrolysis and thermochemistry are coupled to directly produce valuable fuels such as NH_3, CH_4, and C2+ chemicals. In many applications, pressure is beneficial both for the thermodynamics of electrosynthesis as well as for the electrochemical cell performance, thus we will also present initial results in designing and operating PCECs at elevated pressures (up to ~20 bar). Finally, as protonic ceramics move closer to commercial application, we will share our perspective in advancing protonic ceramic cell technology from the small (<1 cm^2) laboratory button-cell scale to the large-area (81 cm^2) industrial manufacturing scale utilizing low-cost, volume-qualified processes with industrial partner Fuel Cell Energy/Versa Power Systems (FCE/VPS). We will review the progress and insights gained through these development activities, highlighting the potential benefits of protonic ceramics for electrosynthesis applications as well as areas where key questions and challenges remain to be addressed.

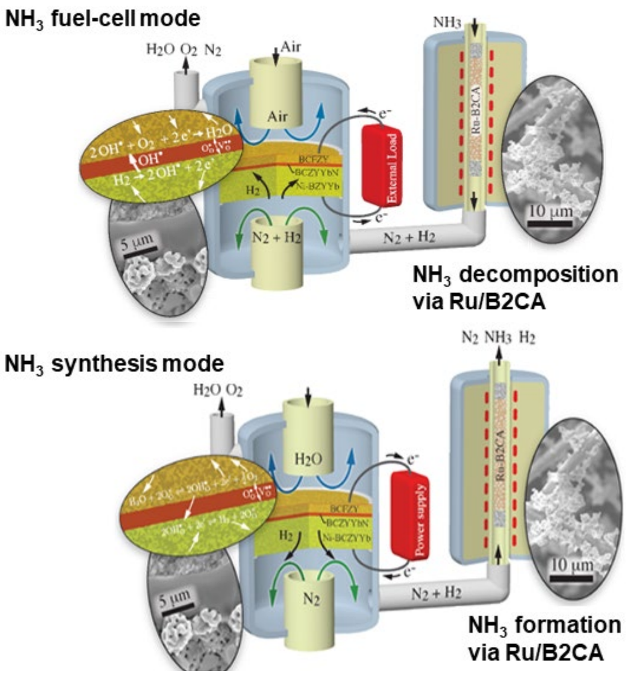

Figure 1. Schematic illustration of a two-stage electrochemical + thermochemical reactor design for a reversible proton-ceramic ammonia synthesis/fuel cell. Ammonia fuel cell mode operation is depicted on the left while ammonia synthesis mode operation is depicted on the right. Mode switching is accomplished by simply reversing the flow of gases and the cell polarization.

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Water-splitting on Pr2NiO4+6 electrodes with BaZr0.7Y0.3-yPryO3-6 overlayers in protonic-ceramic electrolysis cells

Ms. Mayuri Kushare[1]

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Summary: Efficient water-electrolysis at 500-700°C with protonic-ceramic electrolytes requires understanding the water-splitting mechanism on the positive electrode. Thin-film $Pr_2NiO_{4+\delta}$ (PNO) electrodes with and without $BaZr_{0.7}Y_{0.3-y}Pr_yO_{3-\delta}$ (BZYP) overlayers are studied by electrochemical characterization and *in operando* environmental X-ray photoelectron spectroscopy to understand the surface chemistry of water-splitting. Thin-film PNO electrodes with BZYP overlayers reduce the area-specific resistance of the PNO electrode by almost 50%.

Abstract: Protonic-ceramic materials such as $BaCe_{0.8-x}Zr_xY_{0.1}Yb_{0.1}O_{3-\delta}$ (BCZYYb) present a pathway for efficient water electrolysis between 500 and 700°C. The high protonic conductivity of the BCZYYb electrolytes in protonic-ceramic electrolysis cells (PCECs) can lower the operating temperature relative to traditional oxygen-ion conducting solid oxide electrolysis cells (SOECs) [1]. Understanding the mechanism of water-splitting on positive electrode (positrode) materials is crucial to reduce overpotentials associated with water-splitting kinetics and proton incorporation.

Several studies have demonstrated that Ruddlesenden-Popper oxides like $Pr_2NiO_{4+\delta}$ (PNO) as efficient water-splitting electrocatalysts [2–4]. PNO serves as a mixed electron/oxygen ion conductor that can incorporate protonic defects ($OH^{\bullet}$) into the crystal structure. This makes PNO a triple $H^+/O^{2-}/e^-$ conductor, which is essential for water-splitting. However, the electronic conductivity remains dominant in PNO compared to the proton and oxygen-ion conductivities. Low proton and oxygen-ion conductivities limit charge transfer reaction near three-phase boundaries, which increase positrode overpotentials. This study focuses on the deposition of conformal overlayers of mixed (H^+, e) conducting $BaZr_{0.7}Y_{0.3-y}Pr_yO_{3-\delta}$ (BZYP) overlayers onto the PNO positrode to enhance the surface conductivity and, thus, the active surface area. To explore the impact of BZYP overlayers on PNO electrodes, electrolyte-supported PCECs were developed using thin-film PNO positrodes with and without BZYP overlayers. Thin-film electrodes provide well-characterized geometries for electrochemical characterization and *in operando* environmental X-ray photoelectron spectroscopy (XPS) to understand surface chemistry of water-splitting on PNO positrodes.

Electrochemical characterization was performed between 550-700°C at constant positrode air flow with 37% steam content. It was found that the BZYP overlayers reduce the area-specific resistance of the PNO positrode by ≈50% over the full temperature range, with this decrease being predominantly on the ohmic resistance; this suggests that the BZYP increases the surface conductivity and the electrochemical active area of the thin-film electrode.

Environmental XPS at elevated temperatures up to 500°C in 1.5 mbar H_2O pressure on thin-film PNO (uncoated and BZYP-coated) electrodes were performed with and without positive bias in a single-chamber in a Scienta-Omicron HiPP Lab system. The Pr^{4+}/Pr^{3+} ratio for BZYP surface is higher compared to the PNO surface in biased cell condition by 35%. Tracking Pr^{4+}/Pr^{3+} and Ni^{3+}/Ni^{2+} ratios on the surface provides a measure for assessing surface kinetics as a function of temperatures and applied bias will be providing insights to validate water-splitting mechanisms on PNO and BZYP.

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X-ray photoelectron spectroscopy characterization of polymer electrolyte membrane fuel cell and water electrolyzers

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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

X-ray photoelectron spectroscopy characterization of polymer electrolyte membrane fuel cell and water electrolyzers

Jayson Foster[a], Sarah F. Zaccarine[a], Carlos Baez-Cotto[b], Sara Kim[a], Michael J. Dzara[a], Mariah Batool[c], Maxim Shepherd[a], Jasna Jankovic[c], Xiang Lyu[d], Alexey Serov[d], Scott Mauger[b], Michael Ulsh[b], Svitlana Pylypenko[a]

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Summary. Investigation of PEMFC and PEMWE CLs using *ex situ* and *in situ* X-ray Photoelectron Spectroscopy with focus on varied support materials, Pt catalyst loading, and ionomer loading for PEMFCs and CL homogeneity, ink aging, and catalyst-ionomer interface for PEMWEs.

Abstract. Proton exchange membrane fuel cells (PEMFCs) and proton exchange membrane water electrolyzers (PEMWEs) are advanced solutions for on-demand energy and hydrogen production respectively. To continue to move these technologies forward it is necessary to further understand the relationships between catalyst and catalyst layer chemistry, processing and fabrication parameters, and performance and durability characteristics. Understanding catalyst layer (CL) composition, structure, and morphology at all relevant scales is challenging for both devices. X-ray photoelectron spectroscopy (XPS) is a surface-sensitive technique that is capable of measuring chemistries of a sample's surface within 3-10 nm and revealing subtle interfacial interactions which enables better understanding of CL surfaces and interfaces. This study focuses on using XPS to probe the catalyst-ionomer interface for PEMFC and PEMWE CLs.

The PEMFC electrodes were prepared by a Mayer rod coating method such that the catalyst-ionomer interface was investigated as a function of support material in the catalyst, Pt loading on the support, and ionomer loading. Surface information was acquired using *ex situ* and *in situ* XPS using a recently developed approach that mitigates issues with degradation of ionomer possible from XPS conditions. This study emphasizes this technique's capabilities at probing ionomer interactions. Scanning transmission electron microscopy (STEM) catalysts was used to visualize distribution of Pt nanoparticles on support, relating catalyst and support properties to their surface behaviour while integrated with ionomer. Furthermore, scanning electron microscopy (SEM) and STEM scanning in combination with energy-dispersive X-ray spectroscopy (EDS) mapping of electrode cross-sections were utilized to visualize distribution of ionomer and Pt in the CL to further assist with interpretation of XPS data.

The PEMWE CLs were made with IrO_2 catalysts using Mayer rod coating method that enables scale up production of electrodes. Surface information was acquired using *ex situ and in situ* XPS using similar approach used for PEMFC CLSs. First, *ex situ* XPS was used to probe variations between different areas of the CLs to check reproducibility of coatings. Second, *ex situ* XPS was employed to investigate CLs made with inks aged for different amount of time, to investigate impact of ink aging on reproducibility of coatings. And finally, *in situ* XPS was used to probe CLs in the presence of humidification.

Results from these two studies emphasize the strength to using XPS for complex surfaces and interfaces in PEM catalyst layers to motivate further work with other catalysts and ionomers as well as other aspects related to ink and CL stability.

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Caustic Aqueous Phase Electrochemical Reforming of Ethanol for Compressed Hydrogen Production

Benjamin Kee[1]
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Poster Session 1, Green Center Lobby, June 20, 2022, 5:30 PM - 8:00 PM

Caustic Aqueous Phase Electrochemical Reforming of Ethanol for Compressed Hydrogen Production

Benjamin Kee[a], Osman Akpolat[b], Patrick Littlewood[b], Su Ha[a]

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Summary. The Caustic Aqueous Phase Electrochemical Reforming (CAPER) process can convert aqueous-phase ethanol to high-pressure and high-purity hydrogen (H_2) at lower temperatures and energy requirement than traditional methods, while using liquid-phase compression.

Abstract. Caustic Aqueous Phase Electrochemical Reforming (CAPER) of ethanol produces pure compressed hydrogen (H_2) at lower voltages, lower temperatures, and lower energy requirements than water electrolysis, while capturing all carbonaceous products in the liquid phase. Catalysts were screened in a batch reactor using Tafel analysis to determine exchange current densities. In the electrochemical flow reactor, H_2 was produced at 80 bar and voltages less than 0.5 V at 80 °C. The only gas-phase product detected is H_2 and any carbonaceous products are contained in the liquid phase. The H_2 produced on the cathode is measured at $97 \pm 6\%$ faradaic efficiency. Operating at high temperatures and smaller electrode separation distances increased the current density and thus the H_2 production rate. Lower heating value efficiency of the process is limited by conversion of ethanol on the anode. The CAPER process produces compressed H_2 at less than 20 kWh kg^{-1}, which is much lower than electrolysis systems that require upwards of 50 kWh kg^{-1}. Figure 1 illustrates the CAPER process, where ethanol is electrochemically converted into high pressure pure H_2.

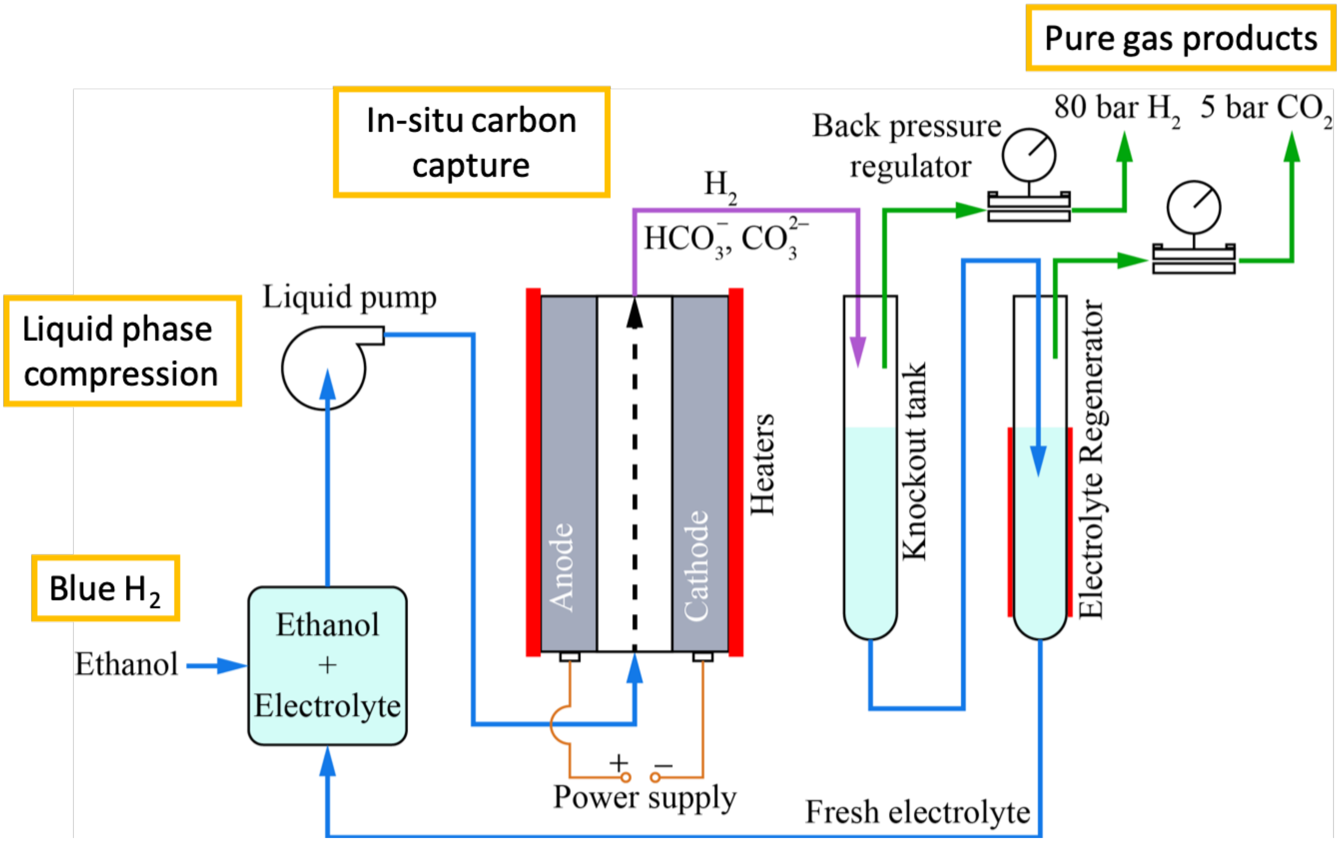

Figure 19: Illustration of the CAPER process

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Optimizing Component Interactions to Fabricate High Performance MEAs for Electrochemical Devices

Sadia Kabir[1], Kendra Kuhl[1]
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Poster Session 2, Green Center Lobby, June 21, 2022, 5:30 PM - 8:00 PM

Optimizing Component Interactions to Fabricate High Performance MEAs for Electrochemical Devices

Sadia Kabir and Kendra Kuhl[a]

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Summary. Nanoscale interactions between catalyst, ionomer and solvents can alter macroscopic properties of colloidal inks that are relevant for coating and MEA manufacturing processes. Optimizing these component interactions is crucial for improving particle dispersion, drying behaviour and stability of inks to fabricate high performance defect-free electrodes.

Abstract. The electrode layer is a critical component of low-temperature electrochemical devices such as PEM fuel cells and water or CO_2 electrolyzers, as it has a major impact on the device's efficiency, high current density performance and long-term durability. As such, the rational design and fabrication of electrode structures and interfaces with optimal component interactions, ionic and gas phase accessibility, as well as water management properties is crucial for advancing the performance and economic viability of these electrochemical devices.

Typically, membrane electrode assemblies for fuel cells and electrolyzers are manufactured using scalable methods such as blade coating, roll to roll, electrospinning or ultrasonic spray coating. These methods rely on homogenizing the catalysts, ionomers, solvents, and any other polymeric additives into a colloidal ink and depositing them onto a substrate. At the *microscopic* level, the combination of electrostatic repulsion and Van der Waals attraction between the individual constituents (solvent, catalyst, polymer) can alter the *macroscopic* properties (i.e. viscosity, surface tension, rheology) of the colloidal inks. These properties are relevant for coating and MEA manufacturing processes, as the net interparticle interaction potentials determine the tendency of particles to aggregate or disperse. Control over these ink properties is important for controlled deposition and electrode formation as changes in ink micro-structure can significantly impact electrode macro-structure and device-level performance.

This talk will highlight current R&D advancements in understanding of component interactions (i) for integrating high performance materials in electrodes for industrially relevant applications, ii) improving electrode structure to maximize active site utilization and iii) mitigating mass transport limitations at catalyst-ionomer interface. This presentation will also discuss approaches to improve particle dispersion, drying behaviour and stability of inks to approach uniform or defect-free electrode morphologies based on factors such as the solvent dielectric constants which determine the aggregate size of particles, and the relative volatilization rate of the solvent which dominate the final pore structure of the electrodes. This presentation will also highlight the importance of establishing structure-property-function correlations using both ex-situ microscopic characterization and in-situ electrochemical diagnostics in order to Identify MEA design parameters (additives, architecture, morphology) that promote gas diffusion, active site accessibility, charge transport and water management in fabricated layers and interfaces.

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Catalyst Development and Elecrode Fabrication for Low-Temperature Water Electrolyzer Operating with Anion Exchange Membrane

Dr. Piotr Zelenay[1], Dr. Luigi Osmieri[1], Dr. Yanghua He[1], Dr. Haoran Yu[2], Dr. David Cullen[2]
[1]Los Alamos National Laboratory, , Unied States, [2]Oak Ridge National Laboratory, , United States

Alkaline Electrolysis 1, Metals Hall, June 20, 2022, 3:40 PM - 5:30 PM

Catalyst Development and Electrode Fabrication for Low-Temperature Water Electrolyzer Operating with Anion Exchange Membrane

Luigi Osmieri[a], Yanghua He[a], Haoran Yu[b], David A. Cullen[b], Piotr Zelenay[a]

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Summary. Anion exchange membrane water electrolysis is a promising technology for the sustainable hydrogen production. We summarize our recent research progress in the development of high-performance electrocatalysts, fabrication of membrane-electrode assemblies, and electrolyzer testing under different operating conditions.

Abstract. Hydrogen is considered a promising energy source owing to its high energy density and CO_2-free emission. Anion exchange membrane-based low-temperature (< 100 °C) water electrolyzers (AEM-LTWEs) can compete with state-of-the-art proton exchange membrane (PEM) electrolysis systems to produce "green" hydrogen.[1, 2] AEM-LTWEs can potentially operate on pure water feed and use less expensive platinum group metal-free (PGM-free) electrocatalysts.[3] The key to realizing this technology is the development of PGM-free catalysts for hydrogen and oxygen evolution reactions, (HER and OER, respectively) in alkaline media, provided they can be successfully integrated into the electrodes and achieve satisfactory cell performance.[4, 5]

In this work, we investigated different classes of OER catalysts: commercial IrO_2 (a PGM OER benchmark), $La_xSr_{1-x}CoO_{3-\delta}$ oxides, Ni-Fe nanofoam oxides, Ni-Fe aerogel-derived oxides, and MOF-derived Co oxides; and HER catalysts: commercial PtRu/C (a PGM HER benchmark) and aerogel NiMo/C catalyst in both three-electrode electrochemical system and AEM water electrolyzer. To enhance cell performance, effects of the membrane-electrode assembly (MEA) fabrication, *e.g.*, ink deposition method, amount of ionomer, incorporation of a binding agent, and the type of anode porous transport layer on performance were examined. AEM-LTWEs were operated in three modes: on pure-water feed, using 0.1 M KOH electrolyte, and 1 wt% K_2CO_3 electrolyte. Catalysts and electrodes before and after testing were characterized by XRD, SEM, EDS, and XPS. The results suggest that the primary factor limiting the AEM-LTWE performance may be effective transport of OH^- ions within the catalyst layer, especially in the pure water-fed operation mode.

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Electrode and MEA Processing Methods for AEM Water Electrolysis

Derek Strasser[1], Max Pupucevski[1], Natalia Macauley[1], Hui Xu[1]
[1]*Giner Inc., , United States*

Alkaline Electrolysis 2, Metals Hall, June 21, 2022, 1:30 PM - 3:20 PM

Electrode and MEA Processing Methods for AEM Water Electrolysis

Derek Strasser[a], Max Pupucevski[a], Natalia Macauley[a], Hui Xu[a]
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Summary. Catalyst coated substrate and catalyst coated membranes were designed and fabricated using PGM and PGM-free oxygen evolution reaction and PGM hydrogen evolution reaction catalysts. The MEAs were manufactured with commercial ionomers to evaluate the ionomer's processability, performance, and durability in full cell electrolyzers with or without supporting electrolyte.

Abstract. Interest in hydrogen production has grown globally due to its clean and flexible energy carrier characteristics, especially when coupled with energy production from renewable sources. Currently most hydrogen is generated from fossil fuels by steam reforming of methane, which releases anthropogenic greenhouse gases. An alternative approach to hydrogen production is water electrolysis and can produce green hydrogen when integrated with renewable electricity sources. Significant progress has been made in alkaline liquid water electrolyzers (ALWE) and proton exchange membrane water electrolyzers (PEMWE). ALWE is a mature technology, where caustic KOH solution is used as the electrolyte and cost-effective nickel catalysts are used in the electrodes. In addition, the gaps between electrodes and diaphragm result in high ohmic losses limiting the achievable current densities, gas crossover eliminates high pressure operation, and poor flexibility toward load changes significantly limit their potential applications. PEMWE technology is very attractive for its zero-emission hydrogen production but uses expensive and scarce catalysts, Ir and Pt, and perfluorinated cation exchange membranes that are produced from perfluoroalkyl substances, a known environmental hazard. It is therefore crucial to develop alternative solutions to the current ALWE and PEMWE technology to produce green hydrogen at scale. Anion exchange membrane water electrolyzers (AEMWE) have the potential to be the low-cost alternative producer of green hydrogen. There are several factors that need to be considered in an AEMWE including temperature, membrane, cell design, feedstock, and catalysts. For AEMWE to compete with PEMWE, high operating current densities and highly active non-PGM catalysts are required to overcome the substantial overpotentials necessary for the kinetically sluggish oxygen evolution reaction (OER). Furthermore, catalyst ink processing, MEA design and fabrication are critical steps in reducing interfacial contact resistance between the catalyst layers, membrane, and porous transport layers and requires additional investigation.

This work aims to explore cost-effective non-PGM catalysts for the oxygen evolution reaction (OER) in AEMWE, electrode fabrication methods, and electrode/membrane interface enhancement methods to lead to highly active and durable AEMWE MEAs. Catalyst coated membrane (CCM) and catalyst coated substrate (CCS) approaches were baselined with PGM catalysts and commercial membranes/ionomers. The performance of NiFe-based catalysts grown directly on nickel foam were then compared to the PGM baseline and commercially available $NiFe_2O_4$ nanopowder electrodes using ionomers from Versogen, Dioxide Materials, Ionomr Innovations, and Xergy. Catalysts were tested in 5 cm^2 electrolyzers cells with a Versogen membrane and a PtRu/C hydrogen evolution reaction (HER) catalyst to minimize the HER impact. Achieving commercially a feasible current density relies on the synergy between the catalysts, electrode design, membrane, ionomer, and conductive substrates. Here, we demonstrated that these NiFe-based catalysts enabled

current densities of 2 A/cm^2 operating under 2 V for over 100 h in a dilute alkaline electrolyte. Much work remains to further improve the MEA design for high performance and long-term durability of an AEMWE.

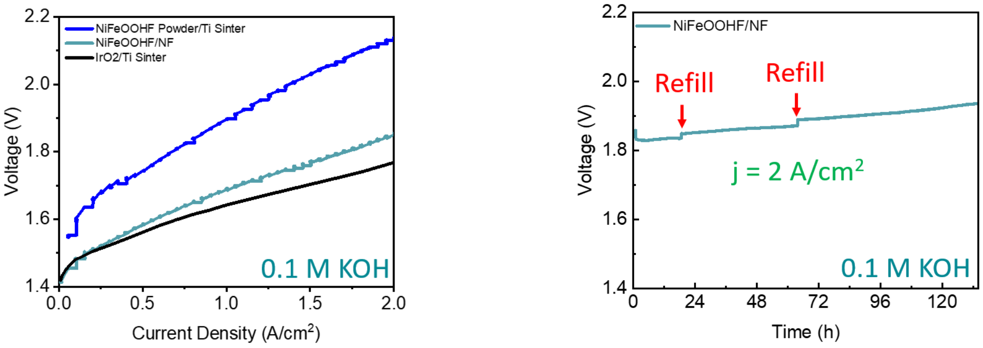

Figure 20. Polarization curves of NiFe-based catalyst powder on platinized Ti sinter, NiFe-based catalyst grown on Ni foam, baseline IrO_2 on Ti sinter (left) and durability data for NiFeOOHF/NF cell in 0.1 M KOH (right).