4th International Conference on Electrolysis

27th August – 1st September, Sun City, South Africa 2023

Scientific editors:	Dmitri Bessarabov Marcelo Carmo Marina Olga Bryan Pivovar Jens Oluf Jensen Tom Smolinka
Production editor:	Louise Botha
Coordinator:	Kyle Meerholz

Book of Abstracts

North-West University

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Organised on behalf of the international science committee by the local organising committee, HySA-Infrastructure, North-West University, Faculty of Engineering, Private Bag X6001, Potchefstroom 2520, South Africa

This Book of Abstracts contains submissions that have been carefully selected and rigorously peer reviewed by the members of the scientific committee. It will serve as a valuable resource for students, researchers, and industry professionals. This Book of Abstracts features cutting-edge research on water electrolysis, providing readers with insights into the most recent advancements in this field.

First published in 2023 for the international conference on Electrolysis (ICE) by the Scientific Committee.

Subject Heading: ICE, Abstracts

Scientific editors: Dmitri Bessarabov, Marcelo Carmo, Marina Olga, Bryan Pivovar, Jens Oluf Jensen and Tom Smolinka

Production editor and Coordinator: Louise Botha and Kyle Meerholz

Preface

We are delighted to present to you the Abstract Book of the 4th International Conference on Electrolysis, ICE2023, held at Sun City, South Africa from 27th August to 1st September, 2023. This book contains the abstracts of papers and posters of all the presenters who participated in the conference. These abstracts were meticulously selected from many high-quality abstracts that were submitted.

The 4th International Conference on Electrolysis is part of a series of conferences organised by the scientific committee. Previous Electrolysis conferences were successfully held in Copenhagen, Denmark in 2017, Loen, Norway in 2019, and Colorado School of Mines in Golden, Colorado, USA in 2022. These conferences provided researchers with a platform to exchange ideas and discuss the current state and prospects of electrolysis.

The preparation and organisation of such a meeting require extensive administration, and we extend our heartfelt thanks to the individuals involved. The authors express their gratitude to Mr. Kyle Meerholz, Mr. Geoffrey Bantom, Mr Tony Morgado and Dr Louise Botha for their dedicated efforts, who contributed to the success of this event. Special recognition goes to Dr Louise Botha for the conscientious preparation of this abstract book.

We sincerely thank all the Sponsors and Partners: DSI (Department of Science and Innovation). Shell, Sasol, Implats, AGFA, Bekaert, Bosch, Greenlight innovation, Air liquid, Fumatech, Toyota, NRF (National Research Foundation), Creamer media and Royal Bafokeng platinum, for their contributions that made possible various social events.

Finally, we thank all the contributors for their enthusiastic submission of abstracts and preparation of papers. The quality of research described in this book is truly inspiring and promises stimulating discussions during the conference.

August 2023.

Dmitri Bessarabov

Chair of ICE 2023

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Table of Contents

Welcome to the 4th International Conference on Electrolysis (ICE 2023)

The research in all aspects of electrolysis for energy conversion and storage is growing rapidly. Demonstration and commercial installation of electrolysers coupled with renewable energy sources have grown significantly recently.

There is an increased recognition and awareness that the conversion of electrical energy to storable chemicals and fuels is an inevitable part of the green transition from a fossil based to a sustainable energy system.

Hydrogen technologies have a special meaning for South Africa. Most of the PGMs that are needed for the related technologies are mined in South Africa. South Africa also offers excellent sources of renewable energy. Electrolytic green hydrogen generation is also one of the cornerstones of the activities mentioned in the Hydrogen Society Roadmap (HSRM) for South Africa.

The entire ICE conferences are devoted to the topic of electrolysis for energy conversion and are very focused. ICE 2023 is the fourth biannual conference of its kind. We hope it will be a thriving conference on electrolysis for energy conversion.

On behalf of the scientific and organising committees, welcome to ICE 2023 in Sun City, South Africa.

We wish you all an interesting and pleasant meeting, filled with fruitful interactions and enlightening presentations.

Dmitri Bessarabov

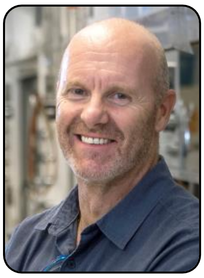
Chair of ICE 2023

Invited Speakers

Dr. Felix Büchi

Paul Scherrer Institute, Head Electrochemistry Laboratory a.i and Fuel Cell Systems and Diagnostics Group.

Prof. Steven Holdcroft



Professor, Canada Research Chair (Tier 1), Electrochemical Materials.

Prof. Hiroshi Ito

Research Institute for Energy Conservation / National Institute of Advanced Industrial Science and Technology (AIST).

Dr. Rangachary Mukundan

Senior Scientist in the Energy Technology area at the Lawrence Berkeley National Laboratory.

Dr. Anders Ødegård

Senior Project Manager, SINTEF.

Dr. Andrew Park

R&D Principal Engineer at The Chemours Company.

Prof. Jennifer Peron

Associate Professor at Université Paris Cité, France.

Dr. Hui Xu

Envision Energy, CTO of Green Hydrogen Head, H_2 Center of Excellence.

Dr. Piotr Zelenay

Professor of Chemistry, Materials Physics and Applications Division, Los Alamos National Laboratory.

Prof. Ryan O'Hayre

Professor of Metallurgical and Materials Engineering, Colorado School of Mines.

Prof. Avner Rothschild

Professor of Materials Science and Engineering, Technion – Israel Institute of Technology.

Dr. Ir. Charudatta Patil

Shell Global Solutions International B.V. Manager Green Hydrogen.

Prof. John Weidner

Professor of Chemical Engineering and Dean of the College of Engineering and Applied Science at the University of Cincinnati.

Dr. Frank Allebrod

Vice President R&D Stack. H-TEC SYSTEMS GmbH.

Dr. Julie Mougin

Deputy Director for Hydrogen Technologies of Liten Institute.

Dr. David Peterson

Hydrogen Production Program Manager at Hydrogen and Fuel Cells Technologies Office within the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy.

Prof. Simon Thiele

Professorship for Electrocatalytic Interface Engineering, Helmholtz Institute Erlangen-Nürnberg for Renewable Energy (HI ERN).

Dr Thembakazi Mali

Senior Vice President for Research and Technology at Sasol.

Dr. Cosmas Chiteme

Director: Hydrogen and Energy at Department of Science and Innovation.

Conference proceedings

Arrival at Sun City

Upon arrival at the conference venue on Sunday, the 27th, all conference attendees are encouraged to take some time to relax until the registration opens at 10:00 AM and continues until 1:00 PM. A delicious lunch will be served at 1:00 p.m., followed by a series of workshop events that will run from 2:00 p.m. to 5:30 p.m. Coffee breaks will be provided at designated times throughout the workshop events, allowing participants to recharge and network. To conclude the evening, a delightful cocktail dinner will be served from 7:00 PM until 10:00 PM.

Registration Desk

The Registration Desk will be available for assistance and inquiries throughout the conference.

Gala Dinner

A gala dinner is a formal event that will take place on the fourth day of the conference, which is on the 30th, from 8:00 p.m. to 11:00 p.m. The venue for this special occasion is the Kings Ballroom, an exceptional ambiance and captivating setting. It promises to be a delightful evening for all attendees.

Poster sessions

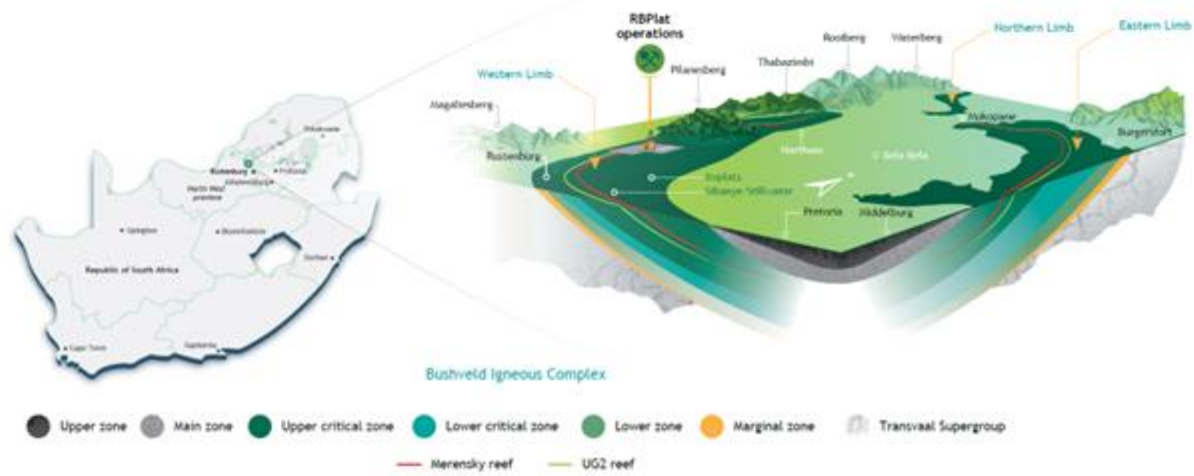
The posters will be on display starting from Tuesday morning, the 29th, allowing attendees ample time to view them at their convenience. Additionally, the poster presenters will be present during the designated poster session on the 29th, from 5:00 PM to 7:30 PM, to address any inquiries or discussions related to their research.

Satellite Events

Industrial Tour – Royal Bafokeng Platinum

Royal Bafokeng Platinum (RBPLAT) is a mid-tier platinum group metals (PGMs) producer that not only produces PGMs (Pt, Ir, Os, Pd, Rh, and Ru) but also base metals (Cu, Ni) and other metals (Au, Ag, Cr, Co).

RBPLAT has a 100% attributable interest in the Mineral Resources and Mineral Reserves, consisting of the Merensky and UG2 reefs underlying the mining right areas of the Bafokeng Rasimone Platinum Mine, Styldrift Mine, and Maseve Mine. The two primary and economically advantageous platinum group metal stratigraphic horizons are the Merensky Reef and the UG2 Reef. These reef horizons are rich in base metal sulfides and platinum group metals, with the Merensky reef serving as the world's most important platinum-producing layer of the world-famous Bushveld Igneous Complex.



Important Information:

- Limited to 50 participants.
- **Starting time:** 7 am
- **Place:** Styldrift
- **Clothing:** PPE will be provided
- **Personal requirement:** Participants should be physically fit to go unassisted underground and be able to walk for several kilometers

Itinerary:

- 75-minute presentation including geology, mining, and concentrator.
- 30-minute change into U/G clothing.
- U/G: 08:45 – 11:00.
- Change: 11:00 – 11:30.
- 30 minutes to the Maseve Plant.
- Plant presentation and lunch: 12:00 – 12:30.
- 2 hours at the Maseve plant

ROYAL BAFOKENG PLATINUM

Game drive – Pilanesberg National Park

The Pilanesberg Game Reserve's 57,000 hectares are home to nearly all of Southern Africa's game species. Pilanesberg, located on the border between the Kalahari and the Lowveld, has a diverse range of fauna and flora. An open safari vehicle game drive in Pilanesberg allows for close encounters with lions, leopards, elephants, rhinos, and buffalo. The Big 5 are joined by a plethora of game, including rare species like wild dogs and cheetahs. More than 300 bird species keep avid birders entertained.

Typically, game drives are conducted in the early mornings or late afternoons. Wildlife is more active during the cooler hours of the day. Predators, in particular, prefer to hunt at dusk or dawn. The game drives are led by knowledgeable rangers and game trackers. The rangers are always eager to share their environmental knowledge and will gladly assist you with your wildlife photography. Open safari vehicles provide excellent views while ensuring the safety of the passengers at all times.

Important Information:

- **Starting time**: 8:00
- **Duration**: 3 hours
- **Depart from**: Cabana Hotel (Sun City)
- **Vehicles**: 25 Seater open safari vehicle
- **Clothing**: Warm clothing is advised

Mankwe GAMETRACKERS

Conference at a glance

Monday ▪ August 28		**Tuesday ▪ August 29**	
06:30	Breakfast	06:30	Breakfast
08:00	Welcome & Opening Session 1	08:20	Welcome Session 6
10:05	Coffee Break	10:05	Coffee Break
10:25	Session 2	10:25	Session 7
11:40	Coffee Break	11:30	Coffee Break
12:00	Session 3A & 3B Parallel sessions	12:00	Session 8
13:00	Lunch	13:00	Lunch
14:00	Session 4A & 4B Parallel sessions	14:00	Session 9
15:20	Coffee Break	15:25	Coffee Break
15:40	Session 5A & 5B Parallel sessions	15:45	Session 10
18:00	Dinner Botsalanong Boma	17:00	Poster session
		20:00	Dinner Valley of Waves

Wednesday ▪ August 30		**Thursday ▪ August 31**	
06:30	Breakfast	06:30	Breakfast
07:00	Satellite events Industrial Tour (07:00-14:00)) Game drive (08:00-11:00)	08:20	Welcome Session 12
		10:05	Coffee Break
		10:25	Session 13
		11:30	Coffee Break
		12:00	Session 14
13:00	Lunch	13:00	Lunch
		14:00	Session 15
15:20	Coffee Break	15:25	Coffee Break
15:40	Session 11	15:45	Session 16
17:00		16:40	Closing remarks
18:00		18:00	Cocktail event
20:00	Gala Dinner		

Conference Agenda

Sunday 27th August		
	Registrations Open (10:00 -13:00)	
Lunch (13:00 - 14:00)		
Conference Workshop (14:00-17:30)		
14:00	Mr. D. Nkala	Low Carbon Energy Solutions at Sasol
14:20	Mr. N. Lecomte	HDF activity in Southern Africa
14:40	Prof. J. de Kock	Load-shedding – Can SA be saved?
Coffee Break (15:20-15:40)		
15:40	Prof. K. Inazu and Prof. Ken-ichi Aika	SA-Japan Green Ammonia and Hydrogen
16:00	Dr M. Fontain	Necessary technologies for enabling cost-effective and large-scale H_2 and NH_3 production technologies: an introduction to HYDROGENi FME
16:20	Prof. P. Modisha	Just transition to green hydrogen: A case of South Africa
16:40	Mr. H. Makgato	Development of a green hydrogen economy in South Africa: Support from GIZ
Coffee Break (17:00-17:20)		
Cocktail Dinner (19:00-22:00)		
Monday 28th August		
Breakfast (06:30-08:00)		
Session 1 (08:00-10:05) **Session Chair: Bryan Piovar**		
	Prof. D. Bessarabov	Opening/Welcome from Conference Chair
	Prof. J. Mphahlele	Message from NWU Deputy Vice Chancellor Research and Innovation
	Dr C. Chiteme	Welcoming address Department of Science and Innovation (DSI)
8:50	Invited Talk: Dr. F. Büchi	On transport limitations in PEWE catalyst layers
9:15	Invited Talk: Dr. D. Peterson	Overview of U.S. Department of Energy Hydrogen Program and Electrolyzer Activities
9:40	Invited Talk: Dr. J. Mougin	Recent Highlights on Solid Oxide Electrolysis (SOE) Technology at Cells, Stacks and Modules Scale
Coffee Break (10:05-10:25)		
Session 2 (10:25-12:00) **Session Chair: Marcelo Carmo**		
10:25	Invited Talk: Dr. H. Ito	Water Transport though Membranes during Anion Exchange Membrane Water Electrolysis
10:50	Invited Talk: Dr. F. Allebrod	Challenges in upscaling PEM Electrolysis Systems
11:15	Invited Talk: Dr. J. Peron	Hierarchically porous iridium-based electrocatalysts: from fundamental studies to application in PEM water electrolyzers
Coffee Break (11:40-12:00)		

Parallel Session 3A (12:00-13:00) **Session Chair: Dr Krzysztof Lewinski**		
12:00	Dr. C. Zalitis	Perspectives on Current and Future Iridium Demand and Iridium Oxide Catalysts for PEM Water Electrolysis
12:20	Dr Z. Dehaney-Steven	Development of OER catalyst testing for PEMWE from a manufacturer's perspective
12:40	Dr. M.Suermann	PEM water electrolysis development needs – from an industry perspective
Session 3B (12:00-13:00) **Session Chair: Marina Olga & John Irvine**		
12:00	Dr M. Olga	Investigating Durability of Solid Oxide Electrolysis Cells
12:20	Mr. M. Wilson	A biogas to fuels system integrating solid oxide electrolysis of bio-CO2 and biomethane reforming with Fischer-Tropsch synthesis
12:40	Mr. M. Gross	Characterization of pressurized steam electrolysis in a 10-layer SOC stack with CO2 purging on the oxygen electrode
Lunch (13:00-14:00)		
Session 4A (14:00-15:40) **Session Chair: Tom Smolinka**		
14:00	Ms. M Rogler	How anodic porous transport layer design enables the use of low Iridium loadings in PEM water electrolysis
14:20	Dr. M. de Groot	The potential of coupling electrolyzer models to rectifiers models
14:40	Mr. J. Horstmann de la Viña	Pushing the limits of screen printing towards low iridium loadings of catalyst layers for PEM electrolysis
15:00	Prof. E. Gyenge	Advances in Bifunctional Oxygen Reduction/Evolution Reaction Electrodes
Session 4B (14:00-15:40) **Session Chair: Dr Julie Mougin**		
14:00	Dr. S. Barnett	Reversible Operation of Electrolyte-Supported Solid Oxide Cells
14:20	Dr. M. Fontaine	Proton ceramic electrolysers and reversible operation: new insights into their performance and durability in pressurized conditions
14:40	Dr X. Cui	Investigation on AC:DC dynamic operations for solid oxide electrolysis cells
15:00	Mr. F. Rocha	PEM-like alkaline water electrolysis using flow-engineered 3-D electrodes
Coffee Break (15:20-15:40)		
Session 5A (15:40-16:40) **Session Chair: Magnus Thomassen**		
15:40	Mr. C.C. Weber	Novel microporous layers for PEM electrolysis with low iridium loadings and thin membranes
16:00	Ms. L.V. Buehre	Exploring Two Reference Electrode Setups in PEMWE: Experimental Investigations and Findings
16:20	Dr. S.M. Skaftun	Degradation of Iridium Oxide Anodes During Oxygen Evolution in Sulfuric Acid
Session 5B (15:40-16:40) **Session Chair: Jens Oluf Jensen**		
15:40	Dr. M. Demnitz	Effect of Fe doped electrolyte on advanced alkaline water electrolysis
16:00	Mr. T.Haegens	Large scale Zirfon production to meet REPowerEU ambitious hydrogen plan - *Presented on behalf of Ms. E. Dom*
16:20	Dr. B. Koyuturk	Effect of Hydroxide Concentration on the Activity of NiFe-based Anodes in Anion Exchange Membrane Water Electrolysis

Dinner: Botsalanong Boma (18:00-22:00)		
Tuesday 29th August		
Breakfast (06:30-08:00)		
Session 6 (08:20-10:05) **Session Chair: Dr Rangachary Mukundan**		
8:20	Dr T. Mali	Welcoming address: Sasol
8:50	Invited Talk: Dr. R. Mukundan	Durability of polymer electrolyte membrane water electrolyzers
9:15	Invited Talk: Prof. J. Weidner	Hydrogen Production in a Hybrid-Sulfur Process
9:40	Invited Talk: Dr. K.Sundseth	REFHYNE - From 10 to 100 MW PEM electrolysers *Presented on behalf of Dr. A. Ødegård*
Coffee Break (10:05-11:25)		
Session 7 (10:25-12:00) **Session Chair: Dr Felix Büchi**		
10:25	Invited Talk: Prof. R. O'Hayre	Electrochemistry Meets Big Data: Rapid Acquisition and Analysis of >20,000
10:50	Dr. C. Klose	All-hydrocarbon PEM water electrolyzers: An engineering perspective
11:10	Ms. S.C. Zerressen	Extraction of performance data from dynamic operating profiles of PEM water electrolysis cells
Coffee Break (11:30-11:50)		
Session 8 (12:00-13:00) **Session Chair: Prof Hiroshi Ito**		
11:50	Invited Talk: Dr. A. Park	Performance and Durability of Thin, Reinforced Membranes for PEM Water Electrolyzers
12:15	Mr. T. Krenz	Improved Current Interrupt: An Enhanced Interpretation for PEMWE Cell Characterization
12:35	Dr. P. Trinke	Overview and new Insights on Recombination Layers for PEM Water Electrolysis
Lunch (13:00-14:00)		
Session 9 (14:00-15:40) **Session Chair: Dr Piotr Zelenay**		
14:00	Dr. N. Bogolowski	Influence of Fe/Co/Cr-Modification on Raney-Nickel Activity and Stability as Oxygen Electrode Catalyst in Alkaline Water Electrolysis
14:25	Mr. R. Lira Garcia Barros	Let's operate it flexibly: evaluating H2 crossover in zero-gap alkaline water electrolysis
14:45	Dr. P. Walter	Thrifting of Iridium: A Crucial Task for "Hyperscaling" PEM Electrolysis
15:05	Mr. N. Hensle	A segmented along the channel PEM water electrolysis cell for the operation at high current densities
Coffee Break (15:25-15:45)		
Session 10 (15:45-17:10) **Session Chair: Prof Avner Rothschild**		
15:45	Mr. N. Guruprasad	The Power of Reference Electrodes in AEM Electrolysis
16:05	Mr. D.L. Martinho	A Three-Dimensional, Multiphysics Model of An Alkaline Electrolyzer
16:25	Mr. V. Wilke	Increasing performance and lifetime of anion exchange membrane water electrolysers
Poster Session (17:00-19:30)		
Dinner: Valley of Waves (20:00-23:00)		

Wednesday 30th August

Industrial Tour: Royal Bafokeng Mine (07:00-14:00)		Game Drive: Pilanesburg National Park (08:00-11:00)	
7:00	Arrival at Styldrift	6:30	Breakfast
	Details to be confirmed	8:00	Game drive
		13:00	Lunch

Coffee Break (15:20-15:40)

Session 11 (15:40-17:05)

Session Chair: Dr Frank Allebrod

15:40	Ms. K.J. Ferner	Analysis of morphological and transport properties of IrO_2 anode catalyst layers for PEM electrolysis using high-resolution imaging
16:05	Mr. J.P. Woelke	Investigating the Potential of a Machine Learning-based Approach for Degradation Modelling in Proton Exchange Membrane (PEM) Water Electrolysis
16:25	Mr. P. Quarz	Advances in processing of catalyst coated membranes (CCM) for PEM electrolysis

Gala Dinner: Kings Ballroom (20:00-23:00)

Thursday 31st August

Breakfast (06:30-08:00)

Session 12 (08:20-10:05)

Session Chair: Dr Andrew Park

8:20	Welcome	Welcoming address: Shell – Dr Jeff Martin
8:50	Invited Talk: Prof. A. Rothschild	Decoupled Water Splitting: Reshaping Water Electrolysis
9:15	Invited Talk: Prof. S. Thiele	Where do you go to my lovely? – on future solid polymer electrolyte water electrolysis
9:40	Invited Talk: Dr. H. Xu	AEM water electrolysis: learning and evolution from alkaline water electrolysis

Coffee Break (10:05-10:25)

Session 13 (10:25-12:00)

Session Chair: Prof Ryan O'Hayre

10:25	Dr J.F. Drillet	Main Catalyst Degradation Mechanisms in AEL, PEMEL and HTEL Electrolyzers
10:50	Dr. T. Rauscher	Efficient alkaline electrolysis with porous 3D electrodes - Influence of the electrode structure on the cell efficiency
11:10	Prof. J.O. Jensen	Development of alkaline membranes at DTU Energy

Coffee Break (11:30-11:50)

Session 14 (12:00-13:00)

Session Chair: Jens Oluf Jensen

11:50	Invited Talk: Dr. P. Zelenay	Platinum Group Metal-free Electrocatalysts for Oxygen Evolution Reaction in Alkaline Media by Combined Experimental and Modeling Approach
12:15	Mr. C. Chatzichristodoulou	Integration of Reference Electrodes in Zero-Gap Alkaline Electrolysis Cells for the Deconvolution of Reaction Overpotentials and Ionic Transport Losses Across the Anode, Cathode, and Separator
12:35	Prof T. Turek	"Pilot-scale testing of a novel alkaline water electrolysis stack "

Lunch (13:00-14:00)

14:00-15:40 Session 15: **Session Chair: Prof Jennifer Peron**		
14:00	Dr. T. Wagner	Contact Resistance (Rc) measurement methods for PEM Water Electrolyser Bipolar plates
14:25	Mr. Z. Zhang	Towards next-generation catalyst coated membranes for polymer electrolyte water electrolyzers
14:45	Dr. K. Witte-Bodnar	Mapping of conductance and electric defects at PEM MEAs using lock-in thermography and microstructural analysis of degradation effects *– presented on behalf of Dr. V. Naumann*
15:05	Ms. Z.S.H.S Rajan	Metal-Organic Chemical Deposition as a Tool for Establishing a Fundamental Understanding Towards the Electrocatalysis of Oxide-Supported Ir-Based Materials for the Oxygen Evolution Reaction
Coffee Break (15:25-15:45)		
Session 16 (15:45-17:10) **Session Chair: Prof John Weidner**		
15:45	Mr F. Pascher	Transfer of Wind Data to Electrolyzer Test Stand
16:10	Ms. M. Milosevic	On the quantification of Ir dissolution in proton exchange membrane water electrolyzers
16:30	Prof D. Bessarabov	Water Electrolysis Research and Development by HySA Infrastructure CoC
16:50	Closing Remarks	
Cocktail Event (18:00-23:00)		
Friday 1st September		
Breakfast (06:30-08:00)		
	Check out of Sun City (08:00-11:00)	

Conference Workshop

Sunday 27th August

Lunch (13:00 - 14:00)

Conference Workshop (14:00-17:30)


Mr. D. Nkala

Low Carbon Energy Solutions at Sasol


Mr Nicolas Lecomte

HDF activity in Southern Africa

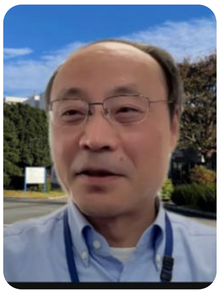

Prof. J. de Kock

Load-shedding – Can SA be saved?

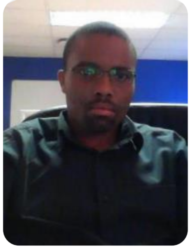
Coffee Break (15:20-15:40)


Prof. Ken-ichi Aika

SA-Japan Green Ammonia and Hydrogen


Prof. Koji Inazu

SA-Japan Green Ammonia and Hydrogen

 Dr M. Fontain	**Necessary technologies for enabling cost-effective and large-scale H_2 and NH_3 production technologies: an introduction to HYDROGENi FME**
 Prof Phillimon Modisha	**Just transition to green hydrogen: A case of South Africa**
 Mr Hector Makgato	**Development of a green hydrogen economy in South Africa: Support from GIZ**

Coffee Break (17:00-17:20)

Refer to the Abstracts section for content on these workshops.

Conference Venue Information

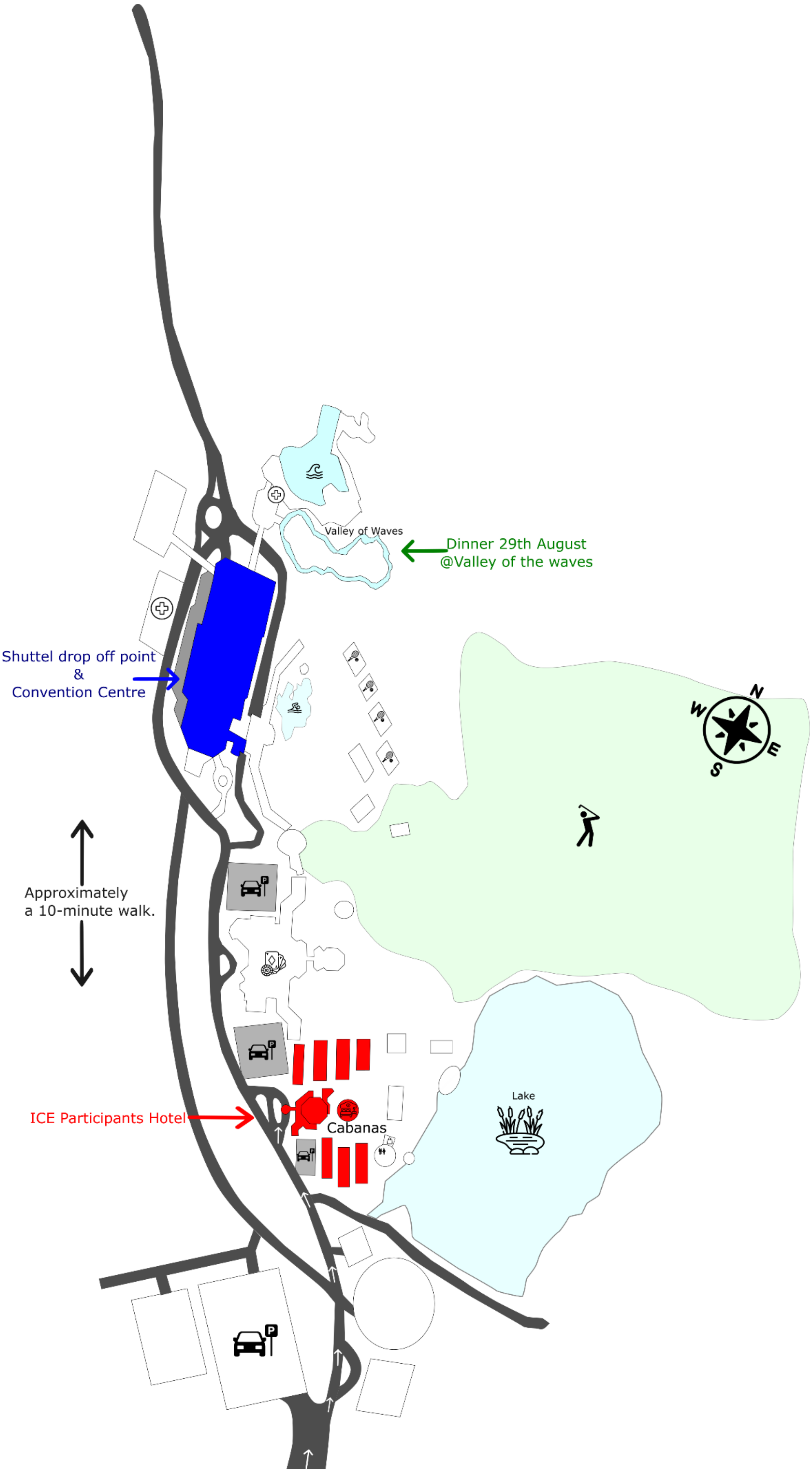
At the edge of the Gary Player Country Club, this high-end resort is 4 km from the southern entrance to Pilanesberg National Park. Unique accommodations are set in different locations and include views of the resort. All come with tea and coffeemaking equipment and minibars. They also have work desks, as well as free Wi-Fi and flat-screen TVs. Free breakfast is served in the poolside restaurant, and other restaurants in the resort feature Asian, Indian, and South African cuisine. There is a café, a cocktail bar and a poolside bar. Activities include 2 water parks, tennis, squash, and golf, plus outdoor pools, a casino, shops, and a spa.

Conference delegates will stay at the Cabanas, which is indicated on the map included in this abstract book. For those who wish to drive, a shuttle service will be provided to pick up and drop off delegates at the convention centre. Alternatively, the convention centre is within walking distance (approximately 10 minutes) from the Cabanas.

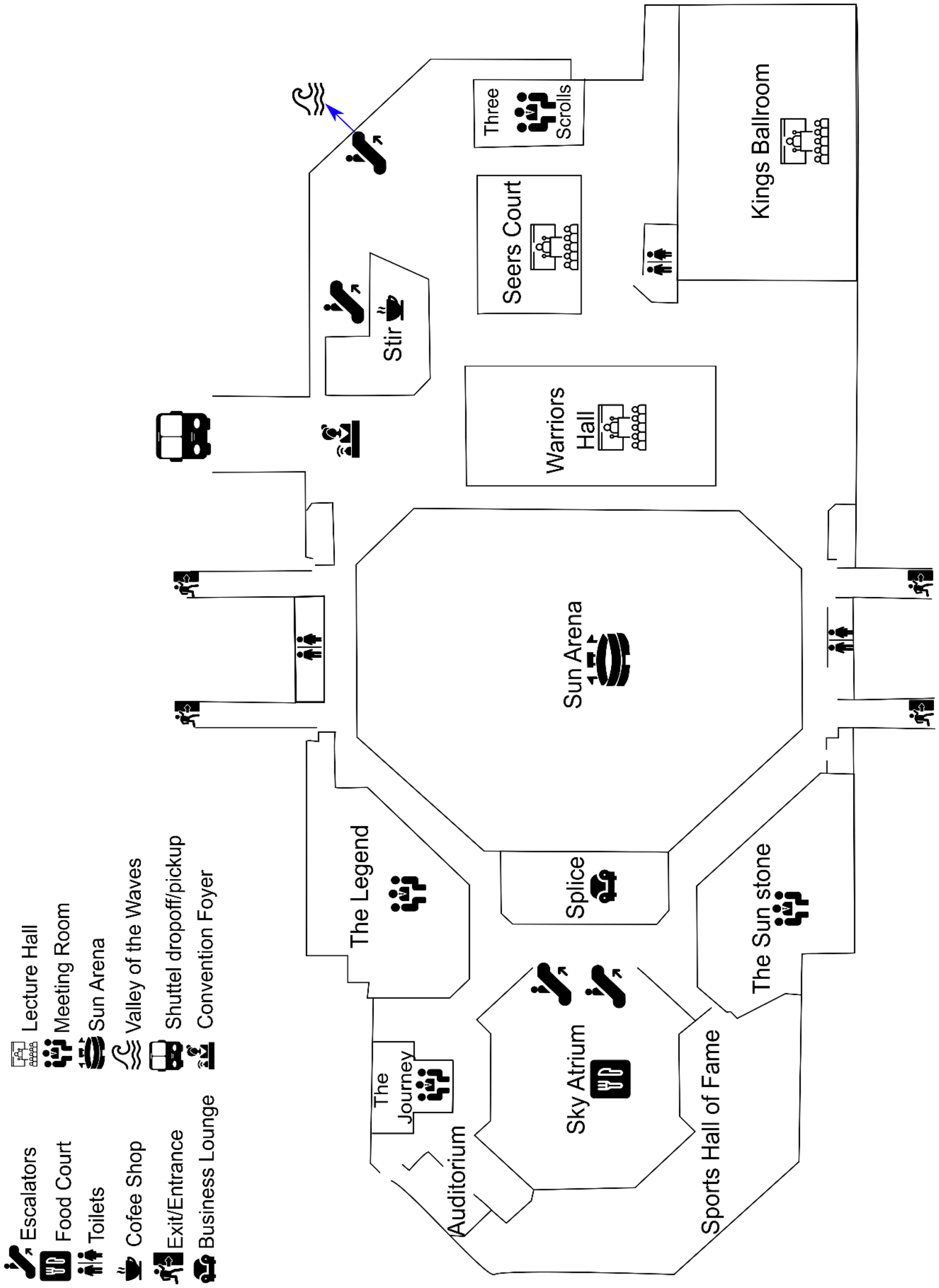
Things to do in Sun City:

- Golfers can choose from two world-class golf courses, and thrill seekers can choose from a variety of adventure activities.
- Spend the day at Sun City's Valley of Waves' man-made beach.
- Visit The Maze of the Lost City, the largest permanent maze in the Southern Hemisphere.
- Go on safari to see the Big 5 at the Pilanesberg Game Reserve.
- The Sun City Casino has your game with a massive selection of slots and tables.

Venue Map – Sun City

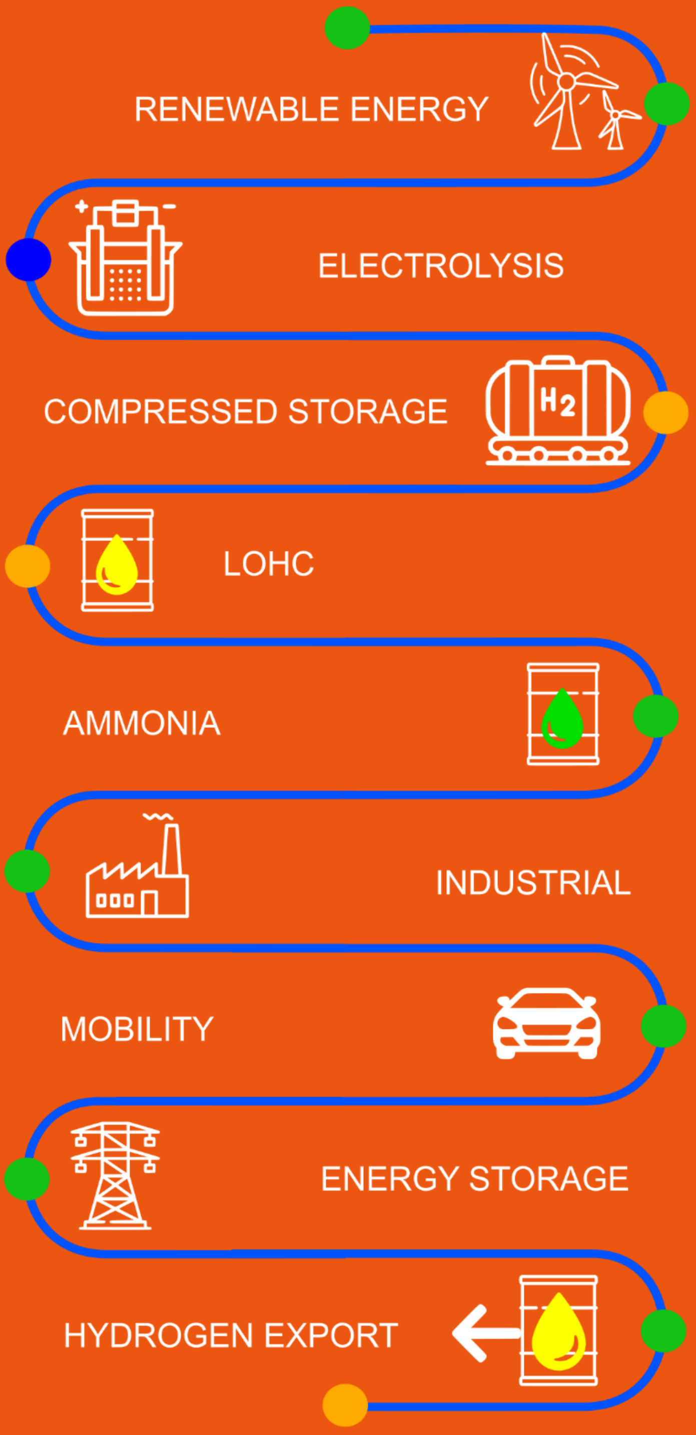


Venue Map – Convention Centre



HYSA INFRASTRUCTURE HYDROGEN

ROADMAP



RENEWABLE ENERGY

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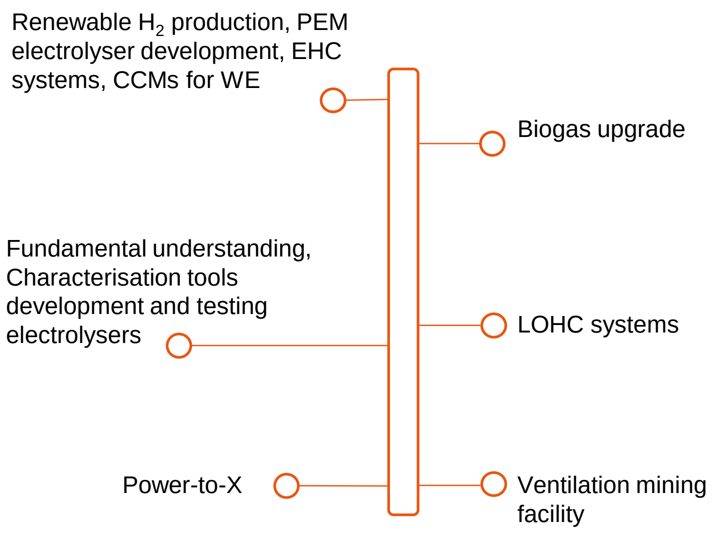
Vision

The HYSA **Infrastructure** forms a Centre of Competence together with the NWU and CSIR. It is the intention of HYSA infrastructure COC wo be a world leader and commercial relevant entity in the area of hydrogen production (electrolysis hydrogen linked to solar recourses), in the area of hydrogen compression, storage and delivery. This will be achieved through partnership with world leading OEMs, investors and research institutions.

Activities and expertise

- Water electrolysis (WE) and components.
- Hydrogen safety, codes and standards.
- H_2 storage expertise (LOHC).
- Power-to-X & Fuel blending.
- Techno-economic expertise.
- Ab-initio modelling expertise.
- Hydrogen recombination.

Projects and competencies



Renewable H_2 production, PEM electrolyser development, EHC systems, CCMs for WE

Biogas upgrade

Fundamental understanding, Characterisation tools development and testing electrolysers

LOHC systems

Power-to-X

Ventilation mining facility

The Department of Science and Innovation (DSI)

The Department of Science and Innovation (DSI) seeks to boost socio-economic development in South Africa through research and innovation. To achieve its goals, the Department provides leadership, an enabling environment and resources for science, technology and innovation.

It is widely accepted that science, technology and innovation are key to unlocking people's potential and creating improved social conditions, a competitive economy, and a workforce positioned to take the country into the future.

In 2019, the DSI produced a new White Paper on Science, Technology and Innovation (STI) for the country, a core policy for driving positive socio-economic outcomes through STI initiatives in fields including energy, healthcare, education, climate change, food security and value-added manufacturing.

The White paper on STI highlights the role that strategic partnerships across the public and private sector, both local and international, will play in promoting innovation that addresses societal needs today and in the future.

The DSI will also draw on the work it has supported over the past two decades to create an enabling environment for the translation of innovations into commercial products and services to modernise mature industries, drive evidence-based decision-making and improve global competitiveness, in line with economic reconstruction and recovery.

science and innovation

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H2

Join Shell at the International Conference on Electrolysis 2023

At Shell, we recognise hydrogen's potential and the several cross-business opportunities it presents. Through our dedicated Hydrogen Technology Programme, we are bringing together a vast global network of tech resources and partners with the ambitious goal of developing commercial projects of a similar scale as our refineries and chemical parks of today.

From production to storage, transport and use, our program focuses on five key technology areas: renewable hydrogen production, liquefaction and insulation for transport, high-capacity underground storage and long-distance pipeline, de-risking hydrogen production via methane pyrolysis, and deployment of decarbonised hydrogen projects at scale (with CCS).

Join us at the International Conference on Electrolysis 2023 to learn more about our partnerships and projects, including our megawatt-scale Solid Oxid Electrolyser (SOEC) demonstrator at the Shell Technology Centre Bangalore and our 200MW electrolyser, Holland Hydrogen I, in the Port of Rotterdam.

Learn more about our approach to hydrogen technology at shell.com/net-zero-tech

NRF
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Research
Foundation

The **Research Innovation Support and Advancement (RISA)** is a multi-disciplinary funding division of the NRF that supports, promote, and advance the creation of knowledge and innovation, through research funding, human capacity development funding, and research infrastructure funding.

Vision

“Research for a better society.”

The National Research Foundation’s (NRF) strategic vision is that knowledge and research are at the epicentre of national development. It is about a knowledge and research enterprise whose products and effects bring about the advancement of the frontiers of knowledge, improve the quality of life for the people of our country, improve competitiveness of strategic sectors and industries of our economy, provide for better protection and preservation of our national natural heritage, and lead to elevation of the technological base of our country. All of these in order to bring about a better society through research.

Mission

As per its statutory mandate, the NRF’s raison d’être is:

“To enable and facilitate the contribution of knowledge and scientific research to national development.”

NRF’s shared values

People-centred

People are our greatest asset and are thus treasured and nurtured. We invest in current and future researchers to create a transformed, excellent and sustainable research enterprise with impact. We invest in our employees to create a transformed, empowering, inclusive and diverse working environment, and to advance health and wellness in the work environment.

Ethics and Integrity

Integrity forms the basis of our business principles. As an organisation, and individually, we act with honesty and probity. We are consistent, fair and transparent in our actions and decisions.

Accountability

We are accountable for the way in which we utilise public resources in pursuit of national development. We make commitments and are prepared to be judged against them. We are responsible for our actions.

Passion for Excellence

We recognise our obligation to society and to the research enterprise to deliver the highest standards in all areas of our mandate and to seek out and support excellence.

World-class Service

We are concerned about our stakeholders, their needs and their perceptions. We aspire to and are committed to provide exceptional service at all levels.

Respect

We recognise the inherent worth of every human being, embrace diversity, and treat everybody we encounter with dignity and respect. We respect the environment and all living creatures, and promote sustainable development.

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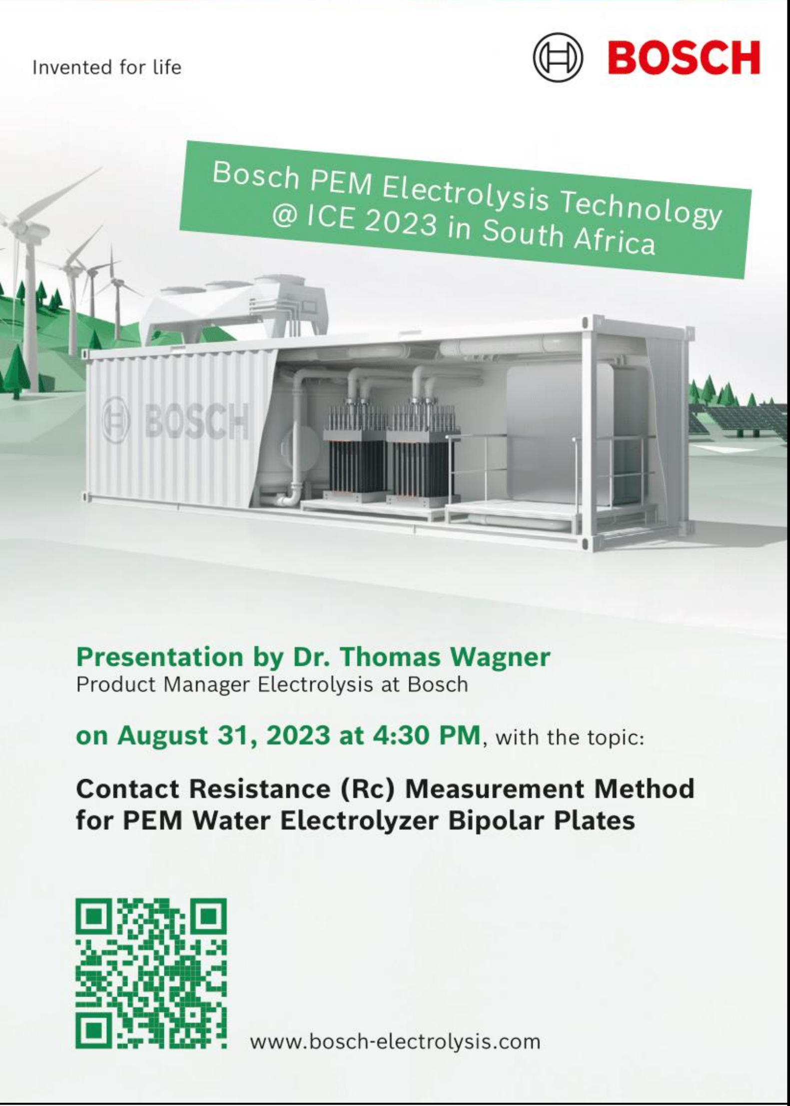
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BOSCH

Bosch PEM Electrolysis Technology
@ ICE 2023 in South Africa

Presentation by Dr. Thomas Wagner
Product Manager Electrolysis at Bosch

on August 31, 2023 at 4:30 PM, with the topic:

Contact Resistance (Rc) Measurement Method for PEM Water Electrolyzer Bipolar Plates

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Development of New Ammonia Synthesis System using Renewable Energy and Hydrogen

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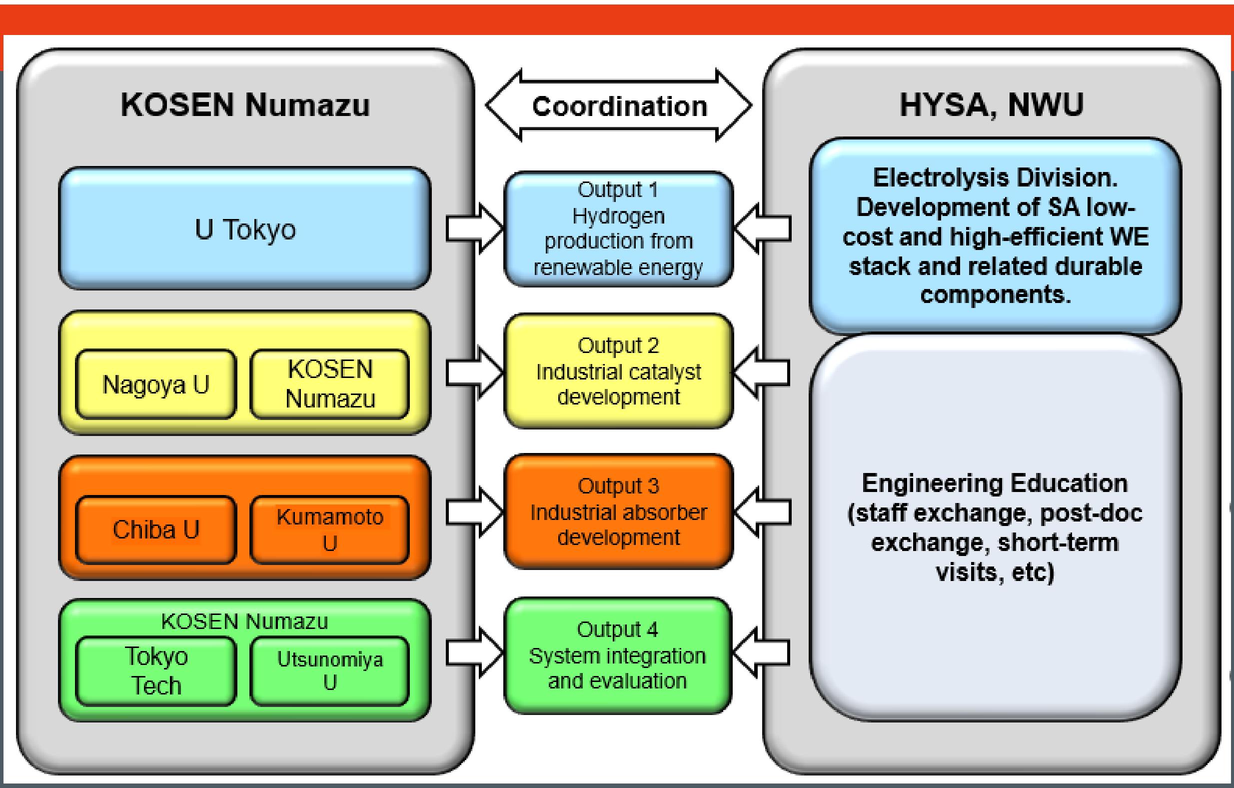

KOSEN Numazu

Coordination

HYSA, NWU

KOSEN Numazu		HYSA, NWU
U Tokyo	Output 1 Hydrogen production from renewable energy	**Electrolysis Division. Development of SA low-cost and high-efficient WE stack and related durable components.**
Nagoya U KOSEN Numazu	Output 2 Industrial catalyst development	**Engineering Education (staff exchange, post-doc exchange, short-term visits, etc)**
Chiba U Kumamoto U	Output 3 Industrial absorber development	
KOSEN Numazu Tokyo Tech Utsunomiya U	Output 4 System integration and evaluation	

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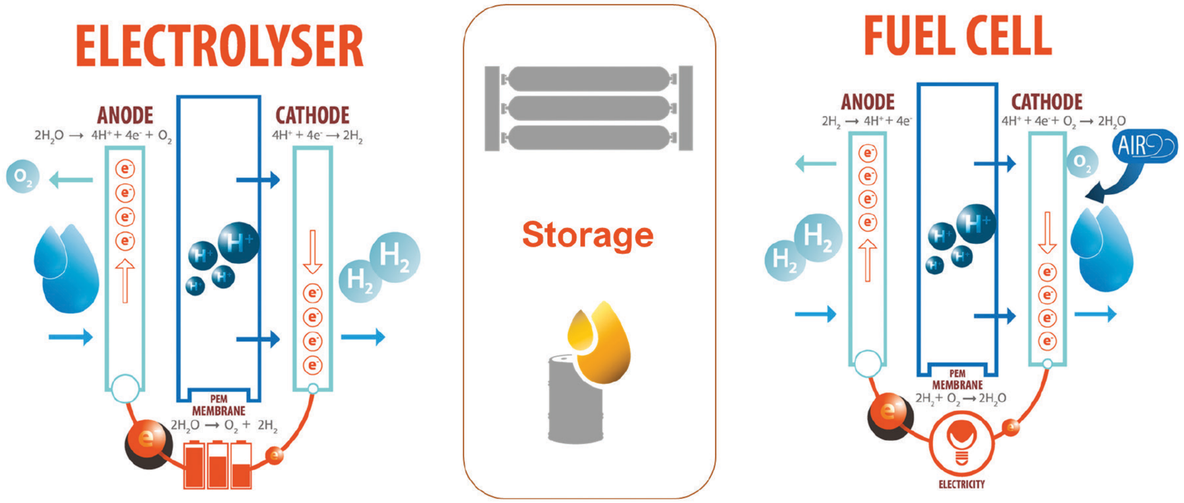
Piloting Renewable Hydrogen Production, Storage, and Utilization by HySA Infrastructure at North-West University

Below is a schematic diagram of hydrogen (H_2) production by means of **Water Electrolysis (WE)**, storage and electrical energy generation via Fuel Cell technology.



With the current expertise in hydrogen and fuel cell technologies at HySA we can provide piloting service, education, training, demonstration, and technology development. Our core expertise includes water electrolysis development, H_2 storage using LOHC technology, Safety technologies and Electrochemical H_2 compression (EHC), including green mining applications.

Arial view of the H_2 piloting cluster and the dedicated PV installation (70kWp, combined) at the NWU HySA Infrastructure facilities to supply **renewable energy (RE)** for green hydrogen production.

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Above are some key elements of the "**green**" H_2 piloting cluster at NWU HySA Infrastructure facilities, including 350 bar H_2 mobile refuelling system, PEM 6 Nm³/h H_2 electrolyser, H_2 storage via Liquid Organic Hydrogen Carrier technology (LOHC) with energy storage capacity equivalent of 1 MWh and 13500 L of compressed H_2 storage.

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Book of Abstracts

The Abstracts of the presentations made at the ICE 2023 conference have been meticulously organized to facilitate easy access and navigation for conference participants. The abstracts are arranged based on the following criteria:

Conference workshop events: Abstracts related to specific workshop events are grouped together, allowing attendees to locate relevant abstracts pertaining to the workshops they are interested in.

Oral Presentations: The abstracts for oral presentations are arranged chronologically, according to the date and order of the presentations. This arrangement ensures that attendees can easily find the abstracts corresponding to each presentation in the conference program.

Poster presentations: Abstracts for poster presentations are categorized based on specific themes or subjects. Within each category, the abstracts are arranged in alphabetical order. This arrangement facilitates efficient browsing and retrieval of poster abstracts based on the specific topic or area of interest.

By organizing the abstracts in this manner, we aim to provide conference participants with a clear and structured overview of the presentations and posters, enabling them to locate the relevant abstracts that align with their research interests or areas of focus.

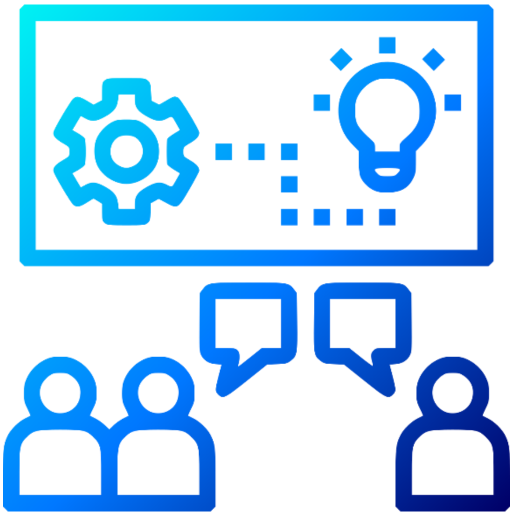
The online version of the abstracts is readily accessible through our official conference website. To access the abstracts, simply visit our website and navigate to the designated section for ICE 2023 conference materials. Alternatively, you can conveniently access the online version by scanning the QR code provided below:

ICE 2023

https://engineering.nwu.ac.za/hysa/book-abstracts

Conference Workshops

Oral Presentations



Necessary technologies for enabling cost-effective and large-scale H_2 and NH_3 production technologies: an introduction to HYDROGENi FME

Marie-Laure Fontaine[a],

SINTEF AS, Norway

Email: marie-laure.fontaine@sintef.no

HYDROGENi (https://hydrogeni.no/) is a Centre for Environment-friendly Energy Research (FME), which seeks to develop expertise and promote innovation through focus on long-term research in selected areas of environment-friendly energy. The HYDROGENi centre aims to build a sustainable hydrogen economy with focus on four main research areas: Cost-efficient and scalable production of hydrogen and ammonia; transport and storage in Norway and Europe; end-use technologies; safety and material integrity. HYDROGENi's activities are a collaborative effort from over 50 Norwegian and European partners from both research and industry covering the entire H_2 value chain. In addition, HYDROGENi will have the largest ever academic research programme in an FME and aims to educate 35 PhD/postdoc students and over 100 MSc/BSc candidates. The presentation will cover activities promoting a technology-neutral approach to clean H_2 and NH_3 production and scaling-up of production capacity needed for domestic use and export. Hence, several electrolyser technologies are integrated in the centre and represented by technology developers and users: PEMEL, AEL, AEMEL and PCCEL. The work encompasses research on materials and manufacturing for optimum performance and durability, efficiency and dynamic behaviour of electrolysers, and design, operation and process integration of large-scale electrolysers. As the Centre started in 2022, we will present the main approaches defined for each technology and current status of knowledge. We will also emphasize on possibilities for collaboration with the Centre.

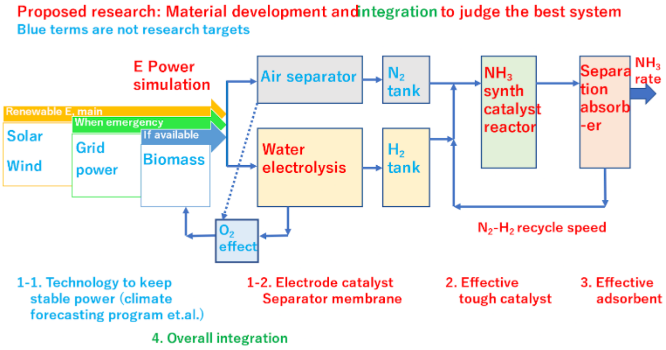
FME HYDROGENi is financed by the Norwegian government through the Norwegian Research Council's Centres for Environment-friendly Energy Research program.

Green Ammonia Production at South Africa: New Technologies through Cooperation between NWU and Japanese Universities

Ken-ichi Aika[a], Koji Inazu[a], Takeshi Furusawa[b], Junichi Ryu[c], Kazuhiro Takanabe[d], Shinichi Matsumoto[e], Katsutoshi Nagaoka[f], Manabu Sugimoto[g], and Dmitri Bessarabov[h]

[a]KOSEN Numazu, Japan;
[b]Utsunomiya U., Japan;
[c]Chiba U., Japan;
[d]U. Tokyo, Japan;
[e]Tokyo Inst. Tech., Japan;
[f]Nagoya U., Japan;
[g]Kumamoto U., Japan;
[h]North West U., RSA

Email: kenaika@c01.itscom.net



A program called "Development of new ammonia synthesis system using renewable energy and hydrogen" has been started since Nov 2022 between HySA Infrastructure, North-West University and Green Ammonia Research Center, KOSEN Numazu, Japan. When Japanese advanced catalysis technologies and NWU's advanced electrolysis technologies are combined with the SA's world cheapest solar energy (as is shown in the **Figure**), green ammonia production at SA is considered as most effective in the world. This paper shows the background technologies[1-9] supporting the program.

[1] Niwa, Y.; Aika, K. Ruthenium Catalyst Supported on CeO_2 for Ammonia Synthesis. *Chem. Lett.* **1996**, 3-4.
[2] Zeng, H. S.; Inazu.; Aika, K. The Working State of the Barium Promoter in Ammonia Synthesis over an Active-Carbon-Supported Ruthenium Catalyst Using Barium Nitrate as the Promoter Precursor. *J. Catal.* **2002,** *211*, 33-41.
[3] Ogura, Y.; Sato, K.; Miyahara, S. I.; Kawano, Y.; Toriyama, T.; Yamamoto, T.; Matsumura, S.; Hosokawa, S.; Nagoaka, K. Efficient ammonia synthesis over a Ru/$La_{0.5}Ce_{0.5}O_{1.75}$ catalyst pre-reduced at high temperature. *Chem. Sci.*, **2018**, *9*: 2230-2237.
[4] Furusawa, T.;et.al., Effect of alkali metal addition to a Ru/CeO_2 catalyst prepared by $NaBH_4$ reduction on the catalytic performance for H_2 production via NH_3 decomposition. *J. Chem. Eng. Jpn*. **2021,** *54*, 77-86.
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[6] Takanabe, K.; et.al. Dynamic surface-coverage alteration based on microkinetic analysis for enhanced ammonia synthesis over ruthenium catalysts at low temperatures. *Chemical Engineering Journal*. **2023,** *452*, 139525-139525.
[7] Matsumoto, H.; et.al. Enhanced ammonia synthesis activity of Ru-supported cerium–lanthanum oxide induced by Ti substitution forming mesopores. *Chem. Commun.*, **2022,** *58*, 3210.
[8] Sugimoto, M.; et.al. A multicolor and ratiometric fluorescent sensing platform for metal ions based on arene–metal-ion contact. *Communications Chemistry.* **2021,** *4*(1), dec.
[9] Bessarabov, D. G.; et.al. Supported Ir-Based Oxygen Evolution Catalysts for Polymer Electrolyte Membrane Water Electrolysis: A Minireview. Energy & Fuels. **2022,** June, *36*(13), DOI:10.1021/acs.energyfuels.2c00951

Load-shedding – Can SA be saved?

Prof. Jan de Kock

Faculty of Engineering, North-West University, Private Bag X6001, Potchefstroom 2520, South Africa

Load-shedding is crippling South Africa. The estimated cost to the economy was as high as R899 million per day in 2022. Load-shedding was implemented for 207 days in 2022, more than double the amount of 2021. 3773 hours of load-shedding was recorded in 2022, more than treble the hours of 2021 and the shed energy more than quadrupled in the same period. Various options have been presented to solve the problem with small generators, PV plants, wind farms and battery storage being the most common suggestions. Can these technologies really solve our problems or are there hidden pitfalls people are not seeing? Are we just so desperate for electrical energy that we are willing to throw caution to the wind and endanger the lives of ordinary South Africans?

Just transition to green hydrogen: A case of South Africa

Phillimon Modisha[a], Stefano Berberis[b], Dmitri Bessarabov[a]

[a]HySA Infrastructure Centre of Competence, North-West University, Faculty of Engineering, Private Bag X6001, Potchefstroom Campus, 2520, South Africa
[b]University of Genoa, Department of Mechanical, Energy Management and Transport Engineering - DIME – Thermochemical Power Group, Via Montallegro 1, 16145 Genova - Italia

Email: phillimon.modisha@nwu.ac.za

JUST GREEN AFRH2ICA is a project funded by the Clean Hydrogen Partnership and the European Union involving key partners from African Union and European Union with an objective of developing mutual benefit Green Hydrogen Roadmaps for the two continents and promoting a JUST TRANSITION approach [1]. This initiative targets establishing African-European transition pathways to a hydrogen economy that is synergistic, sustainable (From economic, social and environmental point of view), and foster a mutually beneficial collaboration between the two continents. The role of HySA Infrastructure in JUST GREEN AFRH2ICA consortium is to be one of the local leader In assessing green hydrogen potential of the continent with a focus on South Africa context assessment. HySA Infrastructure NWU is mandated to conduct a comprehensive assessment of the existing, policies, roadmaps and literature on previous green hydrogen studies and scenarios in South Africa. This provides a solid background to understand the historical and current state of green hydrogen initiatives in the region. The project aims to identify and engage key stakeholders of green hydrogen including government departments, state-owned entities and private companies. Stakeholders' analysis is conducted to investigate (via workshops, events and surveys) their local needs, as well as points of strength and weaknesses. A critical aspect of the initiative will be the assessment of roadmaps, existing policies and the regulatory framework that are linked to green hydrogen [2-4]. The assessment of local hydrogen demand, export potential and existing infrastructure (harbors, roads, gas pipeline, electric transmission lines and water), is conducted to develop a hydrogen export scenario. The data obtained will be modelled together with other partners from various regions (North Africa, West Africa, East Africa) taking into account technical, economic, social, and environmental dependencies in order to determine sustainable hydrogen value chains in the African context. The analysis of South Africa's green hydrogen potential will provide a comprehensive understanding of the opportunities and challenges facing the industry in the country. By leveraging the insights collected from stakeholders, policymakers and industry leaders, targeted strategies can be developed to promote the growth of the green hydrogen industry in South Africa.

[1] https://just-green-afrh2ica.eu/
[2] Department of Science and Technology, National Hydrogen and Fuel Cell Technologies Research, Development and Innovation Strategy, May 2007
[3] Department of Science and Technology, South African Hydrogen Society Roadmap, 2021
[4] Department of Transport, Green Transport Strategy for South Africa: (2018-2050)
[5] Industrial Development Corporation, Green Hydrogen Commercialisation Strategy for South Africa, 2022
[6] Department of Mineral Resources, A Beneficiation Strategy for the Minerals Industry of South Africa, June 2011

Development of a green hydrogen economy in South Africa: The GIZ, H2.SA Project.

Hector Matlou Makgato, Technical Advisor: Research, Innovation, and Capacity Building

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) *GmbH*

H2.SA is a project of the German Development Cooperation with South Africa that was commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ). The project is implemented by the *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ) *GmbH* in close cooperation with the Green Hydrogen South Africa (GHSA) under office of The Presidency of South Africa. H2.SA's main objective is to promote a South African green and sustainable hydrogen economy. Working closely with its partners from Government, private sector, and civil society, H2.SA provides expertise, resources, and builds capacity for a secure and sustainable energy future that holds opportunities for all South Africans.

The presentation will outline the thematic areas of the H2.SA programme and the activities undertaken by GIZ to support stakeholders in the development of a green hydrogen economy. These activities include various technical studies such as, a review of the international standards on green hydrogen, a techno-economic study of sea water desalination, an analysis of the current hydrogen research activities and alignment with government policies and industry needs, as well as environmental and social impact analysis (ESIA) and community beneficiation studies. GIZ's specific contribution is to make available information, tools and knowledge in the public domain that can be used by private and public sector decision-makers to the benefit of the South African hydrogen economy.

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Oral Presentations

Monday 28th August – Session 1

On transport limitations in PEWE catalyst layers

Felix. N. Büchi[1], C. Cesar Weber[1], Salvatore De Angelis[1,3], Tobias Schuler[1,4], Jacob A. Wrubel[2], Guido Bender[2], Kinanti Aliyah[1], Charfeddine Habib[1], Jens Eller[1],

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[2] National Renewable Energy Laboratory, Golden, Colorado, 80401, USA
present address: [3] DTU, 2800 Kgs. Lyngby, Denmark
present address: [4] Robert Bosch GmbH, 70049 Stuttgart, Germany

Email: felix.buechi@psi.ch

When striving for low-Iridium loadings in the anode catalyst layer of polymer electrolyte water electrolysis (PEWE), catalyst utilization affected by the charge, energy and mass transport in the catalyst layer is becoming an important boundary condition.

Interestingly, the electronic charge transport can be limiting as well as the water transport to the active sites. The competition between gas and water transport, water reaching the active sites, may be driving higher overpotentials at high current densities.

At the time there is only limited knowledge of the catalyst layer structure and its transport properties. In this work, the transport properties, based on high-resolution X-ray tomographic data with a voxel size of 16 nm (see **Figure 1**) are analyzed and the charge and mass transport characterized [1]. This data is combined with cell-level characterization using geometrically defined porous transport layer/catalyst layer interfaces.

For the understanding of mass transport in the catalyst layer, gas vs. liquid volume fractions are important. It has been shown for fuel cell catalyst layers that using X-ray scattering methods can provide complementary information. Here, first data demonstrating this technique for PEWE catalyst layers will be discussed.

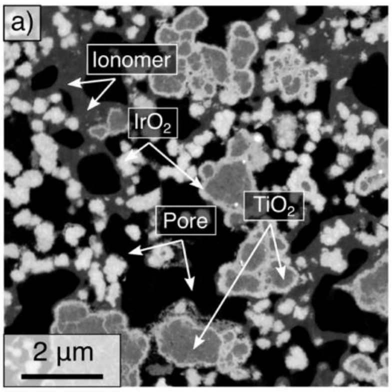

Figure 1. *Two-dimensional slice obtained from the entire tomogram showing all phases present in the catalyst layer (from [1]).*

[1] S. De Angelis, T. Schuler, M. Sabharwal, M. Holler, M. Guizar-Sicairos, E. Müller, and F.N. Büchi, *Understanding the microstructure of a core–shell anode catalyst layer for polymer electrolyte water electrolysis,* Scientific Reports, **13,** 4280 (2023).

We gratefully acknowledge funding from the Swiss Federal Office of Energy, and the Swiss National Science Foundation under the Sinergia grant number 180335.

Overview of U.S. Department of Energy Hydrogen Program and Electrolyzer Activities

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Hydrogen and fuel cells are emerging, versatile examples within a portfolio of advanced and sustainable energy options. The U.S. Department of Energy (DOE) is supporting a comprehensive research, development, demonstration, and deployment (RDD&D) effort to address the challenges to achieving large-scale commercial viability of hydrogen and related technologies across sectors and applications. An overview will be provided on DOE's Hydrogen Program, including the National Clean Hydrogen Strategy and Roadmap, and key priorities within the Bipartisan Infrastructure Law, which includes $9.5 billion for hydrogen technologies, will be covered with an emphasis on the $1 billion Clean Hydrogen Electrolysis Program. The presentation will discuss how hydrogen RDD&D activities are advancing U.S. commitment to tackling the climate crisis through the DOE Hydrogen Program's H2@Scale vision for clean hydrogen across the economy, and the Hydrogen Energy Earthshot seeking to cut the cost of clean hydrogen to $1 per 1 kilogram in one decade. A focus will be on electrolysis activities led by DOE's Hydrogen and Fuel Cell Technologies Office and will include a discussion on current status, key targets, and remaining challenges that need to be addressed to meet Clean Hydrogen Electrolysis Program and Hydrogen Shot goals.

Recent Highlights on Solid Oxide Electrolysis (SOE) Technology at Cells, Stacks and Modules Scale

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Hydrogen can play a key role, as a resource for industrial processes, a fuel for transportation, and a vector for high-capacity and/or long-distance electricity storage [1]. A sharp increase in the share of hydrogen in the overall European energy mix is expected, with a value reaching 13-14% in 2050 against less than 2% currently [2]. In this context, it will be necessary to increase the production capacity of carbon-free hydrogen, primarily through water electrolysis. At European level, a deployment plan for 100 GW of electrolysis is thus proposed by 2030, allowing during its operation to produce 10 million tons of hydrogen per year, to which are added an additional 100 GW for export [1]. However, the production of carbon-free hydrogen is currently not competitive with conventional production routes from fossil fuels (methane steam reforming in particular). The deployment of high-power electrolyzers is likely to significantly lower the cost of the hydrogen produced.

But the efficiency of the electrolysers is also a key parameter towards the Levelized Cost of Hydrogen (LCOH). From that perspective, Solid Oxide Electrolysis (SOE) presents the highest efficiency and is therefore considered to be an highly promising technology to produce hydrogen at low cost [3-4]. In addition, it still has a significant potential for innovation, making it possible to gain in performance and lifetime. To reach large electrolysis plants, the upscaling of the different components of the SOE technology is a cornerstone, which includes cells, stacks and modules. The status of development of the technology will be presented, as well as the remaining challenges. The current R&D developments performed to meet those challenges will be detailed.

[1] European Commission, *REPowerEU: affordable, secure and sustainable energy for Europe*, **18 May 2022**

[2] European Commission, *A hydrogen strategy for a climate-neutral Europe*, **8 July 2020**

[3] J. Mougin *Compendium of Hydrogen Energy*, Volume 1: Hydrogen production and purification, edited by V. Subramani, A. Basile and T.N. Veziroglu, Woodhead publishing series in Energy, Elsevier, **2015,** pp.225-253

[4] Clean Hydrogen Joint Undertaking, *Strategic Research and Innovation Agenda 2021 – 2027*, https://www.clean-hydrogen.europa.eu, **February 2022**

Monday 28th August – Session 2

Water Transport though Membranes during Anion Exchange Membrane Water Electrolysis

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[b] *University of Tsukuba*
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Anion exchange membrane water electrolyzers have attracted attention as a new water electrolysis system. The greatest advantage of this system is that it can achieve the same performance as proton exchange membrane (PEM) water electrolysis in a less expensive system. Another major advantage is that it does not require iridium (Ir), which is indispensable in PEM water electrolysis. AEM water electrolysis can be operated "cathode dry" without supplying electrolyte to the cathode. This operation method simplifies the electrolyte circulation line and hydrogen purification line compared to PEM water electrolysis. The application of cathode dry operation has been considered essential to reduce system costs.

Figure 1 shows the mechanism of water transport through the membrane during cathode-dry operations. As hydroxide ions (OH-) move from the cathode to the anode during electrolysis, water moves from the cathode to the anode by electro-osmosis. Since water is also generated at the anode by the electrode reaction, a water concentration gradient appears in the membrane from the anode (high) to the cathode (low). Water moves from the anode to the cathode by diffusion according to this concentration gradient. The water transferred by diffusion is consumed at the cathode. In other words, all the water consumed at the cathode is supplied by diffusion through the membrane which raises the concern that water would not reach the cathode if the membrane thickness or current density exceeds a certain threshold value. In addition, the difference in water concentration in the membrane appears as a concentration overvoltage, degrading electrolytic performance at the high current density region [1].

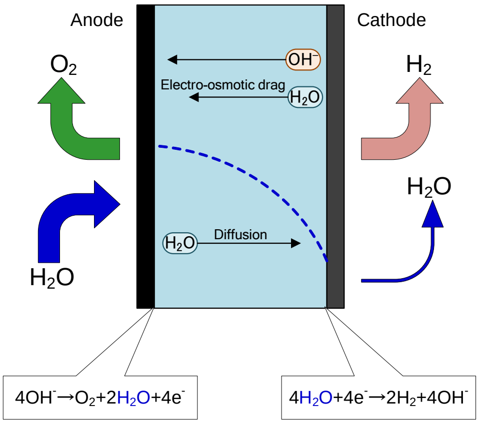

***Figure 1.** Water transport in membranes during cathode-dry operation of anion exchange membrane water electrolysis.*

[1] R. Wang, M. Ohashi, M. Ishida, H. Ito, *Int. J. Hydrog. Energy*, 2022, **47**, 40835-40848.

Acknowledgments

This work was supported partly by the New Energy and Industrial Development Organization (NEDO) (P 14021). The authors wish to express their gratitude to Tokuyama Corporation for their support and helpful advice.

Challenges in upscaling PEM Electrolysis Systems

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H-TEC SYSTEMS is a hydrogen expert, innovation driver and partner in the energy transition. For our future and for our customers we develop innovative PEM electrolyzers and electrolysis stacks for green hydrogen production. As a technological pioneer, we have been playing a decisive role in shaping hydrogen technology for over 25 years.

We believe that mobility, production, and consumption are possible without emissions. H-TEC SYSTEMS builds on cooperation with visionary customers and partners, and the power of our parent company MAN Energy Solutions. Together, we are making hydrogen production green and the CO_2-neutral transformation of all sectors a reality.

That's why our goal is to convert renewable energies into green hydrogen by using leading PEM electrolysis technology. And thus fuel a new, emission-free energy era and avoid 1% of the global CO_2-emissions by our electrolyzers.

To achieve this goal, it is necessary to be able to produce hydrogen at the lowest possible cost. A balance must be struck between manufacturing costs, durability and, especially in times of rising energy costs, very high efficiency. The partial collapse of supply chains makes it necessary to identify alternative materials or the significant reduction of raw materials that cannot be replaced.

It is shown how efficient industrially manufactured PEM electrolysis stacks with thin membranes and loadings of less than 0.3 mg Ir cm^{-2} can produce hydrogen in a long-lasting and particularly efficient way. The necessary, uniform distribution of the surface pressure is determined and improved by means of piezoresistive sensors.

Hierarchically porous iridium-based electrocatalysts: from fundamental studies to application in PEM water electrolyzers

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The development of high performance catalysts and anodic catalytic layers that are compatible with industry fabrication processes is critical for their implementation in proton exchange membrane water electrolysis (PEMWE). We have recently extended the green, cheap and scalable aerosol synthesis technique to the preparation of highly porous iridium pure and mixed oxides. Beside being highly active towards the OER[1] and showing high stability[2], the resulting porous structure is ideally suited for the preparation of highly porous catalyst layers.[1]

We are also taking advantage of the versatility of this process to prepare a large panel of iridium-based oxides with different crystallinity and surface states to provide a better understanding of structure-properties relationship of these highly active electrocatalysts. Indeed, despite extensive studies, the reason of the higher activity of amorphous materials compared to their crystalline counterpart is still the matter of a strong debate. By introducing molybdenum along with iridium into the structure, we are able to decouple the influence of the oxidation state from the structure of the material and provide unambiguous proof of the impact of the interatomic ordering onto the electrochemical activity of iridium based materials towards the OER[3]. These findings are supported by a large set of techniques including SEM, XRD, XRF and STEM-EDX as well as surface (XPS) and bulk (XAS) characterizations, including operando XAS.

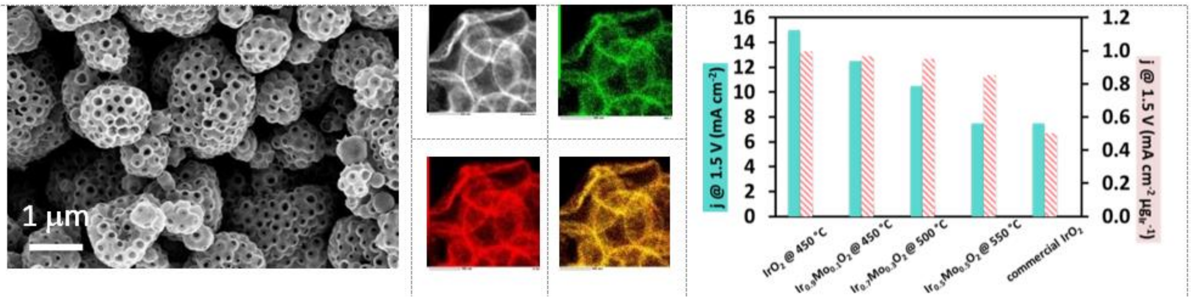
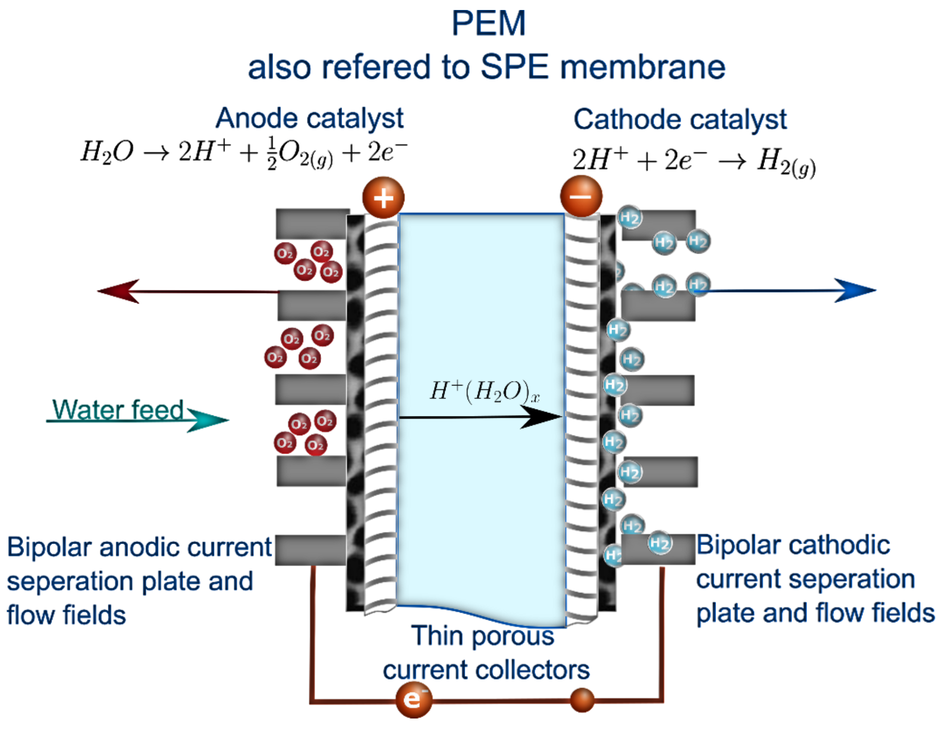


***Figure 1**: from left to right, SEM and STEM-EDX images of Ir0.7Mo0.3O2 calcined at 550 °C, and histogram of activity at 1.5 V for different composition of mixed oxide refer to IrO2*

[1] Faustini, M. et al., *Advanced Energy Materials* **2019**, *9* (4), 1802136.
[2] Ferreira Da Silva C. et al., *ACS Catalysis*, **2021**, 11, 7, 4107-4116
[3] Elmaalouf, M. et al., *Nature Commun.*, **2021**, *12*, 3935

Monday 28th August – Session 3A



Perspectives on Current and Future Iridium Demand and Iridium Oxide Catalysts for PEM Water Electrolysis

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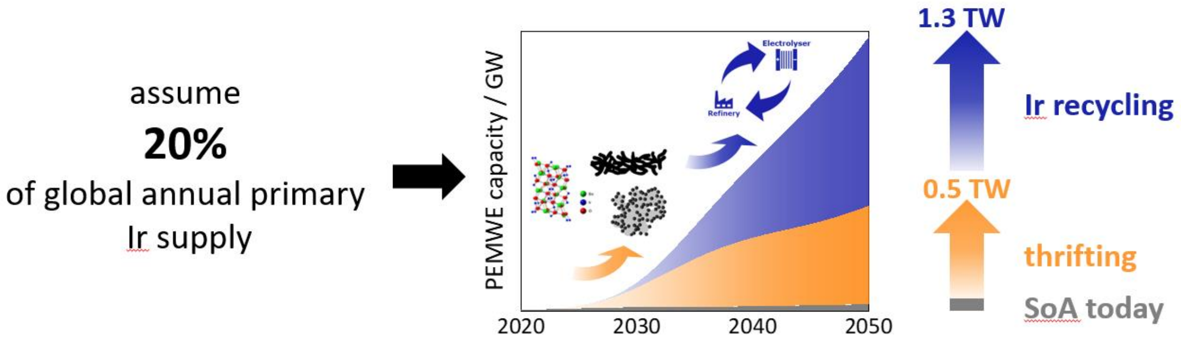
Proton exchange membrane water electrolysis (PEMWE) is projected to become a key technology to enable the decarbonisation of ‘hard to abate’ sectors of the economy. However, the technology’s reliance on iridium, one of the scarcest elements on Earth, as an oxygen evolution reaction catalyst, has led to uncertainty in both the scientific and policy making communities over whether a large-scale PEMWE industry can be realised. This work investigates the future iridium demand of the global PEMWE sector and examines how different catalyst strategies can improve iridium utilisation in the anode catalyst. Iridium utilisation targets necessary to avoid a situation where the PEMWE sector becomes limited by iridium supply are reviewed. Modelling the iridium demand of the PEMWE sector showed that iridium utilisation needs to improve by an order of magnitude by 2050 to avoid iridium supply limiting the capacity expansion. Furthermore, closed-loop recycling of iridium would increase the installed capacity in 2050 by ~170%. If these two conditions are met, global PEMWE capacity could reach 1.3 TW by 2050 using only 20% of annual global primary iridium supply, which we consider to be realistic given future demand projections. Different types of iridium-based anode catalysts are compared in terms of iridium utilisation using catalyst coated membrane (CCM) testing data from the literature. The need to place greater research focus on catalyst stability and the ability to make homogeneous catalyst layers at low iridium loadings is established. As a main result, it is found that a terrawatt-scale PEMWE industry can avoid being constrained by iridium supply as long as technological development of a similar level to that seen in PEM fuel cells and high iridium recycling rates are realised.



Related paper:

Clapp, M.; Zalitis, C.; Ryan, M.; Perspectives on Current and Future Iridium Demand and Iridium Oxide Catalysts for PEM Water Electrolysis, Catalyst Today ‘Catalysis for the Future’ special edition, **submitted**

Development of OER catalyst testing for PEMWE from a manufacturer’s perspective

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Ames Goldsmith Ceimig, UK

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High Ir content catalysts are the state-of-the-art catalysts for industrial PEMWE, however the scarcity of iridium is a potential serious bottleneck in scaling up this technology. Current estimates indicate 20 GW of hydrogen capacity is required globally by 2030, increasing to 90 GW by 2050; 40% of which is expected to be generated from PEMWE requiring a significant reduction in Ir usage per W1. In order to meet these production goals, it is necessary for Ir to be thrifted as far as possible whilst maintaining or exceeding current performance and durability levels. Ceimig’s 1st generation solution to this challenge has been IrRuOx ‘Hyper WE550’, which cuts Ir usage by 36% compared with equivalent loadings of Ir black, and is backed by good performance and proven long term durability in industrial electrolysers. Ceimig is currently able to achieve manufacturing volumes for this product in the region of 500 kg per year. To accelerate the development of our next generation, low iridium catalysts, Ceimig has been building-up the necessary in-house testing capabilities required for OER catalyst electrochemical evaluation. The first step in this process has been benchmarking our state-of-the-art catalyst HyPer WE550. In this talk we outline development of ex-situ RDE testing showing that the mass activity of HyPer WE550 can exceed both IrOx and Ir black on an Ir basis, displaying good stability, in line with real world results in commercial systems. Extending this we demonstrate MEA testing of HyPer WE550, including the effects of ionomer content and catalyst loading, with a comparison of the material to IrOx being presented.

[1] Minke, C., Suermann, M., Bensmann, B. & Hanke-Rauschenbach, R. Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis? Int. J. Hydrog. Energy 46, 23581–23590 (2021).

PEM water electrolysis development needs – from an industry perspective

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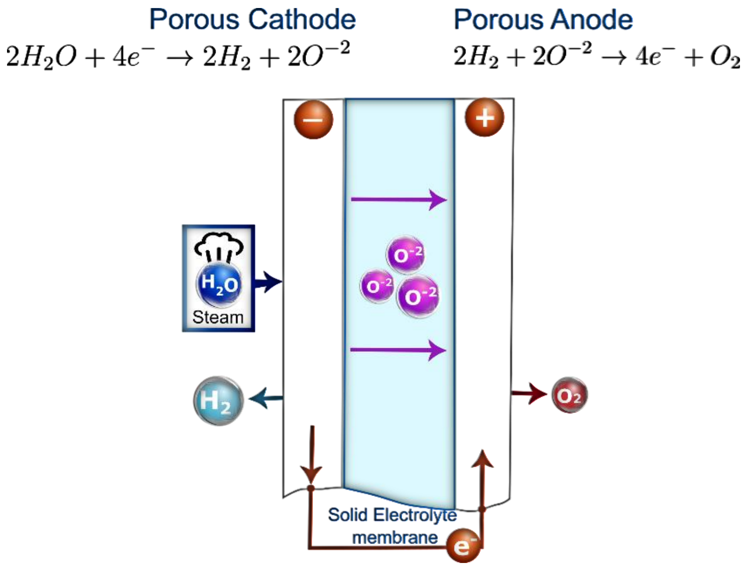
Although proton exchange membrane water electrolysis (PEMWE) systems have been used successfully in various small- (kW range) and large-scale (MW range) applications for years, the ever-increasing technical and financial targets require further improvements in the technology. One prominent example is the “1 1 1” hydrogen shot – $1 per 1 kg in 1 decade – launched June 7, 2021 by the Department of Energy [1].

Obviously, such targets cannot be achieved by improvements in PEMWE technology alone, but rather by considering the entire value chain. For example, further technological improvements and regulatory measures in the generation and use of (green) electricity must of course also be implemented.

Nonetheless, there are still PEMWE development needs that are discussed here. Thematically, it ranges from (research) questions in the field of fluid dynamics and mechanical stack design to component testing in electrochemical cell experiments. This work is intended primarily to serve as a motivation and discussion basis to better align research activities in industry and academia.

[1] Department of Energy, hydrogen and fuel cell technologies office. https://www.energy.gov/eere/fuelcells/hydrogen-shot (accessed 2023-01-04)

Monday 28th August – Session 3B



Investigating Durability of Solid Oxide Electrolysis Cells

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Email: Olga.Marina@pnnl.gov

High temperature electrolysis is the most efficient electrolysis technology available, and SOEC stacks can achieve over 95% electrical efficiency. To become a commercial technology, SOECs need to demonstrate at least a 40,000-60,000 hour life.

In this work, we performed systematic degradation studies of Ni-YSZ and LSCF electrodes in full and symmetric cells for over 5,000 hours in a broad range of experimental conditions, while varying temperature, steam concentration, steam utilization, current, voltage, operating pressure, Cr and S contaminants, and applying dynamic operation in order to map potential degradations and establish their impact on device life. Tests were conducted in either potentiostatic or galvanostatic mode and at the open-circuit voltage (OCV) to separate effects of electrochemical aging from materials thermal aging. Multiple repeats were used to eliminate the occasional artifacts and atypical trends. Steam concentration was varied from 10 to 98% and steam utilization was adjusted to up to 85%. Electrochemical characteristics, such as current, voltage, and area specific resistances were measured continuously over time. In each test, the ohmic and polarization resistances were obtained using electrochemical impedance spectroscopy, and a distribution of relaxation time (DRT) fitting approach was applied to the impedance response.

Following each test termination, extensive post-test characterization of Ni-YSZ and LSCF microstructures using SEM/EDS, EBSD, and STEM was performed. 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 3D, such as triple phase boundary, tortuosity, and particle/pore sizes were calculated and related to test time in attempt to quantify degradation impact.

A biogas to fuels system integrating solid oxide electrolysis of bio-CO_2 and biomethane reforming with Fischer-Tropsch synthesis.

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Electrochemistry in general, and electrolysis in particular, have the capacity to link the electrical and material sectors of renewable energy. To realize the full potential of renewable energy in achieving climate protection objectives, pathways for its application beyond direct electrification are essential. Hydrogen production is receiving the greatest attention as a carbon free energy carrier with the potential to fuel future fleets of hydrogen fuel cell vehicles, to store grid electricity to accommodate asynchronous generation and load, and to a lesser extent to displace heating fuels. However, the highest value application in current markets is the production of liquid transportation fuels such as sustainable aviation fuels (SAF) and low (fossil) carbon diesel fuel. Of course, liquid hydrocarbon fuels only achieve the decarbonization goals if they displace fossil fuels and are produced from sustainable, ideally biogenic carbon resources. Biomass feedstocks for biofuels production are a diffuse resource and considerable effort is required to gather them for processing, creating the concept of an economic gathering radius. The quantity of biogenic matter that can be gathered economically is a limitation on the size of the production facility. Further, in most processing routes between one third and one half of the biogenic carbon is emitted as CO_2. While that is not penalized due to the circular nature of biomass production, it is a wasted resource and a limitation on the size of the biofuels processing plant.

MOXIE, the Mars OXygen ISRU Experiment developed by OxEon has demonstrated the use of CO_2 as an electrolysis feedstock aboard the Perseverance rover which as of this writing has operated thirteen times on Mars, splitting the Mars atmosphere CO_2 to carbon monoxide and oxygen, as the first ever demonstration of In Situ Resource Utilization (ISRU) on another planet. The technology is applicable to efficient resource utilization on this world and OxEon is actively developing power to fuels technology to maximize the conversion of biogenic carbon to high value, energy dense, liquid transportation fuels that are needed by an existing vehicle fleet that will be on the road and in the air decades to come.

OxEon's technologies are being applied to bridge the electrical and materials energy sectors. In The 1980s and 1990s the focus was electrical power generation from natural gas following the path of reformer to SOFC as shown in Figure 1 left. In the 2020s the clearly more attractive business case follows the path from electrolysis through syngas to biofuels. It this project OxEon processes the bio-CO_2 through a SOEC and the bio-CH_4 through a plasma reformer. The combined synthesis gas is supplied to a Fischer-Tropsch synthesis reactor. The combination (Figure 1 right) offers several advantages: the yield of biofuel nearly doubles by use of the bio-CO_2 compared to the bio-methane alone, cooling the FT reactor generates all the steam needed in the SOEC system reducing the effective operating voltage (accounting for raising steam) from > 1.5 V/cell to < 1.3 V/cell, oxygen by-product from the SOEC is used in the autothermal reformer, as is some of the FT produced water. The product fuel is all bio-carbon, but it also embodies renewable electric energy in a high-value, storable and transportable liquid hydrocarbon that will be usable in the current air and ground fleets.

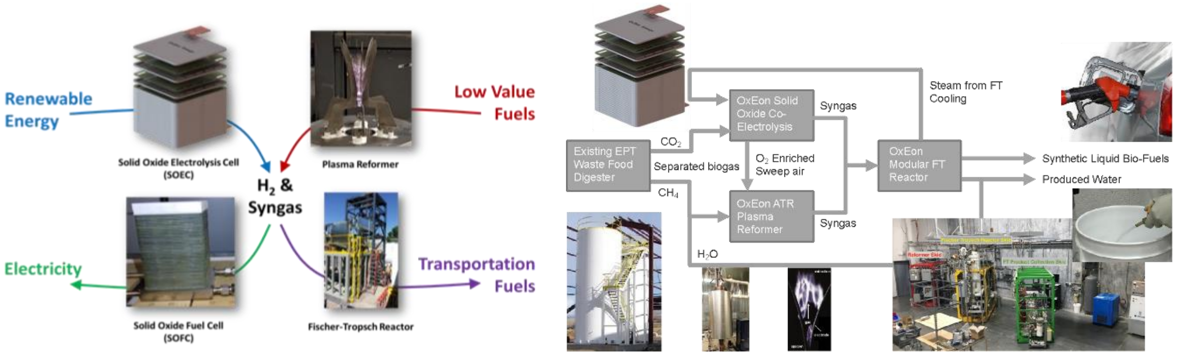

***Figure 1**. OxEon technology connections (left) and OxEon biogas to liquids system integration (right)*

Characterization of pressurized steam electrolysis in a 10-layer SOC stack with CO_2 purging on the oxygen electrode

Maximilian Gross[a], Diana M. Amaya Dueñas[a], Srikanth Santhanam[b], Marc P. Heddrich[a], Asif Ansar[a]

Affiliation: [a]German Aerospace Center (DLR) - Institute of Engineering Thermodynamics, Germany; [b]Shell Global Solutions International B.V., Netherlands

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Green hydrogen is a key energy carrier for reducing the carbon footprint of chemical processes for the synthesis of fuels and chemicals. In the frame of Power-to-X technologies, i.e. efuels/eChemicals produced from green hydrogen, solid oxide electrolysis cells (SOEC) can operate at high electric efficiencies due to the elevated operating temperature and heat integration for steam production. Under pressurized conditions, SOCs can decrease the energy consumption of a Power-to-X process by reducing the compression work. Additionally, the usage of the by-product oxygen in industrial processes like blast furnaces can replace cost- and energy-intensive oxygen production [1], e.g. cryogenic air separation, and further increase the system efficiency of the high temperature electrolyzer. Frequently, air is used for purging the oxygen electrode of SOC electrolyzers to avoid high O_2 concentrations, besides of regulating the heat within the SOC-stack. Supplying the oxygen in air mixture to combustion processes may cause high evolution rates of NO_X species that have to be removed by exhaust gas treatment after the combustion. By flushing the stack with CO_2, expensive flue gas cleaning could be reduced.

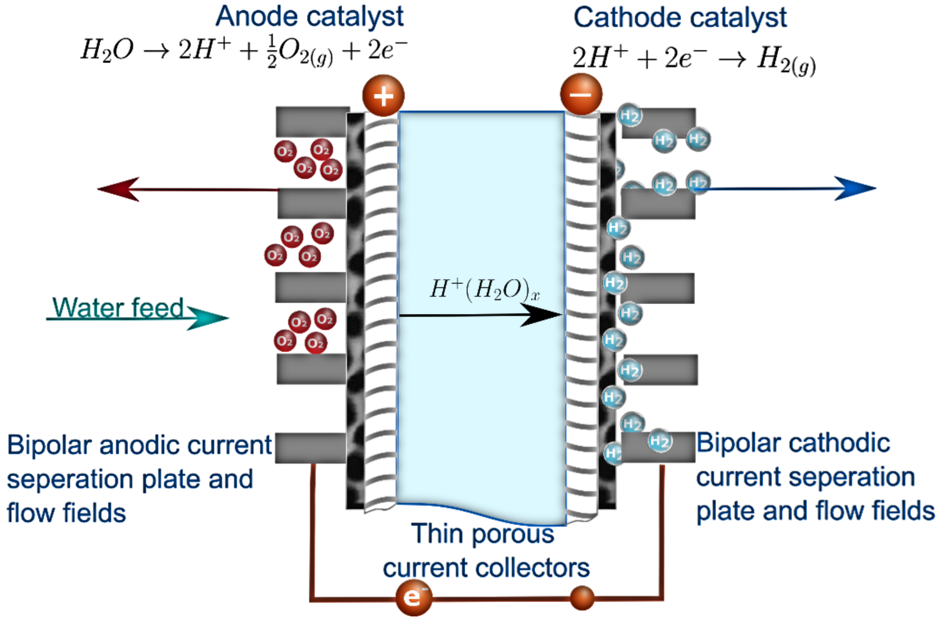
This experimental investigation addresses the effect of CO_2 purge on the oxygen electrode of a 10-layer SOC stack with electrolyte-supported cells (ESC) operating at high temperature steam electrolysis (90 % H_2O/10 % H_2). Experiments were performed on a pressurized test rig for high temperature fuel cell and electrolysis operation of SOC stacks [2, 3]. The SOC behavior was investigated by dynamically recorded *i-V* curves at 750 °C and 800 °C, pressures of 1.4 bar and 8 bar and reactant conversions between 70 % and 80 %. Additionally, steady state *i-V* curves at different current densities with a constant conversion of 70 % were recorded. Electrochemical impedance spectroscopy (EIS) measurements at open circuit voltage (OCV) and at thermoneutral conditions were performed with the aim to investigate the effect of the CO_2 purge on the cell performance, as well as on the oxygen electrode behavior. Further *in situ* characterizations by EIS were performed not only at atmospheric conditions, but also under pressure (up to 8 bar). Durability experiments were carried out in order to investigate the degradation of the SOC stack under pressurized conditions with CO_2 purge on the oxygen electrode. The influence of such CO_2 purge will be compared to typical operation with air.

[1] Kato, T.; Kubota, M.; Kobayashi, N.; Suzuoki, Y. Effective Utilization of by-Product Oxygen from Electrolysis Hydrogen Production. *Energy* **2005**, *30* (14), 2580–2595. DOI: 10.1016/j.energy.2004.07.004

[2] Riedel, M.; Heddrich, M. P.; Friedrich, K. A. Analysis of Pressurized Operation of 10 Layer Solid Oxide Electrolysis Stacks. *International Journal of Hydrogen Energy* **2019**, *44* (10), 4570–4581. DOI: 10.1016/j.ijhydene.2018.12.168

[3] *German Aerospace Center (DLR) – Homepage of test rig Horst (test environment for SOC stacks under pressure of 1.4-8 bar)*. https://www.dlr.de/tt/en/desktopdefault.aspx/tabid-18782/30105_read-80882 (accessed 2023-02-20).

Monday 28th August – Session 4A



PEM
also refered to SPE membrane

How anodic porous transport layer design enables the use of low Iridium loadings in PEM water electrolysis

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[b]*Forschungszentrum Jülich GmbH, Helmholtz Institute Erlangen-Nürnberg for Renewable Energy, Germany*

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Proton exchange membrane water electrolysis (PEMWE) is an established technology for hydrogen production. So far, Iridium is the only viable anode catalyst material offering both, high activity and durability. In recent years, there has been a growing interest in reducing the Iridium content in the anodic catalyst layer (CL), as Iridium is a precious and cost intensive metal. [1] It is well known that the interface between the anodic catalyst layer and the porous transport layer (PTL) has a significant impact on the overall performance of the system. [2,3]

In this study, the complex interface between different PTL surface morphologies and CLs with various Iridium loadings was systematically investigated. Therefore, the three main overpotentials, i.e., ohmic, kinetic and mass transport, as well as key oxygen evolution reaction (OER) kinetic parameters are determined as a function of the anodic catalyst loading and PTL type.[4]

As expected, the OER 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. It was found that a relatively poor in-plane conductivity of the CL can be partly compensated with a relatively good CL/PTL interfacial contact area. These findings provide useful insights into general design parameters to tackle challenges which come along with reducing Iridium loading and may contribute to the development of more cost-effective and sustainable hydrogen production technologies.

[1] Minke, C.; Suermann, M.; Bensmann, B.; Hanke-Rauschenbach, R. Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis? *International Journal of Hydrogen Energy* **2021,** *46* (46), 23581–23590. DOI: 10.1016/j.ijhydene.2021.04.174.

[2] Schuler, T.; Bruycker, R. de; Schmidt, T. J.; Büchi, F. N. Polymer Electrolyte Water Electrolysis: Correlating Porous Transport Layer Structural Properties and Performance: Part I. Tomographic Analysis of Morphology and Topology. *J. Electrochem. Soc.* **2019,** *166* (4), F270-F281. DOI: 10.1149/2.0561904jes.

[3] Schuler, T.; Schmidt, T. J.; Büchi, F. N. Polymer Electrolyte Water Electrolysis: Correlating Performance and Porous Transport Layer Structure: Part II. Electrochemical Performance Analysis. *J. Electrochem. Soc.* **2019,** *166* (10), F555-F565. DOI: 10.1149/2.1241908jes.

[4] Rogler, M.; *et al.*, To be submitted.

The potential of coupling electrolyzer models to rectifiers models

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Electrochemical engineering and electrical engineering are two different worlds with different languages. Electrochemists often just assume and/or demand that the rectifiers provide an almost perfect direct current to the electrolyzer, but they do not realize that this can be costly and is especially difficult if the electrolyzer needs to be operated over a wide operating range. Therefore, these “no ripple” designs are likely to be suboptimal from a techno-economic perspective. Instead, there is a need for a better understanding on the interplay between rectifiers and electrolyzers to come to more optimized solutions. We have developed a model that can describe both the rectifier and a large-scale industrial electrolyzer and have used this to study the effect of ripples on the efficiency of the electrolyzer at different loads [1]. This modeling was carried out with a simple 6-pulse thyristor rectifier, but can also be used for more advanced rectifiers to determine what solution is most cost-effective. Next to that the ripple behavior can potentially also be used to monitor stack characteristics in a way similar to electrochemical impedance spectroscopy.

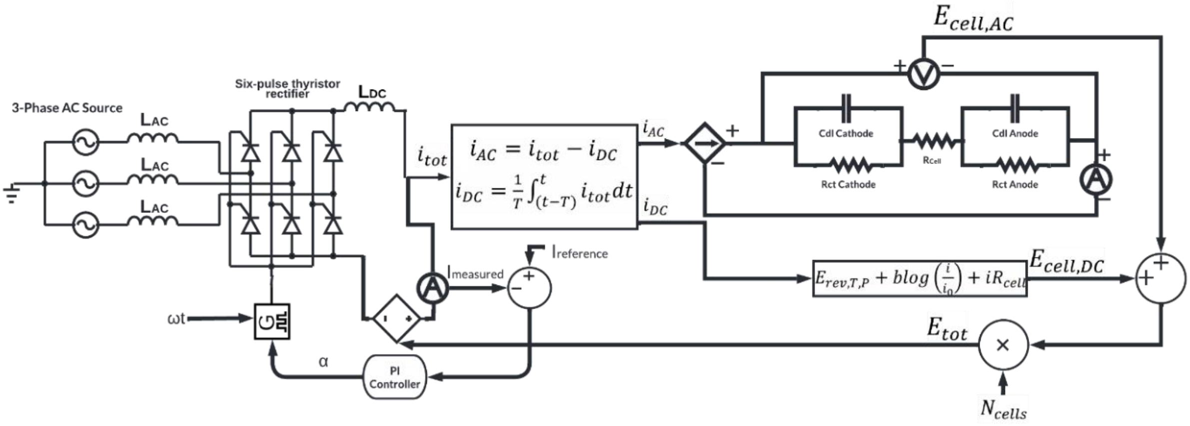

Figure: *Circuit diagram of the power conversion-electrochemical model*

[1] Amireh, S.F.; Heineman, N.N.; Vermeulen, P.; Lira Garcia Barros, R.; Yang, D.; van der Schaaf, J.; de Groot, M.T.: Impact of power supply fluctuation and part load operation on the efficiency of alkaline water electrolysis. J. Power Sources 2023, 560, 232629

Pushing the limits of screen printing towards low iridium loadings of catalyst layers for PEM electrolysis

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In this study, the unique international collaboration of Fraunhofer ISE with the National Renewable Energy Laboratory (NREL), University of Connecticut (UCONN) and Colorado School of Mines (Mines) within the OREO project („Overall Research on Electrode Coating Processes“) allows a comprehensive fabrication, testing and in-situ and ex-situ analysis of catalyst coated membranes (CCMs) for PEM electrolyzers. Additionally, the project partners from industry are providing the materials like catalyst powders from Heraeus Deutschland GmbH & Co. KG as well as ionomers and membrane from Fumatech, ensuring the comparability of measurements. From these materials, catalyst layers (CLs) are produced with slot die coating at NREL and screen printing at ISE. Moreover, STEM/EDS analysis of the cross sections are conducted at UCONN to visualize and quantify catalyst and ionomer distribution, thickness of the layers, porosity, and particle size distribution. At Mines, the CLs are measured using SEM/EDS for surface analysis of the produced layers. The performance of the CCMs is determined with the 4 cm^2 test cell from ISE using polarization curves and impedance spectroscopy.

Within this work, the focus lies on the ink and screen printing process development to enable production towards low Ir-loading CLs for industrially relevant production technologies. Screen printing is a robust and high-throughput coating technology, which can be used to produce CLs for proton exchange membrane (PEM) electrolyzers. This printing method can produce CLs with complex designs, that are not possible with coating methods such as slot-die. The aim of this work is to reach the lowest possible iridium loading that can be printed with commercially available meshes.

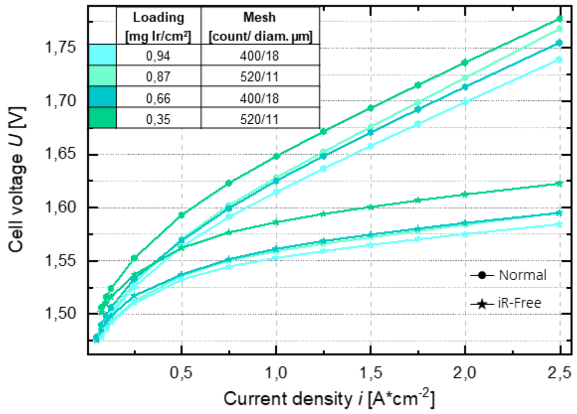

Figure 1: Polarization curves of CCMs with different Ir-loadings and produced with different meshes

Two catalyst pastes are prepared with unsupported iridium oxide powder (Heraeus), Ionomer dispersion (SSC, Fumatech) and solvents, resulting in a paste solid content of 16.67 wt% and 18 wt%. The printing is done with a semiautomatic flatbed screen printer (EKRA XH STS, ASYS Group) and three different screens (KOENEN GmbH): 230/30, 400/18 and 520/11 (Asada Mesh) (mesh count per inch/ mesh diameter in µm). At least 100 CLs are produced with each screen-variation, so that an analysis of the printing process is carried out in view of a larger production scale.

The results of the study show that the DOE target of 0.4 mg_{Ir}/cm^2 in 2026[1] in Ir-loading reduction can be successfully reached with a 520/11 screen at 0.34 mg_{Ir}/cm^2. The electrochemical operation of the CCMs reveals the good result of an iR-free corrected voltage of 1.586 V at 1 A/cm^2.

[1] *U.S. Department of Energy. Technical Targets for Proton Exchange Membrane Electrolysis. https://www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis (accessed Mar 30, 2023)*

Advances in Bifunctional Oxygen Reduction/Evolution Reaction Electrodes

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Overcoming the sluggish electrode kinetics of both oxygen reduction and evolution reactions (ORR/OER) with non-precious metal electrocatalysts will accelerate the development of water electrolysis / H_2 fuel cell unitized devices referred to as regenerative fuel cells. We investigated the electrochemical behaviour and ORR/OER catalytic activity of core-porous shell Mn/Mn_3O_4 nanoparticles (from QuantumSphere (QSI) Inc.) in comparison with other manganese oxides (β- and γ-MnO_2 (EMD)), and benchmarked it against Pt/C and Pt-IrO_2/C.[1] Under reversible operation in O_2-saturated 5 M KOH at 22 ℃, the early stage activity of core-shell Mn/Mn_3O_4 shows two times higher ORR and OER current density compared to EMD and β-MnO_2 at 0.32 V and 1.62 V vs. RHE, respectively. In accelerated degradation tests it was revealed that Mn(III) oxidation to Mn(IV) is the primary cause of Mn/Mn_3O_4 activity loss during ORR/OER potential cycling. To address it, an electrochemical activation method using Co(II) is proposed. By incorporating Co(II) into MnO_x, new active sites are introduced and the content of Mn(II) is increased, which can stabilize the Mn(III) sites through comproportionation with Mn(IV). The Co-incorporated Mn/Mn_3O_4 has vastly superior activity and durability compared to the pristine core-shell and EMD. Furthermore, it also surpassed the activity of Pt/C-IrO_2 with similar durability. Furthermore, insights into the optimization of the gas diffusion O_2 electrode for bifunctional (water electrolysis / fuel cell) operation are provided. This study demonstrates that cost-effective ORR/OER catalysis and associated electrode design could be possible without compromising on performance.

[1] Yu Pei, David P. Wilkinson, Elod L. Gyenge, *Small* 202204585 (2023).

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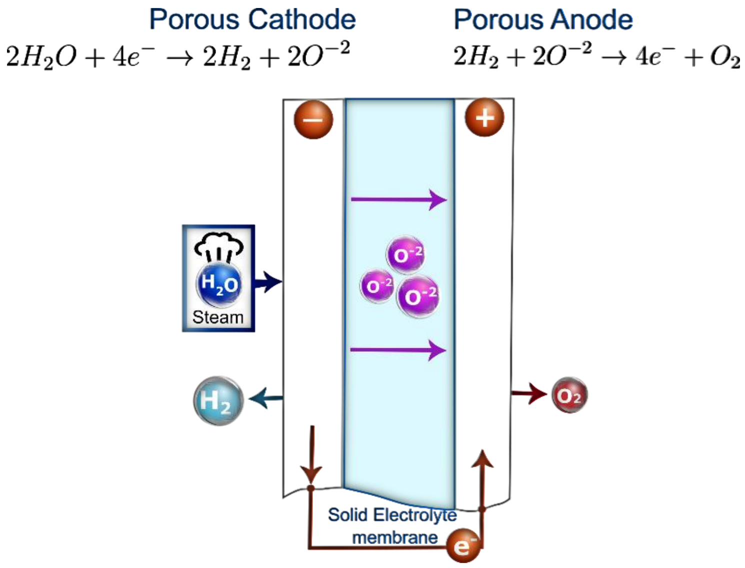

Reversible Operation of Electrolyte-Supported Solid Oxide Cells With Oxide Exsolution Fuel Electrodes

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Solid oxide cells typically utilize Ni-based fuel electrodes that provide high conductivity, good compatibility with electrolytes, and relatively low polarization resistance. Electronically conducting oxide fuel electrodes provide an alternative that can provide similar or even lower polarization resistance than Ni-based electrodes. They should also avoid coarsening and particle migration effects that can lead to long-term performance degradation. However, they have seldom been studied in extended life tests, particularly in reversible and electrolysis operating modes. Here we report on life tests of electrolyte-supported cells utilizing the exsolution electrodes $Sr_{0.95}(Ti_{0.3}Fe_{0.63}Ni_{0.07})O_{3-d}$ (STFN) and $Sr_{0.95}(Ti_{0.3}Fe_{0.63}Ru_{0.07})O_{3-d}$ (STFR) along with $Sr(Ti_{0.3}Fe_{0.6}Co_{0.1})O_{3-d}$ (STFC) oxygen electrodes in reversible operation between electrolysis and fuel cell modes. **Figure 1** shows an example of an ongoing life test with a 12 h cycle showing excellent stability. Results for testing in steam and co-electrolysis modes and also with cell pressurization will be reported, along with pre- and post-test microstructural characterization.

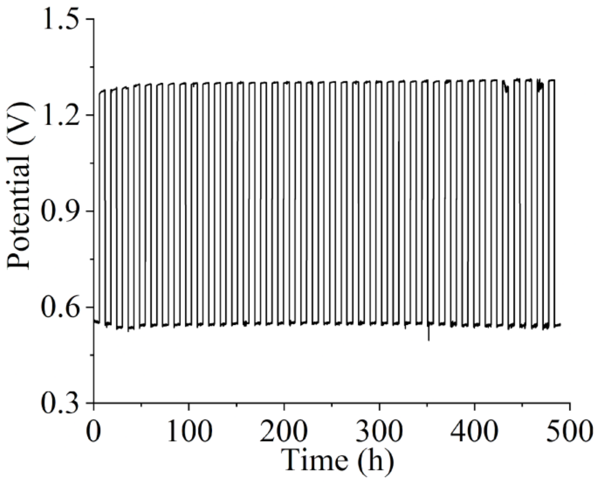

***Figure 1**. Solid oxide button cell life test operated reversibly with 12-hr cycles (6-hr SOFC+ 6-hr SOEC) at 800C and 0.5A/cm2 current density in 50% H2 + 50% H2O and air. The Sc doped ZrO2 electrolyte has a thickness of 0.13~0.17 (Hionic, Nexceris) with Gd-doped Ceria barrier layers on both sides, $Sr(Ti_{0.3}Fe_{0.6}Co_{0.1})O_{3-d}$ (STFC) positive electrode, and $Sr_{0.95}(Ti_{0.3}Fe_{0.63}Ni_{0.07})O_{3-d}$ (STFN) negative electrode.*

Proton ceramic electrolysers and reversible operation: new insights into their performance and durability in pressurized conditions

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Proton-conducting oxides have several unique characteristics that distinguish them from both higher temperature oxygen ion conducting oxides and lower temperature proton-conducting polymers. By enabling proton-mediated electrochemistry under both dry and wet environments at moderate temperatures (e.g. 400–600 °C), these materials provide unique opportunities to enhance a diverse range of complementary electrochemical and thermochemical processes while providing storage solutions. Significant efforts are devoted to the development of proton conducting ceramic electrolysers (PCE) for the direct production of pressurized hydrogen at intermediate temperature. In this work, we are focusing on the technology developed in several European projects* (WINNER, GAMER, PROTOSTACK), which is based on tubular stack technology. This enables e.g. lowering production cost due to reduction of materials costs and processing steps, lowering environmental footprint, and mitigating mechanical failure to the stack geometry and reduced sealing areas. In this presentation, we will show the current state of the art of tubular PCE technology, from cell to stack design development and testing results of those in pressurized conditions up to 10 bar. Emphasis will be given on their high performance and how process conditions affect the area specific resistance, Faradaic efficiency and durability of the components. This will be supported with the use of multi scale multi physic models developed to simulate and predict materials/components/cells behavior as function of operating conditions. Furthermore, new results obtained on operating novel PCE cell architectures in pressurized reversible mode of operation (fuel cell and electrolysis) for more than 3000 hours will be presented. We will show how each mode of operation impacts the performance and evolution rate of the cell as function of time and operating conditions (temperature, steam content, fuel utilization, etc.). Opportunities and current challenges of this technology will be summarized to provide insights into possible research and industrial development pathways.

*The projects WINNER, GAMER, PROTOSTACK are supported by the Clean Hydrogen Partnership and its members Hydrogen Europe and Hydrogen Europe Research.

Investigation on AC:DC dynamic operations for solid oxide electrolysis cells

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The capacity for electrolysis is expected to undergo significant expansion under the Net Zero Emission scenario, reaching above 700 GW by 2030.[1] However, the global electrolysis capacity currently is at a low level of 1–2 GW. This needs the acceleration of the developments for competitive electrolysis technologies. Solid oxide electrolyser cells (SOE cells) are one of the main potential electrolysis technology which is still under maturing (TRL5-7). [2,3] The primary challenge facing SOE technology is its limited stack lifetime, which typically only lasts around 20,000 hours in laboratory conditions.[2] This is still shorter than the stack lifetimes of Alkaline electrolyzer (60,000–90,000 h[3]) and Proton exchange membrane electrolyzer (PEM, 40,000–80,000 h, information provided by suppliers). In addition, the scale-up for SOE electrolyzer is another obstacle to the large-scale implementation and commercialization of this technology. Currently, the cell (active area) and single stack size are at the levels of 100 cm2 and 12.5 kW[2], respectively, which are much lower than those of the commercialized alkaline electrolyzer (scale in MW) and PEM electrolyzer (scales in hundreds of kW).

This work investigated the dynamic operation method for SOE named "AC:DC", which has been proposed in recent times and proved to effectively address the two challenges mentioned above.[4,5] The results of both experimental and modeling studies on SOE cell under AC:DC operations are presented. The potentials of AC:DC in improving lifetime and temperature variations for SOE cell are discussed.

Acknowledgment

This research is part of the MESH project, which has been supported by Innovation Fund Denmark (Grant No. 0143-00023B).

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[2] Hauch, A.; Küngas, R.; Blennow, P.; Hansen, A. B.; Hansen, J. B.; Mathiesen, B. V.; Mogensen, M. B. Recent Advances in Solid Oxide Cell Technology for Electrolysis. *Science (80-.).* **2020**, *370* (6513), eaba6118.

[3] Schmidt, O.; Gambhir, A.; Staffell, I.; Hawkes, A.; Nelson, J.; Few, S. Future Cost and Performance of Water Electrolysis: An Expert Elicitation Study. *Int. J. Hydrogen Energy* **2017**, *42* (52), 30470–30492. https://doi.org/10.1016/J.IJHYDENE.2017.10.045.

[4] Jensen, S. H.; Graves, C. R.; Mogensen, M. B. Electrolysis System with Controlled Thermal Profile. Google Patents June 30, 2022.

[5] Skafte, T. L.; Rizvandi, O. B.; Smitshuysen, A. L.; Frandsen, H. L.; Høgh, J. V. T.; Hauch, A.; Kær, S. K.; Araya, S. S.; Graves, C.; Mogensen, M. B. Electrothermally Balanced Operation of Solid Oxide Electrolysis Cells. *J. Power Sources* **2022**, *523*, 231040.

PEM-like alkaline water electrolysis using flow-engineered 3-D electrodes

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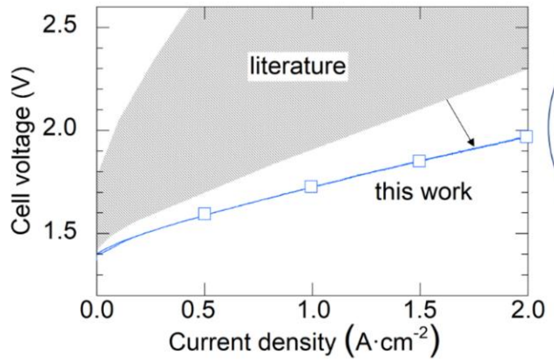
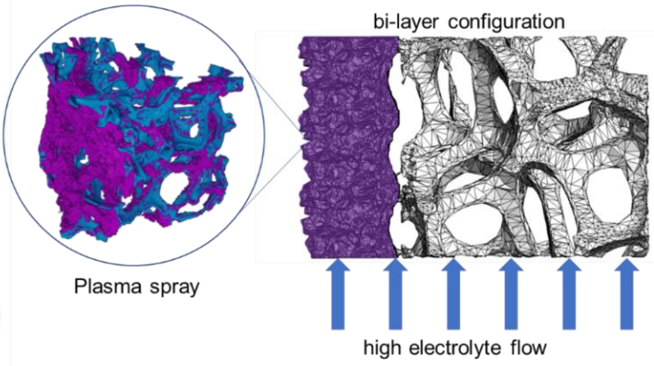
As shown in the **Figure** below, the alkaline water electrolysis performance obtained in this work significantly outperforms the ones reported in the recent literature for Ni-based electrodes separated by a Zirfon diaphragm at typical operating conditions (70-80°C, 30wt% KOH). Reasons for the performance enhancement include plasma spray coating, forced upstream electrolyte flow and the use of 3-D zero-gap electrodes in bi-layer configuration flow-engineered for enhanced gas evacuation.

Firstly, plasma spraying caused a reduction up to 18% in cell voltage at a current density of 2 $A{\cdot}cm^{-2}$. This is partly related to a significant increase in surface area. The plasma coating is done with a powder containing Ni and Al. The Al is then leached out in order to obtain a Raney Ni alloy. What remains is a highly porous and rough surface with a higher surface area: 205 $cm^2{\cdot}cm^{-3}$ compared to 119 $cm^2{\cdot}cm^{-3}$ before coating, according to X-ray tomography analysis. The second factor is related to the presence of Mo in the powder used to prepare the cathode. Like Al, Mo is leached out, causing an increase in surface area. Moreover, a reduction in Tafel slope was observed when Mo was present, from 168-190 $mV{\cdot}dec^{-1}$ to 44-55 $mV{\cdot}dec^{-1}$, indicating a significant electro-catalytic effect.

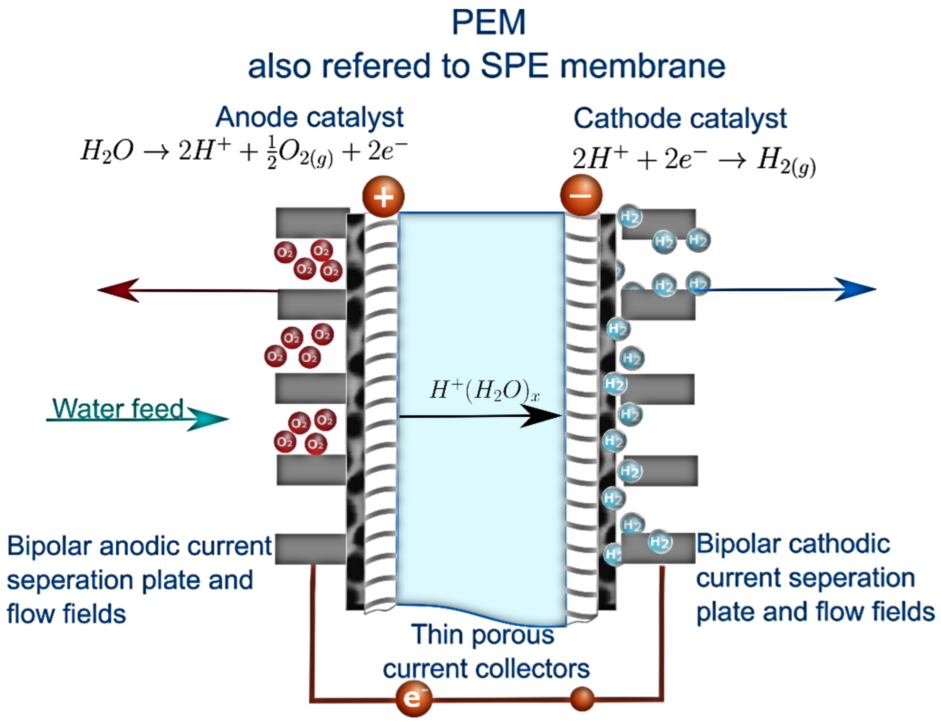
Secondly, subtracting out the Zirfon separator resistance, an increase in electrolyte superficial velocity from 0.05 $m{\cdot}s^{-1}$ to 0.22 $m{\cdot}s^{-1}$ caused a decrease in ohmic resistance of 12-14%. This is a direct result of an improved bubble removal efficiency. The presence of gas bubbles at the electrode surface is indeed known to decrease the active surface area, while their presence within the electrolyte also increases the electrolyte resistance.

Finally, with the help of computational fluid dynamics simulations, a bi-layer electrode configuration was designed to enhance gas removal. It consists of two layers. The first one, a thin layer (1.6 mm) of a Ni foam with a relatively low pore size (450 µm), acts as the gas production layer. The second one is a thick (4 mm) plasma coated Ni foam with a relatively high characteristic pore size (3000 µm), acting as a gas extraction layer. As a result of enhanced gas evacuation under forced upstream electrolyte flow, the ohmic resistance when using this bi-layer configuration was as low as 0.13-0.15 $\Omega{\cdot}cm^2$.





Monday 28th August – Session 5A



Novel microporous layers for PEM electrolysis with low iridium loadings and thin membranes

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Guido Bender [b] and Felix N. Büchi [a]

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Porous transport layers (PTL) and their interfacial properties can significantly impact the quintessential need for cost reduction and performance improvement in PEM water electrolyzers. This work introduces a new generation of titanium microporous layers (MPLs) with ultra-low thicknesses (~20 µm) and advanced interfacial properties. These materials are tailored to achieve improved catalyst layer (CL) utilization at low Ir loadings and for facilitating the use of thinner membranes at safe H_2 crossover rates, ultimately improving the system's turndown ratio. Two types of MPLs were prepared in a calendaring process using different kinds of Ti-particles on a Ti-fiber-based support layer. The bulk morphology and the surface properties of the hierarchically structured PTLs were assessed by X-ray tomographic microscopy (XTM). We characterized and compared the electrochemical performance, focusing on benchmarking the MPLs/PTLs with low iridium-loaded catalyst layers, where a significant performance improvement was obtained. Furthermore, the hydrogen crossover was characterized where at low current densities significantly lower H_2 crossover was observed when an MPL was employed. Implementing this new generation of multilayered PTLs in industrial-relevant sized electrolyzer stacks provides the potential to widen the operating range usually limited by crossover or efficiency at low and high current density, respectively.

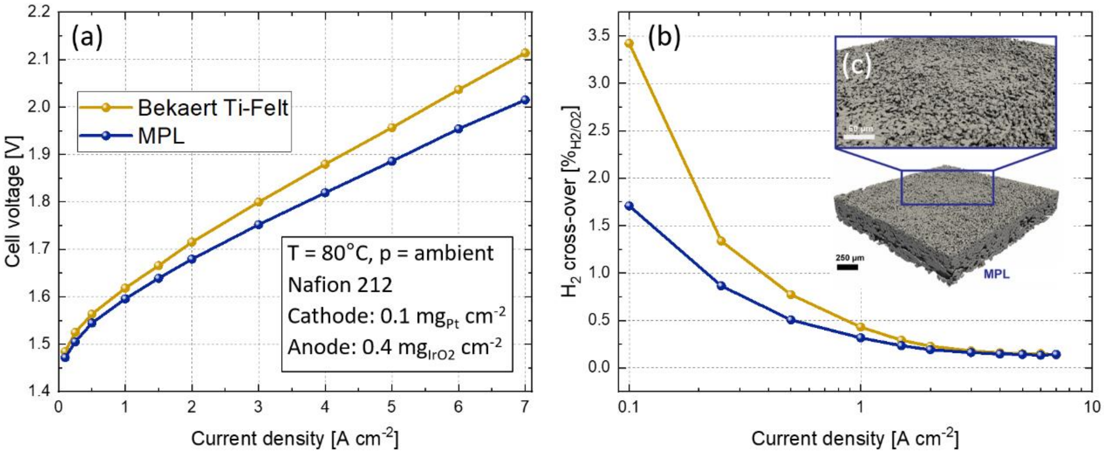

Figure 1 *(a) Polarization curves and (b) measured H_2 crossover of the cells with MPL and the commercial reference (Bekaert) (c) XTM-based surface rendering of the multilayered structure with the MPL on the top part.*

Exploring Two Reference Electrode Setups in PEMWE: Experimental Investigations and Findings

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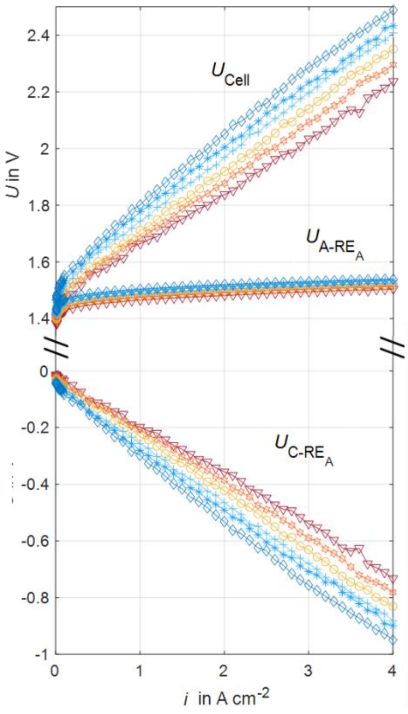
Proton exchange membrane water electrolysis (PEMWE) systems require reference electrodes (RE) to accurately measure the individual electrode potentials, and this presentation focuses on exploring two different RE setups and their experimental investigations in PEMWE.

The first one is a salt bridge reference electrode (SBRE), which probes to the proton potential of the catalyst layer at the interface to the porous transport layer (PTL). It has been used for analysis of half-cell kinetics. At current densities beyond 0.1 A cm^{-2}, a trade-off between the needed ionic connectivity of the PTL and additional losses limited the application[1]. A systematic study was carried out to improve the PTL impregnation with ionomer resulting in almost no performance decline. The improved setup was used to study the effect of temperature on the half-cell kinetics from 80 to 30 °C. Corresponding polarization curves are presented in **Figure 1**, with UA-REA including the kinetic overpotential from oxygen evolution reaction and electric losses at the anode, UC-REA containing all remaining losses from the protonic losses in the anode ionomer to the cathode bipolar plate.



The second type is a platinum wire micro-reference electrode based on the concept of a dynamic hydrogen electrode[2]. The wire is in contact with the membrane outside the active CL area in an isolated compartment of humidified hydrogen. A total of 119 individual tests are carried out to assess the RE reproducibility. The results of the half-cell potential with HFR measurements, and kinetic analysis lead to a discussion on the prevalence of misalignment in solid state systems and the benefits of using EIS to diagnose it. Finally, the robustness and the limitations of the method are discussed through a set of variations of influencing parameters.

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Degradation of Iridium Oxide Anodes During Oxygen Evolution in Sulfuric Acid

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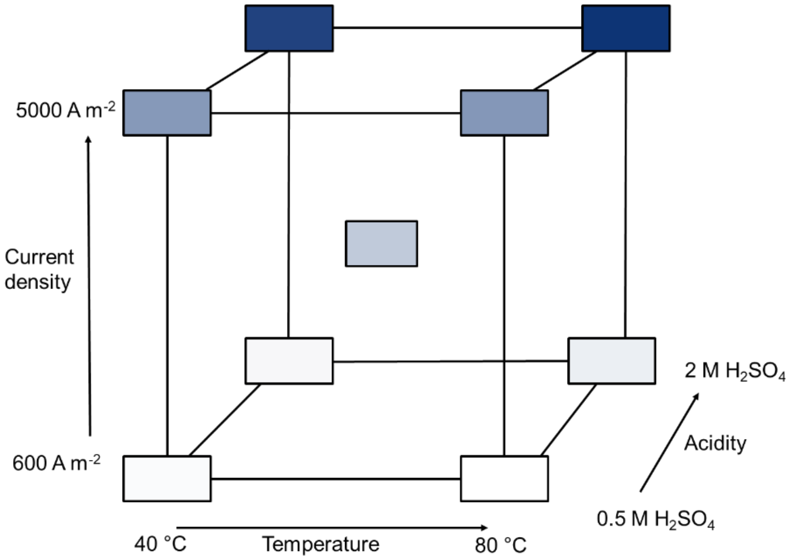
The oxygen evolution reaction (OER) is a technologically important reaction both in water electrolysis and in other electrolysis processes such as copper and zinc electrowinning. Iridium oxide is the preferred catalyst for oxygen evolution in terms of energy efficiency and stability. However, the cost of iridium is a major obstacle towards large scale introduction in copper and zinc electrowinning. Consequently, it is important to maximize the lifetime and stability of iridium oxide electrodes in electrochemical processes involving OER. In this work we investigate how current density, electrolyte temperature and acidity influence the stability of the catalyst as well as the entire electrode.

The electrodes studied in this work are commercially available mixed metal anodes. These consist of a titanium substrate coated with a catalytic layer containing both iridium oxide and tantalum oxide. Degradation of such electrodes can occur by consumption of catalyst material, but also by other mechanisms such as passivation of the base metal. The latter is known to be most prominent at high current densities[1], and this can make it challenging to predict the real lifetime of electrodes based on accelerated tests. In this work dissolution of the catalyst is measured using inductively coupled plasma mass spectrometry (ICP-MS) and passivation of the electrode is monitored using electrochemical impedance spectroscopy (EIS). The catalyst dissolution rate is measured both for unused electrodes and for electrodes that has been run at 5000 A m^{-2} for 10 days, since previous studies have shown that the dissolution rate is large initially before reaching a steady state.[2]

Fig 1. Iridium dissolution rate of mixed metal anodes at different current density, electrolyte temperature and acidity.



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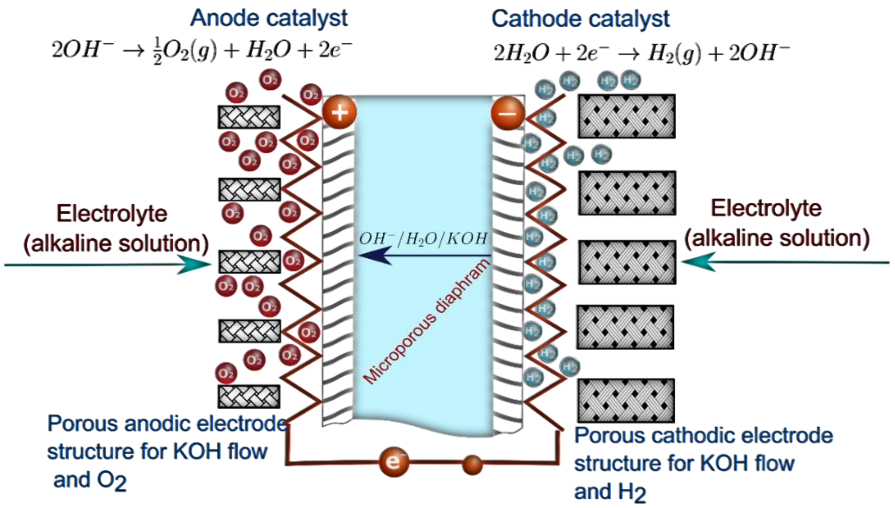
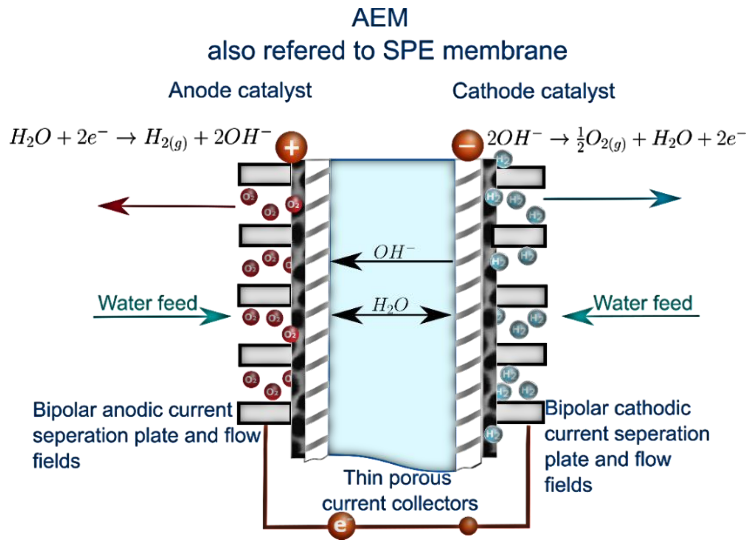
Monday 28th August – Session 5B





Effect of Fe doped electrolyte on advanced alkaline water electrolysis

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Within alkaline water electrolysis, Fe is an omnipresent ion, that is frequently encountered. It may originate from steel pipes, electrolyser components, and KOH impurities. The impact of dissolved Fe in KOH electrolyte on the electrolyser performance is, however, not yet well researched and understood.

We performed studies at near industrial conditions, with varying concentrations of added Fe ([Fe] = 0 µM; 25 µM; 50 µM; 500 µM) in 30 wt.% KOH electrolyte and its effect on the cell performance in a single mixed flow cell at different temperatures (T = 20 °C; 50 °C; 85 °C) using perforated Ni plates as electrodes. The [Fe] in the electrolyte was monitored pre and post electrolysis using ICP-OES, while Fe deposition on cathode and anode was analyzed using SEM/EDX and XPS (see **Figure 1**). For electrochemical characterization, chronopotentiometry and electrochemical impedance spectroscopy were conducted to obtain IV and Nyquist plots, respectively. From the obtained data we were then able to determine the internal resistance corrected IV plots and combined Tafel slopes for cathode and anode.

From the internal resistance corrected cell potential we are able to observe that an increasing [Fe] leads to a decrease in cell potential throughout all current densities (see Figure 1). This effect can be seen even at [Fe] = 500 µM, which is above the solubility limit of Fe in the electrolyte. The enhancement above the solubility limit could be due the formation of mobile Fe hydroxide colloids in the electrolyte. We have further conducted 3-electrode measurements in a steady state cell under the same conditions to show how Fe deposition on cathode and anode changes their respective overpotentials for OER and HER. Our studies results suggest that Fe doped electrolyte can significantly decrease the cell potential in close to industrial conditions by improving reaction kinetics.

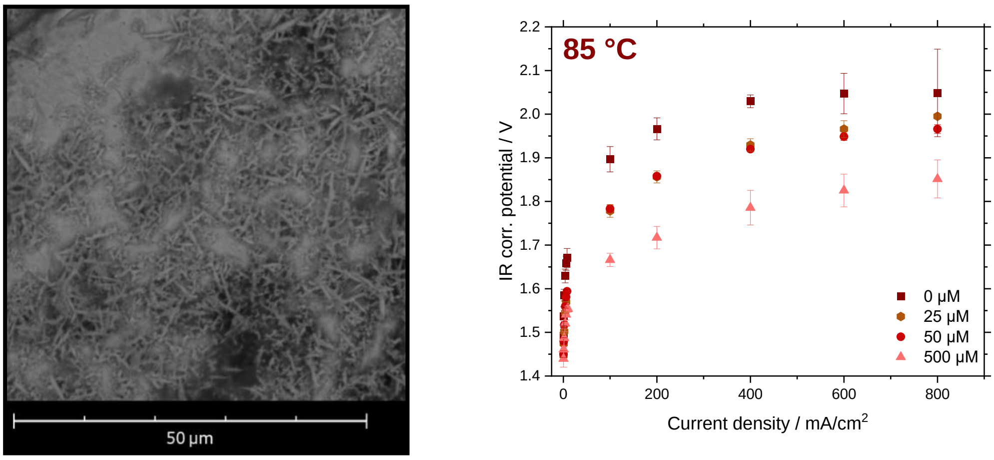

***Figure 2**: (Left) SEM image of Fe dendrite formation on cathode post electrolysis with 30 wt.% KOH containing 50 µM of Fe and (Right) internal resistance corrected IV plots at varying [Fe] in 30 wt.% KOH at 85 °C.*

Large scale Zirfon production to meet REPowerEU ambitious hydrogen plan

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ZIRFON® is today regarded as the state of the art membrane for alkaline water electrolysis. However, due to a lack in green hydrogen demand, the ZIRFON® sales up to end 2021 remained rather limited. Due to the REPowerEU plans, the ambition is to produce 10 million tonnes and import 10 million tonnes of renewable hydrogen in the EU by 2030. It is expected this will result in an exponential growth over the coming years, which was already evident in the course of 2022 (see **graph 1**).

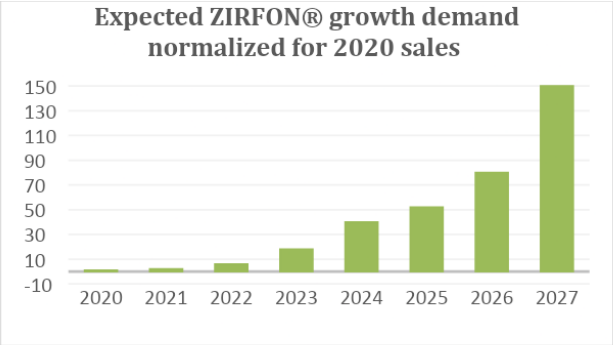

Fig 1: *Expected Zirfon growth demand normalized for 2020 sales.*

To follow this exponential growth in ZIRFON® demand, expansion of and innovations in Agfa's production facility are required. ZIRFON® is to date produced on one smaller production line which should be optimized, further automated and upscaled.

End Q1 2023 Agfa will decide upon the installation of a new state of the art production line for its ZIRFON® portfolio (**Fig 2**). This production line will expand the current manufacturing capacity available in Mortsel, Belgium to avoid supply interruptions to customers. Expected to be delivered in Q2 2025, this new ZIRFON® production line will provide Agfa with an additional ZIRFON® output worth of 20 GW of hydrogen production capacity. Combined with the available production capacity, Agfa will be able to contribute towards 23 GW of newly installed hydrogen production yearly.

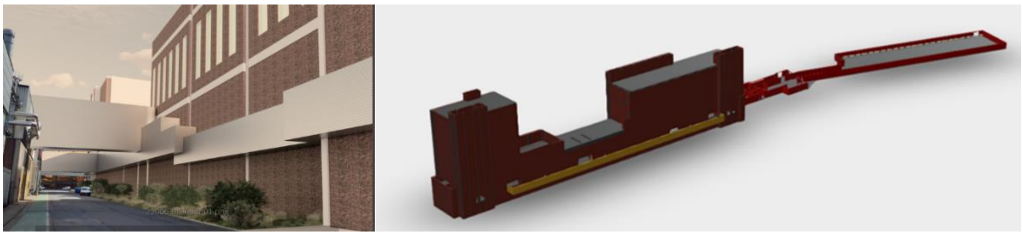

Fig 2: *Agfa's new state of the art ZIRFON® production line*

To successfully put this new production line into service, Agfa will use these coming years to Q2 2025 to investigate thoroughly the process parameters of ZIRFON® production. Deeper understanding of the process, with a focus on dope preparation, changed raw materials, changes in VIPS and LIPS at production, changes of solvents and/or remaining solvent in the membrane after production and reproducibility is key. By fundamentally understanding each process parameter and its relation to the end membrane morphology and performance, the manufacturing process can be simplified and tuned towards the customer requirements.

With a customer focused portfolio which is available at large scale Agfa aims to remain, also in the years to come, the worldwide leader in membrane manufacturing for alkaline water electrolysis.

Effect of Hydroxide Concentration on the Activity of NiFe-based Anodes in Anion Exchange Membrane Water Electrolysis

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Anion Exchange Membrane Water Electrolysis (AEMWE) is a promising technology for green hydrogen production with high efficiency using non-noble materials. Thanks to the alkaline environment, inexpensive Ni-based catalysts can be employed in the electrodes for both the hydrogen evolution reaction (HER) and the oxygen evolution reaction (OER) together with an anion exchange membrane.[1] The research focus on a pure water-fed operation introduces new challenges on both material and device level and systematic studies are needed for a deeper understanding.[2]

In this study, we investigate the effect of KOH concentration on the activity of AEMWE cell having platinum-group-metal-free (PGM-free) catalysts in both anode and cathode. A membrane electrode assembly (MEA) was prepared with decal transfer using NiFe nanoparticles and anion exchange ionomer in the anode, and voltage loss analyses were performed at varying KOH concentration. Ionic and electronic resistances were identified using a Transmission Line Model with and without conductive additives as a proof-of-concept. Our results show that NiFe catalysts suffer from poor electronic conductivity especially at OER conditions, and the conductive additive improves both the cell resistance and the catalyst layer utilization. We also propose Ni255 as conductive and stable additive for OER electrodes.

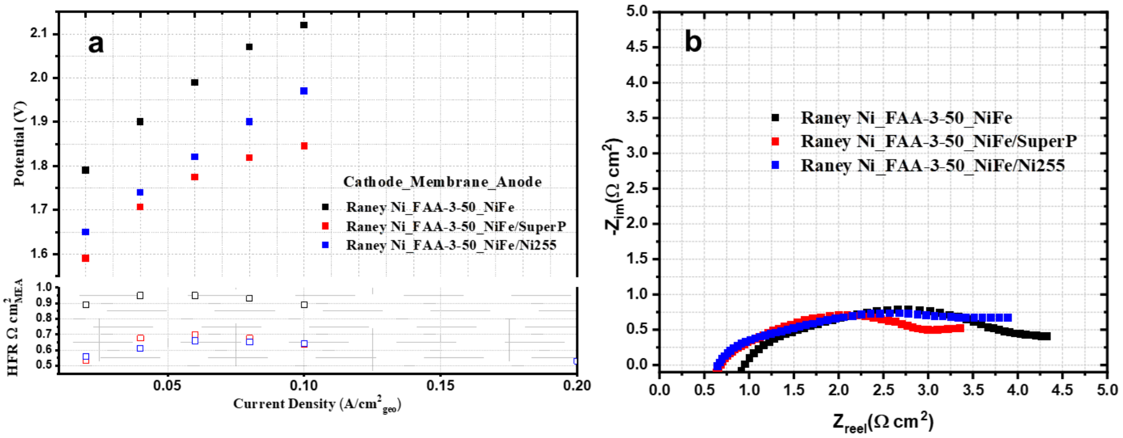

Figure 1. *Polarization curves (a) and Nyquist plots (b) for the MEAs with NiFe, NiFe/Super P and NiFe/Ni255 anodes in 0.01 M KOH.*

[1] Vincent, I.; Bessarabov, D. Low Cost Hydrogen Production by Anion Exchange Membrane Electrolysis: A Review. *Renewable and Sustainable Energy Reviews* **2018**, *81*, 1690–1704. https://doi.org/10.1016/j.rser.2017.05.258.

[2] Ito, H.; Kawaguchi, N.; Someya, S.; Munakata, T.; Miyazaki, N.; Ishida, M.; Nakano, A. Experimental Investigation of Electrolytic Solution for Anion Exchange Membrane Water Electrolysis. *International Journal of Hydrogen Energy* **2018**, *43* (36), 17030–17039. https://doi.org/10.1016/j.ijhydene.2018.07.143.

Tuesday 29th August – Session 6

Durability of polymer electrolyte membrane water electrolyzers

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The Department of Energy has set ambitious goals for hydrogen production costs of $2/kg by 2026 and $1/kg by 2031 via net zero carbon pathways in support of the including the Hydrogen Energy earthshot.[1] Water electrolysis is expected to play a vital role in reaching these goals, with the Hydrogen from Next generation Electroyzers of Water (H2NEW) Consortium leading Research and Development activities in Polymer Electrolyte Membrane Water Electrolyzers (PEMWE), Solid Oxide Electrolysis Cells (SOEC) and next generation liquid alkaline water electrolyzers.[2] This talk will provide a brief outline of the H2NEW consortium structure, highlight some recent research in PEMWEs and discuss in detail the durability of PEMWEs.

A critical issue in the widespread deployment of PEMWEs is the scarcity of Iridium (Ir) which is used in its oxide form as the anode catalyst. The lowering of Ir content and recycling of the Ir that is used, are essential for PEMWEs to play an important role in clean hydrogen production.[3] However, the performance and durability of PEMWEs is tied to the amount of Ir used in the anode. This talk will discuss the stability of the anode catalyst under various operating conditions including shut-down and start-up scenarios where the anode potential can be lower than the Ir/IrOx redox potential. The cell voltage during start-up and shut-down is not a reliable measure of the anode potential since H_2 is removed from the cathode. A reference electrode can be used to track the individual anode and cathode potentials during these operating scenarios and is essential in understanding the degradation of both the anode and cathode catalysts. Extensive characterization of the catalyst will be presented and catalyst degradation mechanism will be discussed in this talk.

[1] https://www.energy.gov/eere/fuelcells/hydrogen-production
[2] https://h2new.energy.gov
[3] https://matthey.com/documents/161599/0/JM+Iridium+White+Paper.pdf/db45aebe-8182-2fc1-548a-a3072a4e6423?t=1669022842596

Hydrogen Production in a Hybrid-Sulfur Process

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Increasing demand for hydrogen are driving the need for the development of more efficient methods to produce hydrogen on a large scale. The main methods for hydrogen production include reforming of hydrocarbons such as natural gas, coal gasification, biological processes, water electrolysis, and thermo-chemical cycles. The processes involving hydrocarbons contribute to CO_2 emissions, and biological processes may not be cost effective on a large scale. Electrolysis is commercially viable but may be too inefficient for large-scale applications. Hence the interest in using thermochemical cycles for large-scale hydrogen production. Thermochemical cycles produce hydrogen through a series of chemical reactions that result in the splitting of water at much lower temperatures (~500-1000ºC) than direct thermal dissociation (>2500ºC). All other chemical species in these reactions are recycled resulting in the consumption of only heat and water to produce hydrogen and oxygen. Since water rather than hydrocarbons are used as the source of hydrogen in these thermochemical cycles, no carbon dioxide emissions are produced and the hydrogen is highly pure.

Although there are hundreds of possible thermochemical cycles, the hybrid-sulfur (HyS) process is the only practical, all-fluid, two-step thermochemical cycle. If the energy input into the process is solar energy, solar radiation is used in a solar receiver/reactor to provide the energy needed to vaporize and decompose sulfuric acid. The resulting sulfur dioxide (SO_2) is used in the second step consisting of an SO_2-depolarized electrolyzer (SDE) that electrochemically oxidizes SO_2 with water to form sulfuric acid at the anode and hydrogen at the cathode (blue reaction). All sulfur species are recycled, and the overall reaction is the splitting of water to form hydrogen and oxygen. Excess SO_2 is stored during daylight operation and used at night to permit continuous electrolyzer operation and hydrogen production. Electricity is supplied from a companion solar-electric plant or obtained from the grid. Approximately 80% of the energy input to the process is solar-thermal energy, and 20% is electricity for the electrolyzer and auxiliaries. We have developed and patented a gas-fed SDE that we tested over a range of operating conditions (e.g., current, temperature, SO_2 flow rate) and design variations (e.g., catalyst type and loading, membrane type and thickness). Results of our research will be presented and the challenges that remain in making this an economically viable process for large-scale hydrogen production will be presented.

REFHYNE - From 10 to 100 MW PEM electrolysers

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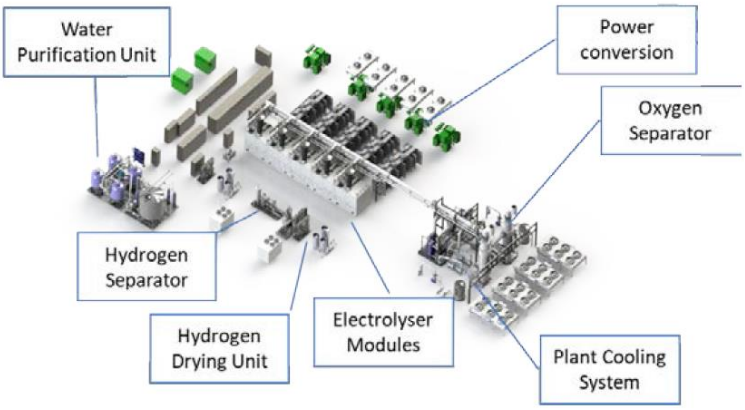
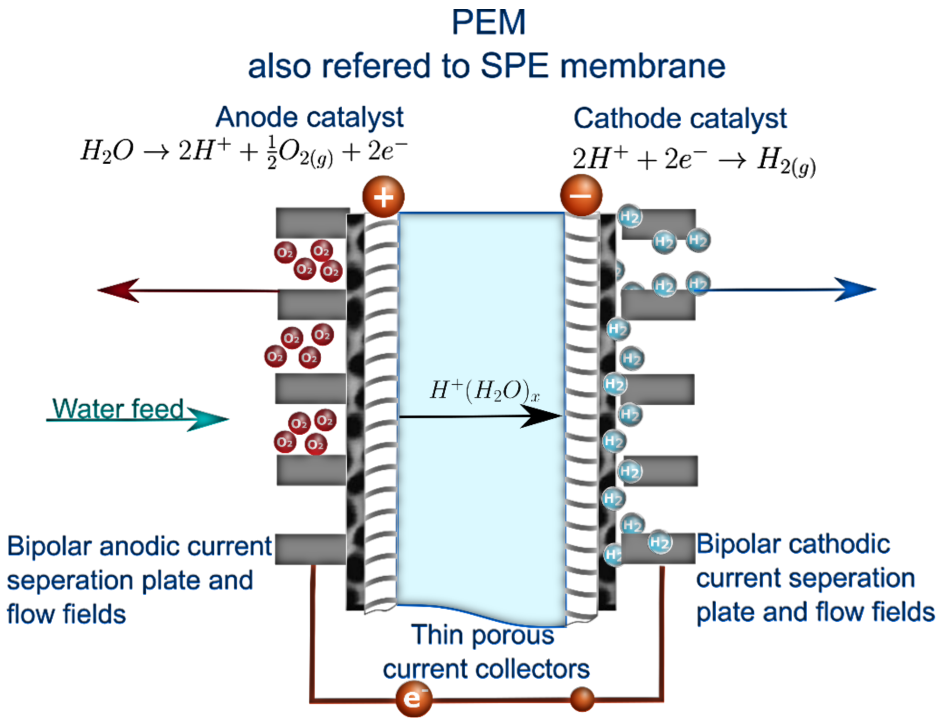
The REFHYNE 10MW electrolyser system from ITM Power is installed at the Shell Energy and Chemicals Park, Wesseling, Germany. It consists of 15 MEP stacks contained in five modules, with a total maximum hydrogen production rate of 4000 kg per day. The inauguration of the electrolyser system was in July 2021, and it is now mechanically complete and fully integrated in the control system of the refinery process plant. Before the main operational phase began, the electrolyser was run for over 1200 hours and produced more than 21,000 kg hydrogen.



Learnings from the 10 MW project feeds in to REFHYNE 2, which takes the next step to 100 MW-size electrolysers. Amongst other things, the REFHYNE project has shown the importance of BoP components and support systems, and how vulnerable large electrolyser systems are to external components and factors. Most of the challenges experienced in operation have been related to peripheral or BoP equipment. Related to that is also communication software integration of the electrolyser controls with the overall chemical plant and other relevant processes. Further upscaling will lead to more complex systems and interdependencies, where one important aspect is renewable power and the impact on dynamic operation. It's no longer the highly responsive electrolyser itself which will be the main design challenge, but the overall electrolyser plant and integrated or linked processes. Many other components also impact flexibility. Some of these can be much slower/static than the electrolyser itself. Also, the offtaker and/or storage/distribution might be a bottleneck or limitation to the direct connection between a large electrolyser and intermittent energy systems.

Tuesday 29th August – Session 7



Electrochemistry Meets Big Data: Rapid Acquisition and Analysis of >20,000 Measurements via Novel Hybrid Electrochemical Impedance Spectroscopy (HEIS) Method Provides New Insights into Reversible Protonic Ceramic Electrolyzer/Fuel Cells.

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The fundamental relationships between performance metrics, impedance spectra, and electrochemical processes in electrolysis devices and other electrochemical systems are highly complex and often difficult to disentangle. This lack of knowledge hinders identification and evaluation of physicochemical processes, limits understanding of how materials and device architecture influence performance, and ultimately inhibits principled design choices. There is a need for practical, robust procedures to gain physical insight into electrochemical device performance. This requires effective design of experiments to sufficiently characterize varying conditions within reasonable time constraints. In addition, new methods for coherent analysis of large electrochemical datasets are necessary to extract meaning from vast amounts of raw data.

Here, we introduce a novel approach to accelerate electrochemical characterization with standard instrumentation by utilizing rapid measurements in both the time and frequency domains. This “hybrid electrochemical impedance spectroscopy” (HEIS) method provides excellent resolution across a broad range of timescales while decreasing measurement time by more than an order of magnitude compared to conventional electrochemical impedance spectroscopy. The technique can be applied to quickly construct detailed electrochemical maps of energy conversion devices across multiple measurement condition dimensions, revealing physicochemical relationships that are hidden in sparse conventional datasets. We use this new approach to comprehensively characterize reversible protonic ceramic electrolyzer/fuel cells (PCECs) under different temperature, atmosphere, and bias conditions. Altogether, more than 20,000 distinct HEIS experiments are performed, resulting in a rich dataset that can be assembled to form relaxation hypersurfaces - multi-dimensional analogs of the one-dimensional distribution of relaxation times (DRT) - which are then processed with new analysis techniques to reveal the underlying processes that govern device performance. This approach describes the electrochemical behavior of PCECs with an unprecedented level of detail made possible by accelerated measurement and scalable data processing strategies. However, this study represents just one possible form of the mapping concept. The underlying principles and techniques can be adapted to develop various new ways to examine a wide variety of energy-conversion devices. The conceptual approach demonstrated here has the potential to reduce the time required to understand electrochemical materials and device architectures, enabling a faster design cycle.

All-hydrocarbon PEM water electrolyzers: An engineering perspective

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[a]Hahn-Schickard, Germany, [b]Electrochemical Energy Systems, IMTEK - Department of Microsystems Engineering, University of Freiburg, Germany; [c]Agricultural University of Georgia, Georgia, [d]Max-Planck-Institut für Festkörperforschung, Germany;

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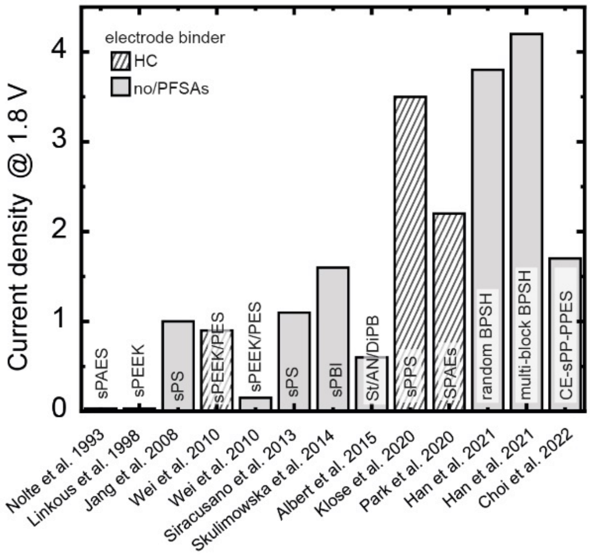
The most common polymers used in polymer electrolyte membrane water electrolysis are perfluorosulfonic acids (PFSAs) due to their high proton conductivity and mechanical and chemical stability. However, hydrocarbon materials are being explored as an attractive alternative to PFSAs since their distinct properties promise lower gas permeation while maintaining high efficiency (**Figure 1**) [1,2]. The crucial next steps to increase the technological maturity of fully hydrocarbon-based membrane-electrode assemblies are i) to improve their long-term stability and ii) to investigate scalable manufacturing [2]. In this regard, we present i) potential crosslinking strategies and mechanical membrane reinforcements to improve the lifetime and ii) the utilization of direct coating of the electrodes onto hydrocarbon membranes for the fabrication of membrane-electrode-assemblies on larger scales. Both developments contribute to the positive perspective of hydrocarbon membranes in next generation electrolyzers.



[1] Klose, C.; Saatkamp, T.; Münchinger, A.; Bohn, L.; Titvinidze, G.; Breitwieser, M.; K.-D. Kreuer; Vierrath, S. All-Hydrocarbon MEA for PEM Water Electrolysis Combining Low Hydrogen Crossover and High Efficiency. Adv. Energy Mater. 2020, 10(14), 1903995.

[2] Nguyen, H.; Klose, C.; Metzler, L.; Vierrath, S.; Breitwieser, M. Fully Hydrocarbon Membrane Electrode Assemblies for Proton Exchange Membrane Fuel Cells and Electrolyzers: An Engineering Perspective. Fully hydrocarbon membrane electrode assemblies for proton exchange membrane fuel cells and electrolyzers: An engineering perspective. Adv. Energy Mater. 2022, 12(12), 2103559.

Extraction of performance data from dynamic operating profiles of PEM water electrolysis cells

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The direct coupling of polymer electrolyte membrane water electrolyzers (PEMWE) and renewable energy sources represents a promising method to store green electricity. However, this dynamic mode of operation has the disadvantage that ageing of the electrolyzer during operation is usually not recorded. Classic approaches to specify performance data of electrolyzers based on polarisation curves can only be applied with an interruption of operation. In addition, polarisation curves do not necessarily reflect the behaviour of the electrolyzer in ongoing dynamic operation. Higher performance values are usually achieved when polarisation curves are recorded than in dynamic operation with rapid current changes. This finding is due to the typical behaviour of PEMWE cells when the load is switched on. After starting to supply constant current to the cell from rest, the cell potential usually rises within the first few minutes to hours[1]. Depending on how long an operating point was held for plotting a polarisation curve, the slope of the curve will also change and may not adequately reflect the individual performance parameters that the electrolyzer will reach during dynamic operation. Therefore, we herein discuss how to track performance of PEMWE cells over a longer experimental period without interrupting the hydrogen production to improve the monitoring of electrolyzers. On the long run, this method realises a trouble-free monitoring based on real operating data. **Figure 1** shows one possible form of analysis of data points from a dynamic operation of a PEMWE cell.

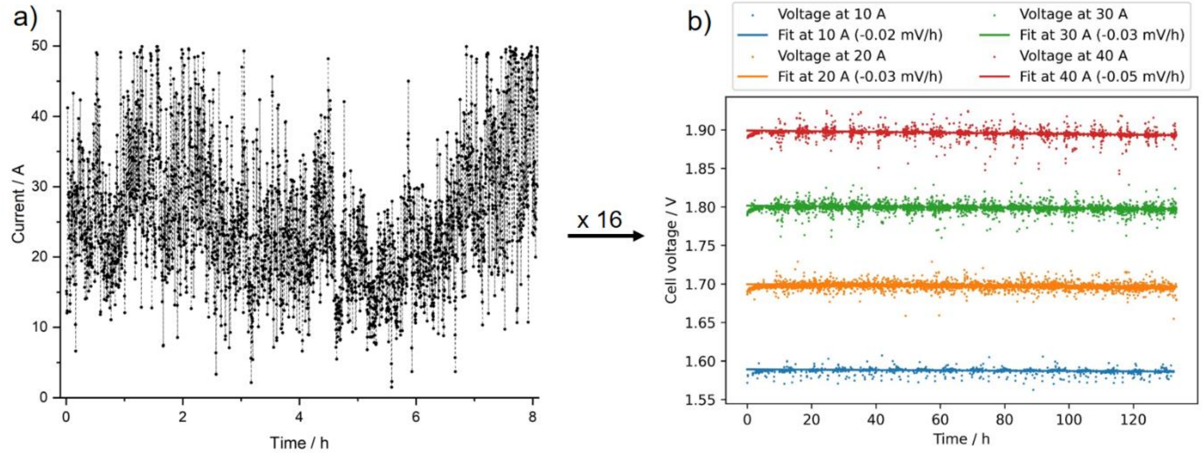
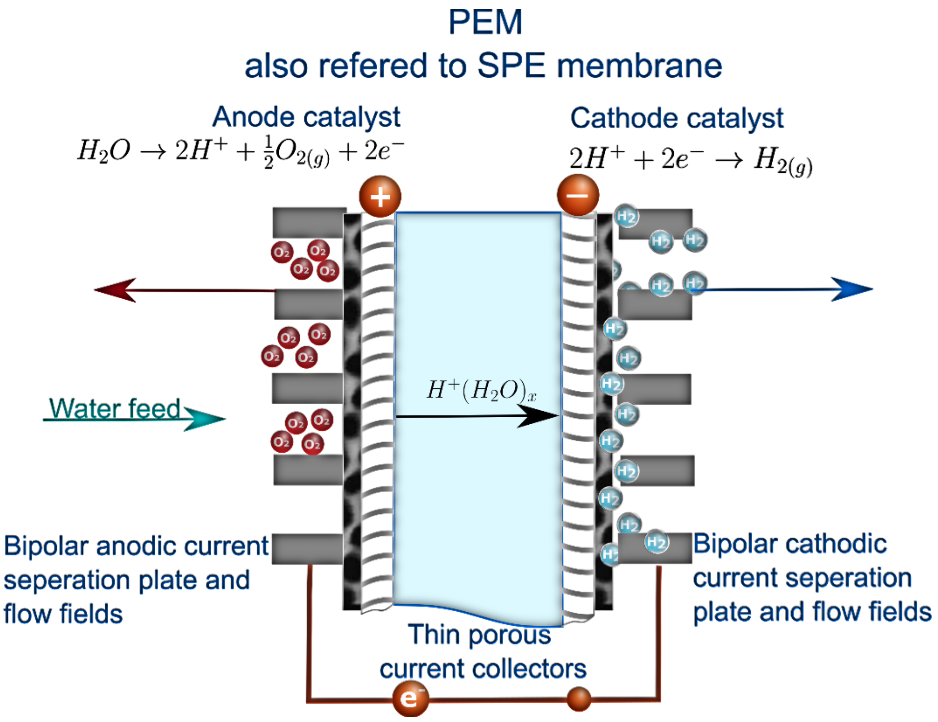


***Figure 1:** a) Current profile for PEMWE cells generated from wind turbine performance data, b) Voltage changes for different current levels during dynamic operation of a PEMWE cell.*

[1] Siracusano, S.; Trocino, S.; Briguglio, N.; Pantò, F.; Aricò, A. S. Analysis of performance degradation during steady-state and load-thermal cycles of proton exchange membrane water electrolysis cells. *J. Power Sources* **2020**, *486*, 228390. DOI 10.1016/j.jpowsour.2020.228390

Tuesday 29th August – Session 8



Performance and Durability of Thin, Reinforced Membranes for PEM Water Electrolyzers

Andrew M. Park[a], Ryan T. Gebhardt[a], Jacob A. Wrubel[b], Kaustubh Khedekar[c], Claire Arthurs[d], Arthur Dizon[d], Benjamin M.S. Wright[a], Meghan G. Vander Woude[a], Ahmet Kusoglu[d], Rodney L. Borup[c], Siddharth Komini Babu[c], Guido Bender[b]

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The hydrogen economy is a critical component of global climate goals, enabled by the widespread adoption of clean hydrogen produced by green technologies such as proton exchange membrane water electrolysis (PEMWE). In order to meet cost targets for produced hydrogen (at or below $1/kg), voltage efficiency must be maximized to most effectively utilize incoming electricity. To accomplish this goal, new membranes specifically engineered for low proton transport resistance and high durability in a PEMWE environment are required.

A multigenerational plan has been established at Chemours to improve the performance of Nafion™ membranes while maintaining their best-in-class durability. One major contributor to membrane improvement is a reduced proton transport resistance, which can be achieved in part by manufacturing thinner membranes. However, as membranes become thinner, they invite higher gas crossover, especially in a high differential pressure environment. Mitigation strategies in the membrane can help to ensure safe operation and long lifetimes of the thinnest membranes in advanced PEMWE membrane concepts.

In this presentation, an overview of the activities and strategic developments within Nafion™ membranes for water electrolyzers will be summarized. The multigenerational product development program will be discussed, highlighting the significant contribution possible from Nafion™ membranes on the development and proliferation of clean hydrogen.

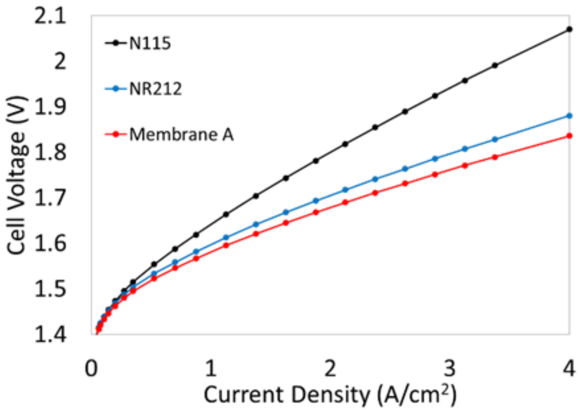

Figure 1: *Comparison between current state-of-the-art PEMWE membranes and R&D alternatives. The cell was operated at 80°C, ambient pressure, and at current densities from 0-4 A/cm^2*

Improved Current Interrupt: An Enhanced Interpretation for PEMWE Cell Characterization

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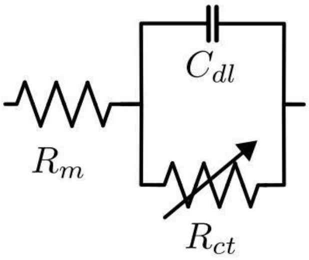
It is common practice to characterize Polymer Electrolyte Membrane Water Electrolysis (PEMWE) cells by Electrochemical Impedance Spectroscopy (EIS) and Tafel analysis [1], which require special equipment and operation procedures. Additionally, these techniques are not suitable for large cells with very low impedances. We will present a much simpler approach based on a novel current interrupt test and improved evaluation. This improved current interrupt grants access to equivalent information as the established standard method, while being applicable to all cell and stack sizes without requiring special equipment.

The current interrupt technique utilizes an instantaneous drop of electric current to identify the membrane resistance R_m, charge resistance R_{ct} and double-layer capacity C_{dl} in a simplified equivalent circuit of the cell. Efforts for interpretation of tests focused on advancing the equivalent circuit to higher complexity [2]. The important improvement of our approach is to consider the non-linear charge transfer coefficient instead of assuming a constant charge transfer resistance (**Figure. 1**). In this work a direct link to results of typical EIS and Tafel analysis is defined by using the improved current interrupt method. The classical elements of voltage breakdown, ohmic resistance, Tafel slope, and exchange current density as well as the capacitance of the equivalent circuit can be directly derived from the time resolved voltage signal after the current interrupt. The agreement with experimental data is significantly improved over the assumption of a constant charge transfer coefficient. Consistency of the proposed interpretation with explicit Tafel and EIS analysis is demonstrated and options for application of the evaluation scheme are discussed as well as simplifications of tests offered by this procedure.



$$R_{ct} = \frac{b_a \cdot ln(i/i_0)}{i}$$

Figure 1: Equivalent circuit used for cell characterization

[1] Millet, P. (2016). Characterization tools for polymer electrolyte membrane (PEM) water electrolyzers. In PEM Electrolysis for Hydrogen Production (pp. 191-230). CRC Press.
[2] Martinson, C. A., Van Schoor, G., Uren, K. R., & Bessarabov, D. (2014). Characterisation of a PEM electrolyser using the current interrupt method. International Journal of Hydrogen Energy, 39(36), 20865-20878.

Overview and new Insights on Recombination Layers for PEM Water Electrolysis

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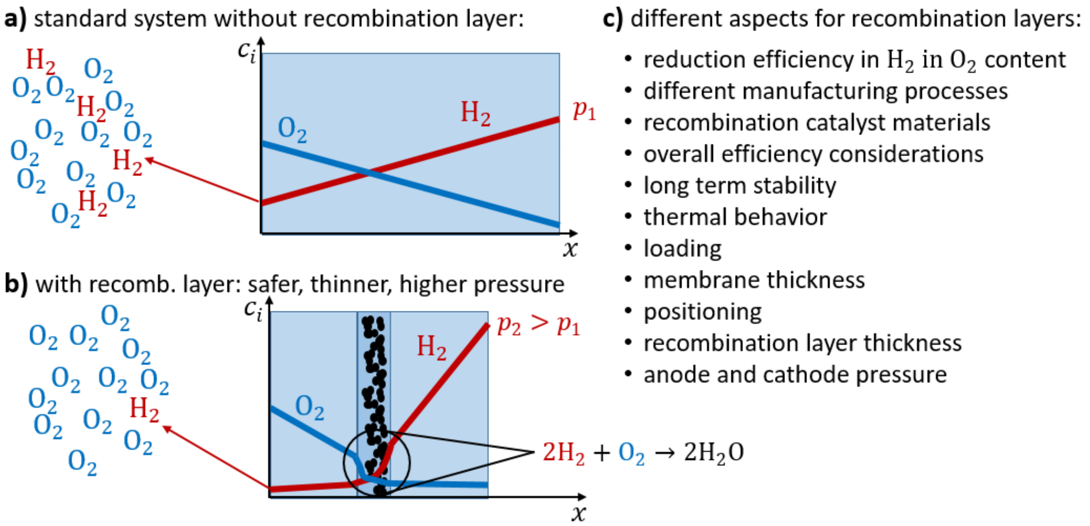
Recombination layers for Proton Exchange Membrane (PEM) water electrolysis enable a direct recombination of permeated hydrogen with oxygen to water. This leads to a strong reduction of the crucial hydrogen in oxygen content of PEM water electrolysis systems and thus recombination layers enable a safe operation. However, the recombination layers not only solve the safety issue and thus increase the partial load capability, but recombination layers also enable the operation with thinner membranes and also at higher hydrogen pressures (**Fig 1. a**) and **b**)). Consequently, recombination layers can increase the system efficiency and reduce the capital costs, e.g. reduction the amount of mechanical compression stages. Thus lead to further reduction of the levelized cost of hydrogen. Therefore, recombination layers are gaining more and more interest[1–3]. However, there are a lot of different methods and options how to realize those layers and still open questions. In this presentation we want to give an overview of the current state of the art on recombination layers. For this purpose, we focus on important aspects (**Fig. 1c**)), collect and comment these findings and give finally a perspective of the further development.



c) different aspects for recombination layers:

- reduction efficiency in H_2 in O_2 content
- different manufacturing processes
- recombination catalyst materials
- overall efficiency considerations
- long term stability
- thermal behavior
- loading
- membrane thickness
- positioning
- recombination layer thickness
- anode and cathode pressure

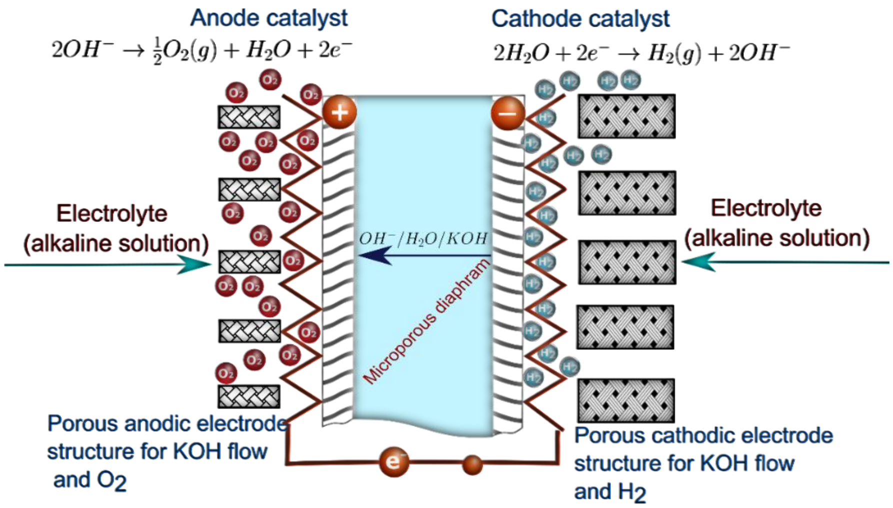
***Fig. 1**: Schemes of the concentration profiles of a typically PEM without recombination layer a) and with recombination layer b). c) shows a list of different interesting aspects of recombination layers.*

[1] Stähler, A.; Stähler, M.; Scheepers, F.; Lehnert, W.; Carmo, M. Scalable Implementation of Recombination Catalyst Layers to Mitigate Gas Crossover in PEM Water Electrolyzers. *J. Electrochem. Soc.* **2022**, *169*, 34522. DOI: 10.1149/1945-7111/ac5c9b.

[2] Garbe, S.; Samulesson, E.; Schmidt, T. J.; Gubler, L. Comparison of Pt-Doped Membranes for Gas Crossover Suppression in Polymer Electrolyte Water Electrolysis. *J. Electrochem. Soc.* **2021**, *168*, 104502. DOI: 10.1149/1945-7111/ac2925.

[3] Klose, C.; Trinke, P.; Böhm, T.; Bensmann, B.; Vierrath, S.; Hanke-Rauschenbach, R.; Thiele, S. Membrane Interlayer with Pt Recombination Particles for Reduction of the Anodic Hydrogen Content in PEM Water Electrolysis. *J. Electrochem. Soc.* **2018**, *165*, F1271-F1277. DOI: 10.1149/2.1241814jes.

Tuesday 29th August – Session 9



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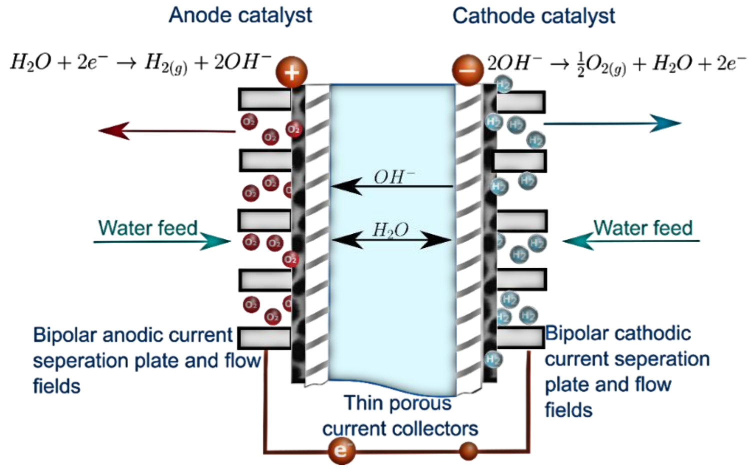

Influence of Fe/Co/Cr-Modification on Raney-Nickel Activity and Stability as Oxygen Electrode Catalyst in Alkaline Water Electrolysis

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Through decentralized electrolysis of water from renewable energies like photovoltaics or wind power, green hydrogen can be used as a chemical energy carrier and feedstock in the chemical industry for e.g., steel, aluminum, fertilizers, methane and ammonia production. This should contribute to reduction of CO_2 emission and help to struggle global warming. Electrochemical alkaline water electrolysis (AWE) is the most technically advanced technology for the industrial production of hydrogen.

To fabricate different Fe, Co and Cr -modified Raney-nickel electrodes, corresponding amount of the metals was melted in a vacuum centrifugal casting furnace. Thus, the ingots were mechanically crushed and Al was leached in 30 wt.% KOH either at room temperature or 80°C for comparison. After leaching treatment, the powder materials were investigated by XRD, SEM/EDX and BET to identify phase formation, particle size/morphology and composition as well as surface area, respectively.

For electrochemical tests, the different powders were mixed with PTFE binder and calendered on a Ni mesh to form a 5 cm^2 Raney-nickel electrode. Effect of Fe, Co and Cr on their activity for OER was investigated by cyclic voltammetry, impedance spectroscopy and short-term (16 h) galvanostatic polarization in half-cell experiments with Ni-foil as cathode and RHE as reference in 30 wt.% KOH at room temperature. Best performing electrodes were further tested for up to 1000 h in a homemade full-cell with a commercial Raney-nickel cathode, a Zirfon 500 diaphragm in 30 wt.% KOH at 80°C. Post-test analysis of electrolyte was performed by ICP-OES for quantifying dissolved elements such as Al, Ni, Fe, Co and Cr. Influence of Raney-nickel phase composition, alloying ratio and electrode porosity on electrochemical activity/stability under AWE condition will be presented.

Let's operate it flexibly: evaluating H_2 crossover in zero-gap alkaline water electrolysis

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The use of a zero-gap assembly with a thinner diaphragm [1] is considered attractive to perform advanced alkaline water electrolysis. It reduces energy losses by minimizing the cathode-anode distance, but also leads to increased H_2 crossover from cathodic to anodic compartment. For electrolyzers operated at well-balanced pressures and industrial flow rates, diffusion is the main contributor to H_2 crossover and local H_2 supersaturation at the diaphragm interface significantly contributes to this [1]. This implies that increasing the gap size between the electrode and the diaphragm should decrease supersaturation and hence suppress H_2 crossover. To confirm this hypothesis, in-situ gas analysis experiments were conducted in an electrolysis setup equipped with in-line gas chromatography.

In **Figure 1-b** it is shown that for a zero-gap assembly, H_2 crossover rates are much higher than equilibrium diffusion rates, confirming a high H_2 supersaturation at the diaphragm interface ($pH_2^{ss,diaphragm}$ in **Figure 1-a**). In contrast, by using a finite-gap of 500 μm the gas crossover is much lower and close to equilibrium diffusion. For the zero-gap design, there are large standard deviation bars in Figure 1-b that could be related to small variations in the gap size between electrode and diaphragm, which can have a large influence on the local supersaturation: an "imperfect zero-gap configuration".

Our work shows that gas crossover is a key aspect for zero-gap alkaline electrolyzers, especially at low load operation. Using an electrode-diaphragm gap of a couple of hundred micrometers could be beneficial to make advanced alkaline water electrolyzer more flexible.

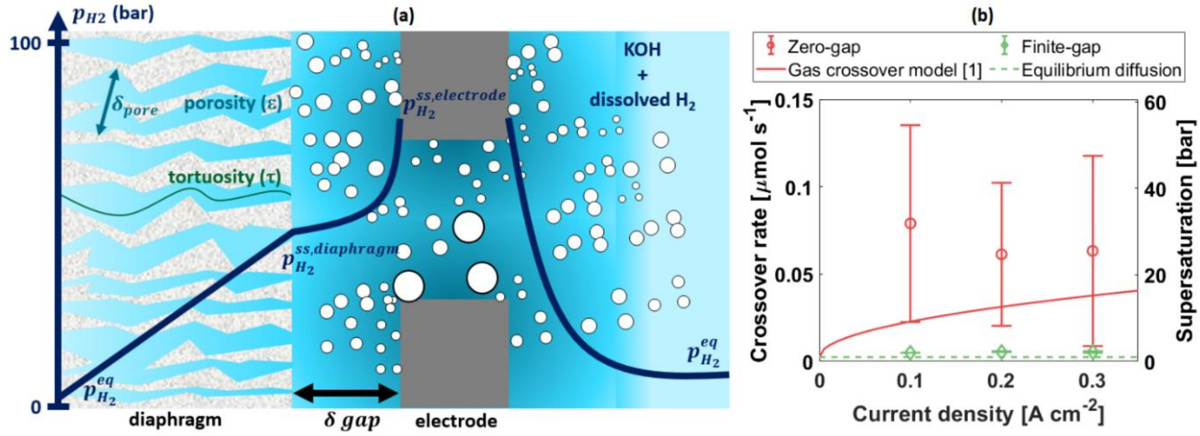

***Figure 1:** (a) Schematic representation of H_2 concentration profile in an imperfect zero-gap configuration; (b) H_2 crossover rate and supersaturation as a function of current density in zero- and finite-gap (500 μm) designs relative to equilibrium diffusion and gas diffusion model [1]. Conditions: 25°C, 12 wt% KOH, Zirfon UTP220 used as diaphragm.*

[1] de Groot, M. T.; Kraakman, J.; Lira Garcia Barros, R. Optimal operating parameters for advanced alkaline water electrolysis. *International Journal of Hydrogen Energy.* **2022**, *47* (82), 34773-34783. DOI: 10.1016/j.ijhydene.2022.08.075

Thrifting of Iridium: A Crucial Task for “Hyperscaling” PEM Electrolysis

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Increasing demand for green hydrogen (H_2) needs a significant increase of water electrolysis capacity. PEM electrolysis will cover a significant share of the planned GW installations to reach the ambitious H_2 generation goals. However, all electrolysis technologies and particularly PEM electrolysis require critical raw materials; for the latter these are platinum group metals, in particular iridium.
Iridium is one of the scarcest platinum group metals. The primary production ranges between 7 and 9 metric tons (t) per year. However, the iridium market is balanced. This means that the iridium being mined is used mainly in existing applications. Additional production of iridium is unlikely, as it is a by-product of platinum mining. As a consequence of substitution and thrifting in current applications of iridium, in our opinion approx. 1.5 t of iridium could be made available per annum to be used in PEM Electrolysis.

Iridium is a crucial electrode material for PEM Electrolysis as it combines activity and stability for the oxygen evolution reaction. The current loading of iridium in PEM Electrolyzers ranges between 0.3 and 0.5 g/kW. Hence, considering the availability of iridium, this would allow for between 20 and 35 GW of PEM Electrolyzers until 2030 only.

In the presentation we will provide a snapshot on the iridium market and show how to reduce the amount of iridium through novel and proven catalyst systems, leading to iridium loadings of 0.1 g/kW and below, enabling the hyperscaling of PEM Electrolysis with respect to iridium availability and electrolyzer costs. Furthermore, we will touchbase on recycling of spent membranes from PEM Electrolyzers, improving the availability of iridium in the long-term.

A segmented along the channel PEM water electrolysis cell for the operation at high current densities

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With the improvement of PEM water electrolysis components high performances even at current densities > 7 A/cm² can be reached. Already today it is possible to have cell efficiencies over 60% (referred to thermoneutral voltage) at those high currents with cell voltages < 2.4 V. In the future it is expected to decrease these voltages even more, e.g. by using thinner membranes. At such high current densities, the gas evolution is enormous which could block the access for water to get to the electrode and lead to mass transport limitations (MTL). Especially regarding industrial stack designs with large cell areas, the accumulation along the water-gas channels can course transport and heat management issues.

To investigate these phenomena, an along the channel cell was designed. The cell has a width of 2 cm and a length of 30 cm with straight parallel channels. To be able to do locally resolved measurements along the channel the cell is separated into 10 segments without any current connection in between. Thus, electrochemical impedance spectroscopy (EIS) is possible for each segment and the whole cell in parallel. In addition to this, highly resolved measurements of current density and temperature distribution are feasible. The cell was successfully tested up to 10 A/cm² and a differential pressure of 5 bar including EIS during an unsegmented full cell measurement. **Figure 1** shows the along-the-channel test cell (left), a polarization curve up to 10 A/cm² (middle) and full cell EIS at high current densities and differential pressure of 5 bar at the cathode and 1 bar at the anode.

The future investigations will be to understand the behavior of MTL along the channel under different operation conditions and structural parameters of porous transport layers (PTL). Furthermore, unclear phenomena like the inductive behavior at low frequencies (see **Figure 1**, right) will be investigated.

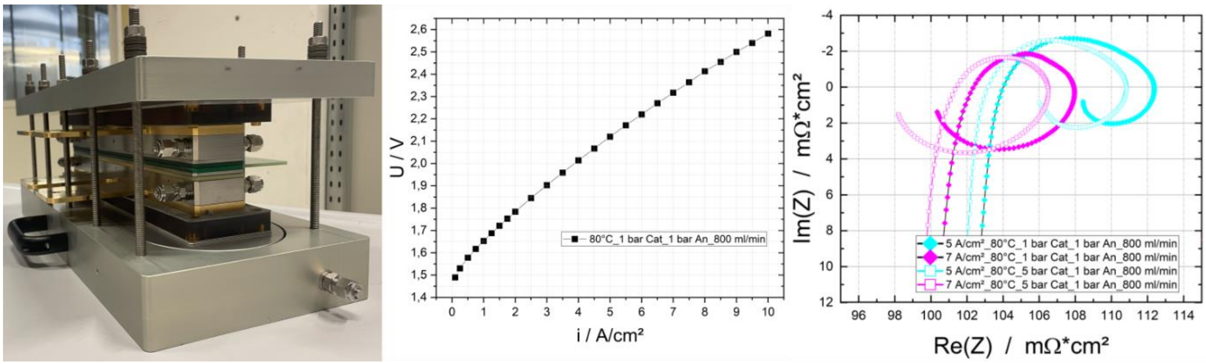

***Figure 1**: Picture of the assembled along-the-channel test cell (left), full cell polarization curve up to 10 A/cm² (middle) and full cell EIS at high current densities and differential pressure (right). Cell setup: commercial state of the art catalyst coated membrane (CCM, 125 µm thickness) and titanium fiber PTLs (0.5 mm thickness) at anode and cathode.*

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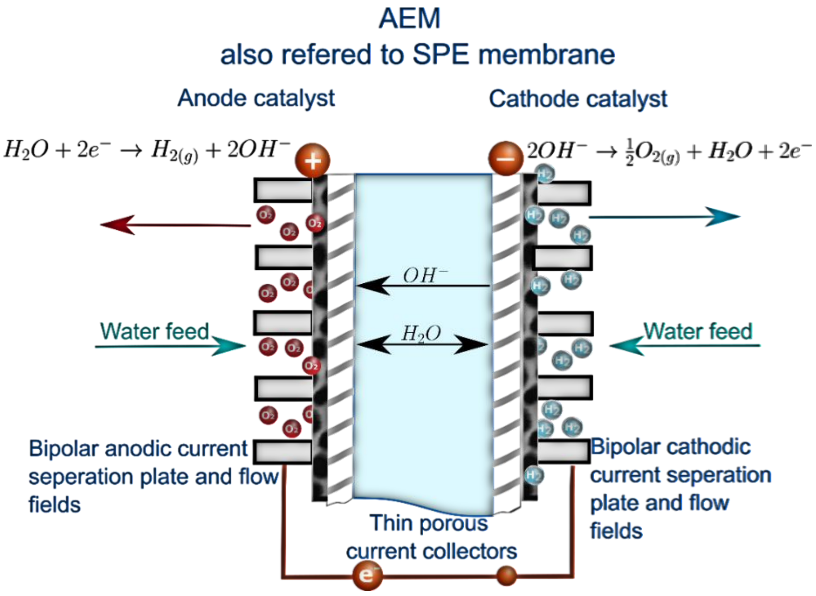

The Power of Reference Electrodes in AEM Electrolysis

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The use of reference electrodes is a powerful diagnostic tool to determine the overpotentials associated with oxygen and hydrogen evolution reaction. Yet, the use of reference electrodes in flow cells is still uncommon and provides several challenges a.o. related to the stability of the potential of the reference electrode. This study investigates the use of a reference electrode in a well-performing iridium-free AEM flow cell with a cell potential of <1.8 V @ 1.5 A cm^{-2}. The reference electrode consists of electrically insulating foil with two platinum wire electrodes on one side as shown in *Figure 1(left)*. A small micro-current is passed through the platinum wires to maintain hydrogen coverage on the reference electrode to establish equilibrium cell potential. The use of the reference electrode shows that the platinum-ruthenium cathode performs particularly well with an overpotential of <0.1 V @ 0.2 A cm^{-2}.

The reference electrode also is useful for the study of cell degradation. One of the major challenges of coupling electrolyzer directly to renewables are reverse currents flowing after shutdown in alkaline and AEM electrolyzers [1]. In this study, polarities were reversed to simulate these reverse currents. This lead to a significant increase in cell potential. It is clearly evident from ***Figure 1****(right)* that the cathode overpotentials increased significantly after this reverse current application., thereby indicating that the platinum-ruthenium cathode is vulnerable to reverse currents.

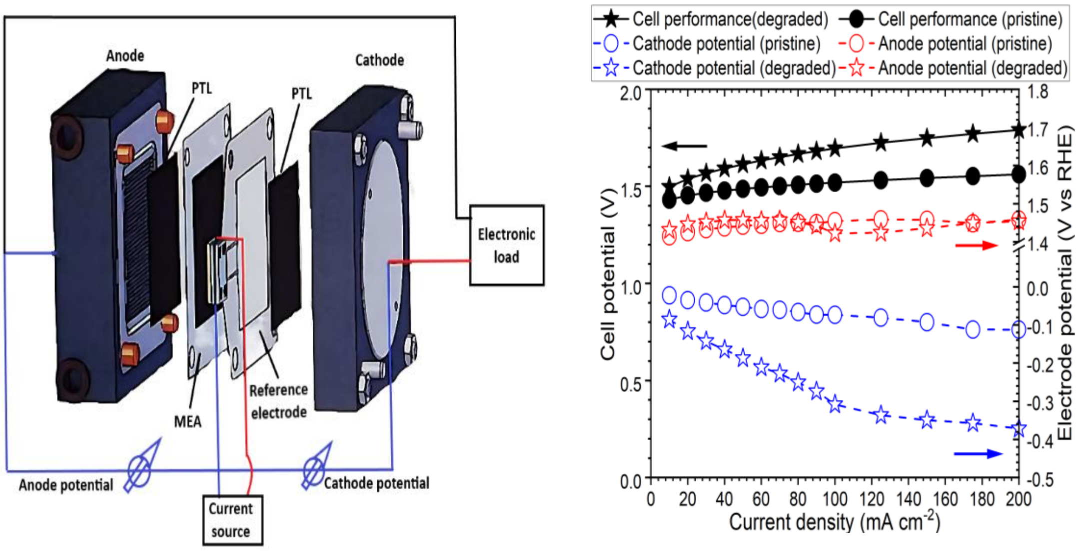

Figure 3: *Exploded view of active area [5 cm^2] (left) showing various cell components along with positioning of reference electrode. Polarization curve data of cell performance(right) along with half-cell potentials calculated from reference electrodes in kinetically controlled region before and after application of reverse currents. Cell conditions: 60°C, 1M KOH, Flow rate:50 ml/min at both half cells, Electrocatalysts: NiFe-LDH and PtRu/C, Membrane: Piperion (60 µm)*

[1] Ashraf Haleem et al, Effects of operation and shutdown parameters and electrode materials on the reverse current phenomenon in alkaline water analyzers, Journal of Power Sources, Volume 535, 2022, 231454, ISSN 0378-7753, https://doi.org/10.1016/j.jpowsour.2022.231454

An Isothermal, Single-Phase Multiphysics Three-Dimensional Model of An Alkaline Electrolyzer

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From the last few years, the society has been working together towards a critical reduction in the greenhouse gas emissions. The development and advancement of newer and greener technologies has been the researcher's focus in order to decrease or even eliminate those emissions. All governments are now investing in technologies as wind turbines, photovoltaic cells, batteries, fuel cells and, finally electrolyzers. This work is related to the computational fluid dynamics modelling of an alkaline electrolyzer.

The alkaline electrolyzer, although it is the most mature technology within the electrolyzer topic, still has some and valuable advantages when comparing to newer technologies such as the simplicity of the system, the cost of its components and the attainability of the required elements (non-precious metal electro catalysts and an alkaline electrolyte). In order to better understand the phenomena and the physics of such system, a numerical model is developed in this project.

An isothermal, three-dimensional model is developed to replicate the phenomena in a small single cell. To describe the electrochemistry phenomena presented in this system, equations as Butler-Volmer, Nernst Equation and Nernst-Planck equation are implemented in this model. Due to low Reynolds, the flow is considered laminar and the species conservation equation are written to solve the molar concentration of each species. Also, the initial concentration of the species is changed in order to evaluate its effect on the output of the system. This model thus replicates the distribution of all species involved across the entire domain. The first results seems to present a good consistency with previous works [1],[2].

[1] - Lee J, Alam A, Ju H. Multidimensional and transient modeling of an alkaline water electrolysis cell. International Journal of Hydrogen Energy. 2021 Apr 14;46(26):13678-90.

[2] - Schalenbach M, Tjarks G, Carmo M, Lueke W, Mueller M, Stolten D. Acidic or alkaline? Towards a new perspective on the efficiency of water electrolysis. Journal of The Electrochemical Society. 2016 Aug 31;163(11):F3197.

Increasing performance and lifetime of anion exchange membrane water electrolysers

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[b]*University of Stuttgart, Germany;*
[c]*Esslingen University of Applied Sciences, Germany*

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Anion exchange membrane water electrolysis (AEMWE) combines the advantages of proton exchange membrane water electrolysis (PEMWE), i.e., high current density while maintaining high efficiency and fast dynamic response with the advantages of alkaline water electrolysis (AWE), i.e., low-cost materials. However, AEMWE technology still depends on a supporting electrolyte and its durability is low. In this regard, the German Aerospace Centre (DLR) is developing novel approaches and cell components to increase performance and lifetime of AEMWE. A central component that is critical in AEMWE is the membrane. Novel low-cost, crosslinked multi-cation styrene ethylene butylene styrene (SEBS)-based AEMs were developed, retaining 87% conductivity after 500 hours in 90°C, 1 M KOH, outperforming other non-crosslinked SEBS based AEMs[1]. SEBS is a readily available, low cost material with excellent stability and mechanical integrity, while the inserted piperidium functional groups are known to be one of the most stable functional groups, showing good stability against nucleophilic substitution and β-elimination. Additional quaternary ammonium (QA) groups were introduced, flexible ethylene glycol side chains were added and crosslinking was carried out to further improve conductivity and stability. Other key components in AEMWE are the electrodes. In this regard, a novel multi walled carbon nanotube (MWCNT) supported nickel iron phosphide catalyst was characterized as anode catalyst in an AEMWE cell, showing performance equal to metallic iridium at lower catalyst loading. In continuation of this study, ultra-low loadings will be tested and the anodic stability of the MWCNT will be investigated by HR-TEM. In ongoing work, distribution of relaxation times (DRT) analysis of AEMWE impedance spectra recorded in parameter variation tests and degradation studies, using an integrated reference electrode, will facilitate the development of strategies that improve AEMWE lifetime.

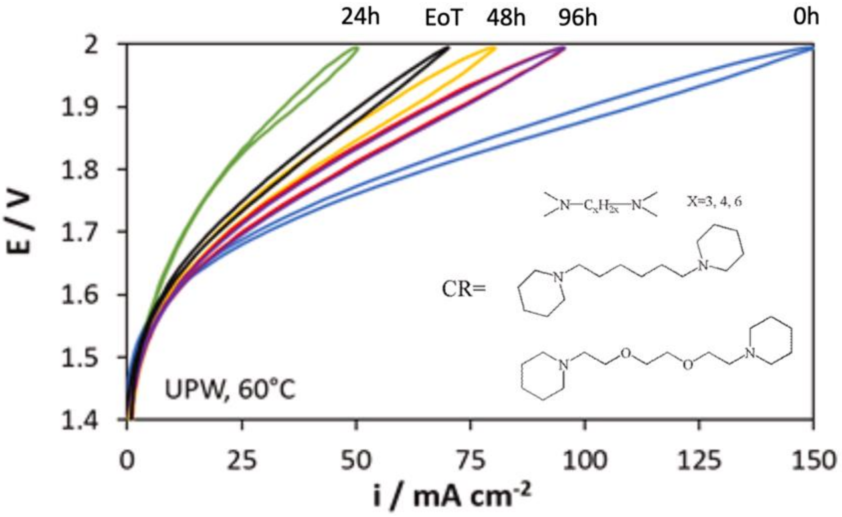

Figure: AEMWE single cell IV curves recorded during constant operation, using the novel SEBS AEM in ultra-pure water. The insert shows the utilised crosslinking structure.

[1] Xu, Z.; Wilke, V.; Chmielarz, J. J.; Tobias, M.; Atanasov, V.; Gago, A. S.; Friedrich, K. A., Novel piperidinium-functionalized crosslinked anion exchange membrane with flexible spacers for water electrolysis. *Journal of Membrane Science* **2023,** *670*.

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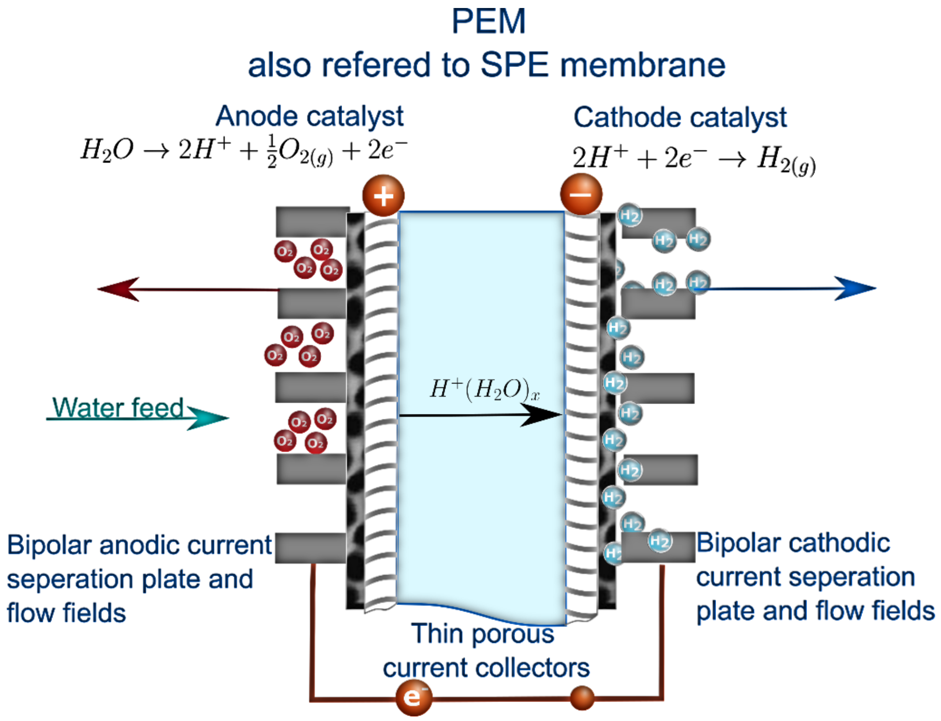

Analysis of morphological and transport properties of IrO_2 anode catalyst layers for PEM electrolysis using high-resolution imaging

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Proton exchange membrane water electrolysis (PEMWE) is a promising method for clean hydrogen production; however, one of its current limitations to achieving global techno-economic viability is the use of expensive iridium (Ir) for the anode catalyst layer (CL) material. The general approach for improving the specific cost of the Ir-based anode CL is two-fold: lowering Ir loadings as well as increasing the utilization of Ir. In this work, we aim to address this problem by using high-resolution imaging to characterize micro- and nano-scale features of iridium oxide (IrO2) anode CLs towards a better understanding of the relationship between CL fabrication, morphology, and performance. We use two methods of 3D, high-resolution imaging: (1) nanoscale X-ray computed tomography (nano-CT), and (2) Xe-plasma focused ion beam with scanning electron microscopy (pFIB-SEM). We use nano-CT imaging to characterize IrO_2 CLs varying in coating methods (i.e., spray-coated versus blade-coated) and steps along the fabrication and testing timeline (i.e., pristine versus tested CL), focusing on micro- and electrode-scale differences particularly of electrode heterogeneity and thickness distributions. We then use pFIB-SEM with ultra-high-resolution at the nano-scale to characterize different regions within the same CL, finding that regions vary in structure due to compression caused by contact with the titanium porous transport layer (PTL), focusing on porosity and pore size distribution effects. We then demonstrate how image-based modeling techniques can provide insight into effective transport properties, such as formation factor values, electrical conductivity, water retention curves, and relative permeability curves. A deeper understanding of how structural differences between different CLs as well as between varying regions within a particular CL can lead to differences in transport phenomena through the porous medium will be crucial for improved manipulation of IrO_2 CL fabrication to optimize lower loadings and increased catalyst utilization.

Acknowledgments
This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) Hydrogen and Fuel Cell Technologies Office (HFTO). The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.
The nano-CT instrument was acquired with the support of a Major Research Infrastructure award from the National Science Foundation under Grant No. 1229090. The pFIB-SEM instrument was acquired with the support of a Major Research Infrastructure award from the National Science Foundation under Grant No. 1428480. The authors acknowledge use of the Materials Characterization Facility at Carnegie Mellon University supported by grant MCF-677785.

Investigating the Potential of a Machine Learning-based Approach for Degradation Modelling in Proton Exchange Membrane (PEM) Water Electrolysis

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Managing degradation of critical cell components, associated performance losses and safety risks represent a major challenge for the widespread market introduction of industrial electrolysis plants. Without reliable information about the current and future state of health (SOH), it is impossible to operate such plants professionally and meet customer requirements for efficiency and durability. Therefore, sophisticated diagnostic and prognostic methods are essential during the operation to have the ability to make a reasonable statement about the end of life and the remaining useful lifetime (RUL).

However, although research towards the physicochemical understanding of specific degradation mechanisms is intensified, it is still not possible to explain and, especially, model ageing in its entirety. Here, data-driven approaches can help to complete the description of occurring phenomena. Methods from the field of machine learning (ML) are system model-free, consider the investigated effects as a black box and thus have the great advantage that no prior knowledge of the physical fundamentals is required [1]. Instead, they can capture the underlying relationships based only on the available data. In this work, an ML pipeline for degradation modelling is presented and tested using an exemplary long-term laboratory dataset. A typical pipeline is shown in **Figure 1** and contains several sequential sub-steps to bring an ML model into the desired application. This analysis shows that using this workflow, the SOH of a PEM water electrolysis cell can be predicted and forecasted with high accuracy. Additional and more advanced techniques like transfer learning on the one hand and specific integration of domain knowledge into the modelling process on the other hand help to further increase the accuracy, generalisability and physical consistency of the model results [2].

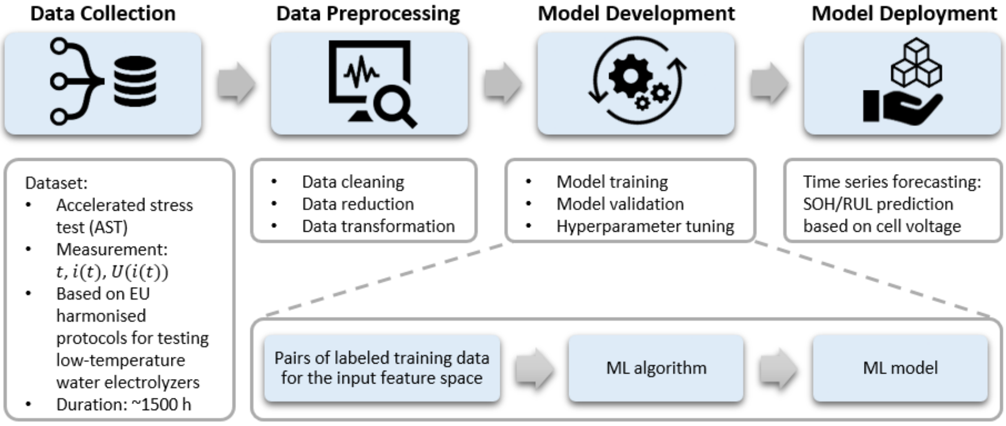

***Figure 1**: Applied pipeline for ML-based degradation modelling*

[1] Oji, T.; Zhou, Y.; Ci, S.; Kang, F.; Chen, X.; Liu, X. Data-Driven Methods for Battery SOH Estimation: Survey and a Critical Analysis. *IEEE Access* **2021**, 9, 126903-126916. DOI: 10.1109/ACCESS.2021.3111927

[2] Karniadakis, G. E.; Kevrekidis, I. G.; Lu, L.; Perdikaris, P.; Wang, S.; Yang, L. Physics-informed machine learning. *Nat. Rev. Phys.* **2021**, 3 (6), 422–440. DOI: 10.1038/s42254-021-00314-5

Advances in processing of catalyst coated membranes (CCM) for PEM electrolysis

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Electrolysers have to fill an important role in the desired energy transition.[1] They can be used to produce green hydrogen to support energy transition and establish a hydrogen based economy. For a broad market penetration, electrolyser production must still be improved and critical process steps must be understood.

The heart of the polymer electrolyte membrane water electrolyser (PEM-WE) is the catalyst coated membrane (CCM). The CCM consists of a perfluorosulfonic acid (PFSA) membrane, e.g. Nafion™, and a catalyst layer coated on both sides. The catalyst layers must satisfy several requirements such as a high reactive surface area, suitable porosity and a high number of multiphase boundaries.[2] In particular, the catalytic electrode layers are relevant to the performance during operation of the system. The production of functional, high-quality catalyst layers with specific properties is therefore necessary. For this reason, the goal is firstly to produce these high-quality layers and secondly to do so cost-effectively. This is because high material and, to date, production costs must be reduced.

A promising approach for cost-effective CCM processing is membrane direct coating, as it saves one process step compared to established decal process. A current problem with this processes is the formation of defects in the electrodes during the production of the catalyst layers.[3] In this work the formation of electrode defects is investigated and process engineering approaches for their avoidance. The focus here is on coating and drying of the electrodes from catalyst inks. Particularly in these two process steps, the material-specific mass flows have a significant influence on the subsequent coating appearance. Due to the formulation of the coating inks as complex inks out of nano-particles, polymers and solvent mixtures, various influencing factors come into play which can be specifically influenced.

In this work, the essential material flows are first identified, then systematically influenced by varying the coating and drying parameters. The effect of the process parameters on the coating properties and possible defects are thus clearly illustrated. Further, correlations for the interaction between ink formulation and process parameters to the finished electrode are derived. This enables a deeper understanding of materials and processes during the fabrication of catalyst layers. From this, essential aspects for the production of CCM can be derived.

[1] EU-Commission, Powering a climate-neutral economy: An EU Strategy for Energy System Integration. Communication COM/2020/299, **2020**.
[2] U. Schelling, in: Energietechnik: Systeme zur konventionellen und erneuerbaren Energieumwandlung. Kompaktwissen für Studium und Beruf, R. Zahoransky (Ed.); Springer Fachmedien Wiesbaden, **2019**; pp 273–308.
[3] Park, J; Kang, Z; Bender, G; Ulsh, M; Mauger, SA, Roll-to-roll production of catalyst coated membranes for low-temperature electrolyzers. Journal of Power Sources, **2020**, 479, 228819.

Wednesday 30th August – Session 12

Decoupled Water Splitting: Reshaping Water Electrolysis

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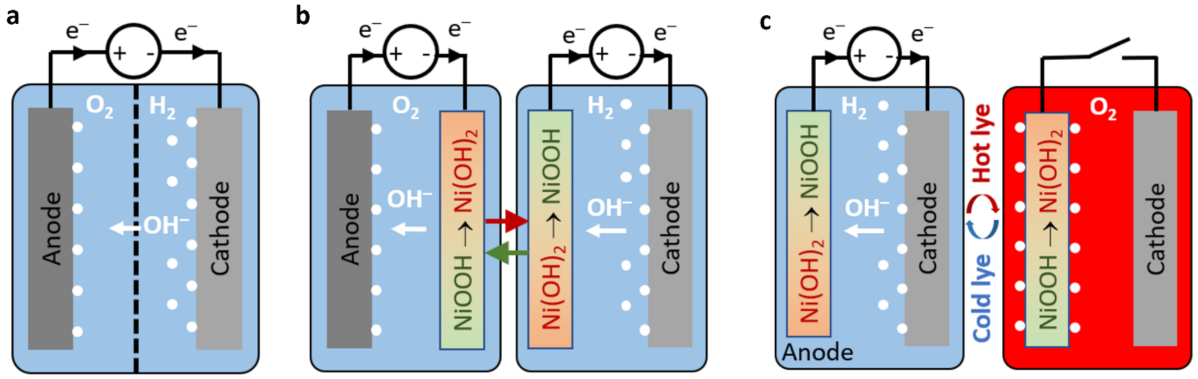
The present water electrolysis technologies present challenges to increase their economic competitiveness, scale up and performance. These challenges arise from the co-production of H_2 and O_2 in the same cell and from energy losses. To prevent H_2 and O_2 mixing, the electrolytic cell is divided by a membrane or diaphragm into cathodic and anodic compartments **(Fig. a)**. This membrane architecture complicates the electrolyzers construction by adding gaskets and compression sealing to prevent H_2/O_2 crossover. This adds substantial costs and limits operation at high pressures and low-purity water. In addition, substantial energy losses, mostly due to the difficult OER, increase the cost of energy in this energy intensive technology. These drawbacks give rise to high cost of green hydrogen.

To overcome these challenges, we developed alternative processes that decouple the generation of hydrogen and oxygen into two cells (space separation, **Fig. b**),[1] or two consecutive stages (time separation, **Fig. c**) [2], avoiding the need for membrane and sealing. In addition, we divided the OER, a difficult electrochemical reaction that requires four electrons and protons to generate an O_2 molecule on a single atomic reaction site, into two sub-reactions that occur on four sites, thereby enabling facile reactions and reducing the energy losses in water electrolysis. An ultrahigh efficiency of nearly 99% was demonstrated at lab scale,[2] and we expect reaching above 90% at system scale. To bring this breakthrough process to reality we established H_2Pro, an Israeli startup company that aims to produce green hydrogen at $1/kg by the end of this decade, based on our invention.



[1] Landman et al., *Photoelectrochemical water splitting in separate oxygen and hydrogen cells*, Nature Materials 16, 646–651 (2017).
[2] Dotan et al., *Decoupled hydrogen and oxygen evolution by a two-step electrochemical – chemical cycle for efficient overall water splitting*, Nature Energy 4, 786–795 (2019).

Where do you go to my lovely? – on future solid polymer electrolyte water electrolysis

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Looking into the history of electrolytes, polymer electrolyte membranes are so far the best electrolyte type mankind came up with. As an example of its superior properties one can compare proton exchange membrane water electrolyzers (PEMWE) with classical alkaline water electrolysers (AWE): The use of a polymer electrolyte membrane is central for the significant increase in PEMWE current density and conversion efficiency, compared to AWE. Still, the cost of titanium flow fields and porous transport layers as well as the scarcity of noble metal catalysts such as iridium pose a significant obstacle for the wide spread application of PEMWEs [1]. The further development of the solid electrolyte membrane will be the pivotal point for radical changes in the water electrolyser technology which can be envisaged in the following directions:

i. Using anion exchange membranes for water electrolysers (AEMWE), noble metal catalysts and titanium components can be potentially replaced by cheaper and more abundant components [2].
ii. Bipolar membrane water electrolysis (BPMWE) is a novel research direction currently in its infancy, but it could offer the best of the acidic world with fast hydrogen evolution reactions and the best of the alkaline world with low cost materials for the oxygen evolution reaction [3].
iii. Elevated temperature operation for PEMWE, AWE, AEMWE or BPMWE has the potential for strongly improved conversion efficiency, but poses a grand challenge for materials stability – particularly for the membranes.

This talk gives a comprehensive overview of the possible benefits of the new technologies but also pictures their possible drawbacks. Also, experimental results from our institute and from literature are presented.

[1] C.V. Pham, D. Escalera-López, K. Mayrhofer, S. Cherevko, S. Thiele, Essentials of High Performance Water Electrolyzers – From Catalyst Layer Materials to Electrode Engineering, Adv. Energy Mater. (2021). https://doi.org/10.1002/aenm.202101998.
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AEM water electrolysis: learning and evolution from alkaline water electrolysis.

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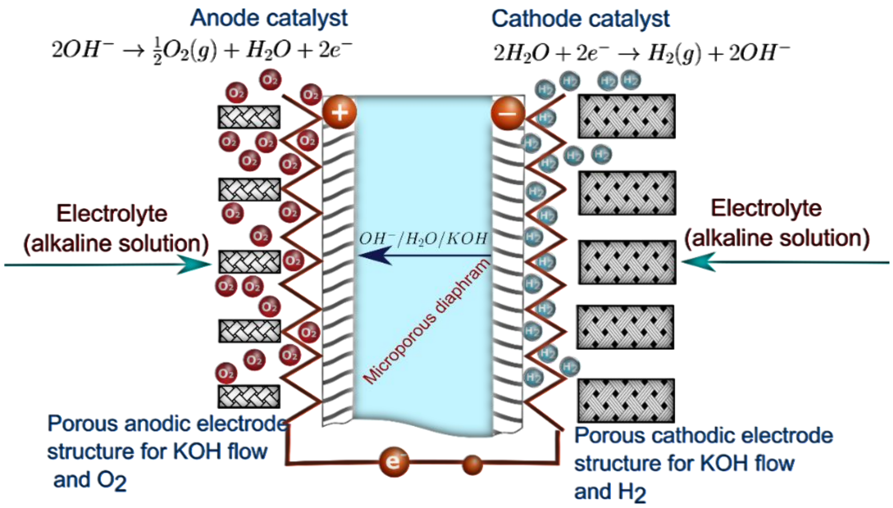
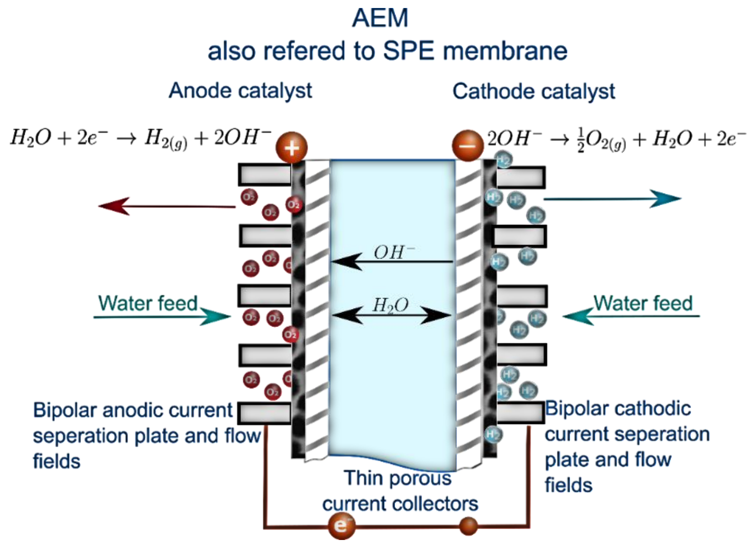
Water electrolysis has become one of the most viable technologies to produce green hydrogen towards the goal of global decarbonization, particularly when integrated with renewable solar and wind energy. However, this technology still faces some grand challenges including high cost and insufficient lifetime, which make it less competitive against methane reforming that however releases large quantity of CO_2 while producing hydrogen.

Alkaline water electrolysis (AWE) is one major water electrolysis technology. AWE has been successfully commercialized for decades; however, its drawbacks include low operating current density, high shunt current, difficult in integration with renewable energy. The hybridization of AWE and proton exchange membrane water electrolysis enables anion exchange membrane water electrolysis (AEMWE). Currently, AEMWE faces some challenges like instability of membrane/ionomer and non-optimal electrode design.

The development of AWE technologies has provided some insightful information for the AEMWE. The improvements of AEMWE needs deep understanding of some key factors like non-precious metal catalyst activity, membrane chemical and mechanical stability, membrane/electrode interface, and component corrosion. Advanced research in materials like catalysts and membranes can significantly help to address these challenges. In addition, some effective probes and analytical approaches must be developed to fully elucidate these important phenomena before we can transform the performance and lifetime of AEMWE. Finally, the scale-up of water electrolysis via mass manufacturing and automation will be addressed to meet ever-increasing demands for green hydrogen. A strong collaboration between industry and research institutions becomes highly crucial for efficiency improvement, cost reduction, lifetime upgrading of water electrolysis, thus enabling the viable implementation of green H_2 towards global decarbonization.

Wednesday 30th August – Session 13





Main Catalyst Degradation Mechanisms in AEL, PEMEL and HTEL Electrolyzers

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The success of sustainable transition from fossil to renewable energies relies on available natural sources such as solar, wind, hydro and biomass. Since most of them are prone to fluctuations, the surplus in produced energy has to be stored in batteries and/or transformed in liquid or gaseous energy carriers such as e.g. hydrogen. Moreover, grey and blue hydrogen obtained from steam reforming of natural gas and methane for chemical, metallurgical and agricultural applications have to be substituted by green hydrogen. When considering the net zero emission roadmap by 2050, installed electrolysis capacity in industrial countries should increase from 0.3 GW today to close to 850 GW by 2030 and almost 3.600 GW by 2050[2].[1,2] By assuming that alkaline (AWE), proton exchange membrane (PEMWE) and high-temperature (HTWE) water electrolysis contributes by 60, 35 and 5% to power generation in 2050, respectively and overall catalyst loadings can be reduced by 50% during this period, following tonnage will be required for target achievement: Ni ($1{,}17.10^6$ tons) for AWE, Pt (162 tons) & Ir (378 tons) for PEMWE, and Ni (18.000 tons), Zr (3.600 tons), La (1.800 tons) & Y (450 tons) for HTWE. This rough projection illustrates quite well the urgent need in both reducing drastically catalyst loadings and improving their long-term stability. This talk aims at summarizing the main chemical and electrochemical degradation mechanisms of catalyst materials in current electrolyzer technologies and finally exposing some promising strategies to circumvent main crucial catalyst material issues.

[1] https://www.iea.org/reports/net-zero-by-2050
[2] https://www.iea.org/reports/global-hydrogen-review-2021

Efficient alkaline electrolysis with porous 3D electrodes - Influence of the electrode structure on the cell efficiency

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In modern AWE systems, a zero-gap cell architecture is used where electrodes are directly pressed on the membrane to reduce the ohmic losses related to the electrolyte. This technology requires perforated plates or novel porous 3D electrodes. Additionally, at high H_2-production rates, the enormous gas evolution leads to losses which are related to the blocking effect of adherent gas bubbles and/or the increased electrolyte resistance [1]. In this regard, optimized porous structure is required which enables enhanced removal of gas bubbles and a direct flow to the backside of the electrodes resulting in high cell efficiency.

In this contribution, powder metallurgy route in combination with a space holder method [2,3,4] was used to produce novel porous 3D electrodes so called porous metal foil or porous sintered metal papers. This approach allows to adjust the porosity, the thickness as well as the pore size of the catalytic material. Consequently, the accessible surface area of the electrode can be enhanced and the flow of gas bubbles through the porous structure can be optimized. The implementation of the porous electrodes in a zero-gap single cell were investigated with respect to the cell resistance, cell voltage and the pressure distribution on the separator. Singel cell measurements indicates that the efficiency at high current densities (up to 1 Acm^{-2}) is mainly related to the efficient gas bubble removal. Cell voltage of 1.83 V at 1 Acm^{-2} was determined if an anode with an optimized pore structure is utilized.

[1] Philips R. et al. Int. J. Hydrogen Energy 2017, 42, 23986. [2] Hakamada M. et al., Mater. Trans., 2005, 46, 2624. [3] Rauscher T. et. al, Electrochim. Acta, 2019, 317, 128–38. [4] Andersen et al., Euro PM 2018

Part of this work was supported by the Federal Ministry of Education and Research – Germany, through the WBC2019 call – project NOVATRODES 01DS21010 and of the AiF founded project “H2PaperElectrodes” (IGF-project-No. 22335 BR)

Development of alkaline membranes at DTU Energy

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Regarding separators or membranes for alkaline electrolyzers, a strict distinction is often made between *liquid alkaline* and *AEM*.[1] The liquid alkaline technology is seen as the traditional one with high concentration aqueous KOH as electrolyte contained in a porous matrix or separator of which the state-of-art porous materials are referred to as diaphragms. The emerging technology is the one based on anion-exchange membranes (AEM) as analogues to the acidic proton exchange membranes (PEM) of the successful PEM electrolyzer. In contrast to the liquid alkaline electrolyzer, the AEM electrolyzer is operated on dilute KOH and ideally in the future on pure water.

These two technologies, although both alkaline, appear to represent two distinct and separated worlds. However, one may also see them as two extremes of a continuum. It is well-known that the AEM electrolyzer in practice works much better with dilute KOH that with pure water and non-porous membranes can replace the diaphragms in the high concentration KOH cells. The latter is the concept of ion-solvating membranes.[2]

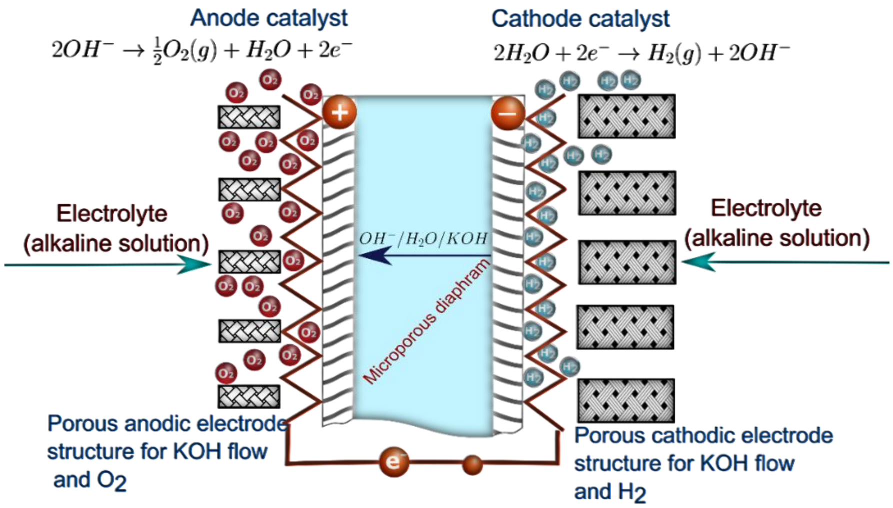
AT DTU Energy, we are involved in the development of both porous diaphragms and non-porous ion-solvating membranes. This presentation compiles our recent results, trends and strategies of the membrane development, all at high pH. A common challenge is to develop materials with sufficient long-term stability.[3]

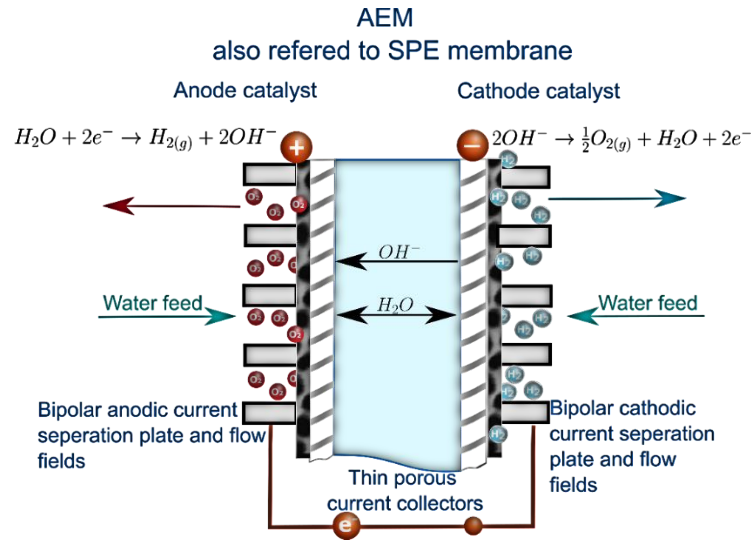
[1] D. Aili, M. R. Kraglund, S. C. Rajappan, D. Serhiichuk, Y. Xia, V. Deimede, J. Kallitsis, C. Bae, P. Jannasch, D. Henkensmeier and J. O. Jensen. Electrode Separators for the Next-Generation Alkaline Water Electrolyzers. *ACS Energy Lett*. (2023). DOI: 10.1021/acsenergylett.3c00185

[2] M. R. Kraglund, M. Carmo, G. Schiller, S. A. Ansar, D. Aili, E. Christensen and J. O. Jensen. Ion-solvating membranes as a new approach towards high rate alkaline electrolyzers. *Energy Environ. Sci*. **12**, 3313 – 3318 (2019). DOI: 10.1039/c9ee00832b

[3] D. Serhiichuk, T. Patniboon, Y. Xia, M. R. Kraglund, J. O. Jensen, H. A. Hansen, D. Aili. Insight into the alkaline stability of arylene-linked bis-benzimidazoles and polybenzimidazoles. *ACS Appl. Polym. Mater.* **5,** 803–814 (2023). DOI: 10.1021/acsapm.2c01769

Wednesday 30th August – Session 14





Platinum Group Metal-free Electrocatalysts for Oxygen Evolution Reaction in Alkaline Media by Combined Experimental and Modeling Approach

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Platinum group metal-free (PGM-free) electrocatalysts represent a low-cost alternative to their precious-metal counterparts, especially platinum group metal (PGM) catalysts for reactions of fundamental importance in electrochemical energy conversion and storage, including green hydrogen generation in anion exchange membrane water electrolyzers (AEMWEs). The non-precious metal catalysts for AEMWEs are typically based on transition-metal based oxides, including in particular Ni oxides doped with Fe, which have shown the highest OER activity in alkaline media.[1,2]

In this presentation, we will summarize recent progress at Los Alamos in the development of PGM-free electrocatalysts for oxygen evolution reaction (OER) in low-temperature AEMWEs, focusing in particular on a series of Ni oxide-based aerogel materials combined with Fe in different proportions. These catalysts have shown respectable OER performance in liquid alkaline electrolyte and in AEMWE anode operating with supporting electrolytes, KOH or K_2CO_3, as well as on pure water.[3] The focus of this presentation will be on improvements to both activity and performance durability of the catalyst/ionomer systems (a combination of Ni-Fe oxide aerogel catalysts with AEIs having different backbone chemistries and OH^--conducing functional groups) on the AEMWE performance. Among others, we will show that full activation of the catalyst by phase transition from the original Ni oxide-like structure to the active layered (oxy)hydroxide is essential for achieving high OER activity.

Following our prior machine learning (ML) studies aimed at optimizing the synthesis of oxygen reduction electrocatalysts [4,5] we will show how to ML-optimize the synthesis of aerogel-derived Ni-oxide catalysts for OER. This work has been supported by density functional theory (DFT) modeling studies of reaction mechanisms, active sites, and ultimately of the role of transition-metal dopants (Fe and Co) on OER activity. Studies of dissolution of these dopants using DFT-generated, phase-constrained Pourbaix diagrams can guide further synthesis through understanding of this main catalyst degradation pathway.

[1] S. Fu *et al.*, *Nano Energy* **44**, 319-326 (2018).
[2] D. Xu *et al.*, *ACS Catal.*, **9**, 7-15 (2019).
[3] P. Zelenay and D. Myers, *ElectroCat 2.0 (Electrocatalysis Consortium)*, 2022 Annual Merit Review of DOE Hydrogen and Fuel Cell Program.
[4] M. R. Karim *et al.*, *ACS Appl. Energy Mater.* **3**, 9083-9088 (2020).
[5] W. J. M. Kort-Kamp *et al.*, *J. Power Sources*, **559**, 232583 (2023).

Integration of Reference Electrodes in Zero-Gap Alkaline Electrolysis Cells for the Deconvolution of Reaction Overpotentials and Ionic Transport Losses Across the Anode, Cathode, and Separator

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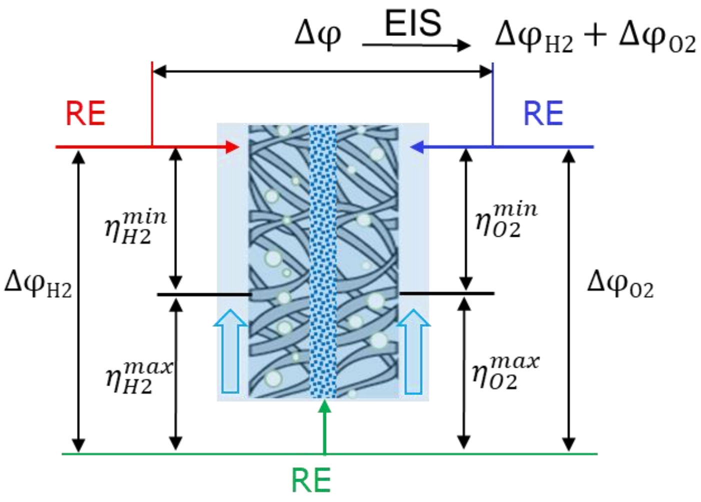
Alkaline electrolysis (AEL) is one of the most promising technologies for large-scale production of green hydrogen. Although AEL is well proven in terms of reliability and scalability, its efficiency and productivity are inferior to other competing electrolysis technologies. Porous electrode theory considerations suggest that mass transport plays an important role in terms of influencing electrode performance. Designing more efficient and productive AEL cells requires the identification of electrode architectures that facilitate mass transport and thereby reduce associated ionic transport losses in the electrodes. Here we propose a method that employs a minimum of three reference electrodes (RE) to separate the voltage losses within the anode, cathode, and separator during zero-gap operation at industrially relevant conditions, as well as to deconvolute the Galvani potential losses (Δφ) associated with ionic migration within each of the electrodes and the separator.



Different Ni electrode structures have been investigated to assess the effect of thickness, surface area, and porosity; our findings pointing at substantially different optimal electrode architectures for the anode and cathode. Overall, the proposed methodology can guide the rational design of improved electrode microstructures and lead the way to the development of more efficient and productive alkaline electrolysis cells in the future.

Pilot-scale testing of a novel alkaline water electrolysis stack

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The conversion of the energy system to renewable energies will create an enormous demand for green hydrogen produced by water electrolysis [1]. Among the available processes, alkaline water electrolysis (AEL) is already well developed and also cost-effective, because it does not require precious metal electrocatalysts [2]. However, further improvements for lowering capital and energy costs of electrolysis systems are urgently needed. In the present contribution, a radically new concept for an alkaline water electrolysis stack is introduced. By using low-cost materials for electrodes and cell components, and in particular by massively reducing the material demand, the costs for the stack can be significantly reduced. This is supported by introducing automated manufacturing technologies for electrolyzer production, which have not been used in the field before.

The new concept was experimentally investigated by deploying full-scale shortstacks in a new test facility, which allows measurements at pressures up to 1.4 bar(a), temperatures up to 90 °C, and a maximum load of 150 kW. Special emphasis was placed on mitigation strategies for reduction of gas impurities during dynamic operation and in the part-load range, e.g. through adaptive electrolyte flow rates or temporarily separated electrolyte cycles [3,4]. It was shown that the new design combines low cost with competitive efficiency and operational flexibility.

Acknowledgment

The research was funded by the German Federal Ministry of Education and Research under the grant no. 03HY102.

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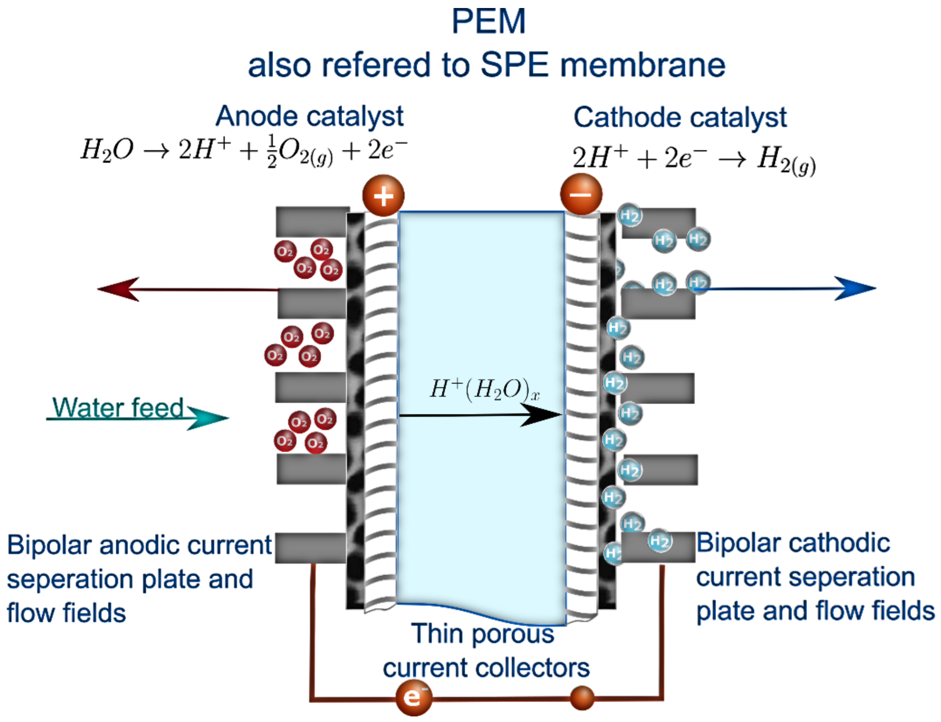
Wednesday 30th August – Session 15



Contact Resistance (R_c) measurement methods for PEM Water Electrolyser Bipolar plates

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The quality control of bipolar plates (BPPs) becomes important for mass production of PEM water electrolysers (PEMWEs). BPPs are a multifunctional component of PEMWEs, serving for heat and current conduction, gas/liquid distribution and physical separation between the single cells in a stack. Therefore, selection and control of BPP materials relies on a multi-aspect analysis of electrical, thermal and mechanical properties and cost. Electrical properties are particularly crucial for the performance and can be measured ex-situ. The in-plane resistance of BPPs as well as the interfacial contact resistance (ICR) between the BPP and gas diffusion layers (GDLs) can dramatically increase due to passive oxide layer formation and possible corrosion during operation in the harsh environment of PEMWEs. In-plane resistance can be measured using the four-probe approach. The ICR between BPPs and GDLs is measured in a sandwich-type configuration pressed with outer metal plates, and it depends strongly on the clamping force.

This work presents a methodology for adapting the ICR experimental setup in order to enable simultaneous measuring of the through-plane (bulk) resistance of BPPs. The latter is important since it dictates the conduction of current between individual cells in the stack. A BPP was sandwiched between two GDLs, stacked between two planar Au-coated Cu electrodes, to probe the surface of a GDL/sample/GDL. Contact pressure of 20-200 N/cm^2 [1] was applied via computer controlled Zwick Roell system. The resistance values were extracted at 150 N/cm^2, which is equivalent to compaction force of operating PEMWEs.

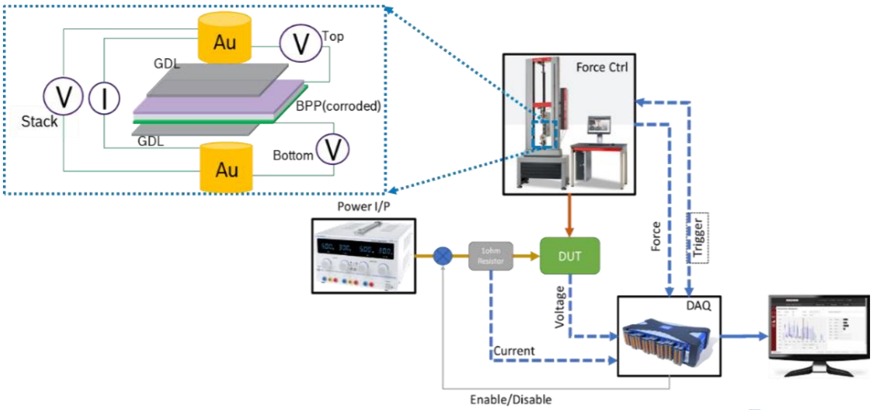

Figure 4:Component overview of the contact resistance measurement setup.

Applied voltage ranges 0-1 V (range for common samples 0-5000 mΩ.cm^2), current is kept constant (1 A), and voltage drop is measured over the configuration as shown in Error! Reference source not found.**,** allowing for ICE measurement. Additionally, Au wires were introduced to measure separately the voltage drop at the top (V_{top}) and the bottom (V_{bottom}) side of BPPs, allowing for the measurement of through-plane BPP resistance. This methodology can improve our understanding in optimizing Au and Pt BPP coatings and in improving stack efficiency.

[1] Sigrid Lædre, Corneliu M. Craciunescu, Thulile Khoza, Nicolae Vaszilcsin, Andrea Kellenberger, Vlad Bolocan, Ion Mitelea, and Aurel Ercuta. *Issues regarding bipolar plate-gas diffusion layer interfacial contact resistance determination.* J. Power Sources, Vol. 530, (2022),231275

Towards next-generation catalyst coated membranes for polymer electrolyte water electrolyzers

Zheyu Zhang[a], Axelle Baudy[a], Zongyi Han[a], Andrea Testino[b,c] and Lorenz Gubler[a]

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[c]STI SMX-GE, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland

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The production of green hydrogen by water electrolysis plays a key role in the concept of power-to-gas and power-to-X. Manufacturers of polymer electrolyte water electrolyzers (PEWEs) aim to use thin membranes, such as Nafion NR 212, in order to minimize ohmic losses and thus improve the voltage efficiency. One of the challenges associated with thin membranes is an increased hydrogen crossover. The extent of the issue is further amplified when the cell operates under differential pressures, with the cathode at elevated pressure. To address the problem, we report a summary of recent studies we conducted for the optimization of the catalyst coated membrane in PEWE. A parametric investigation on the effect of cathode catalyst layer structure, including catalyst loading, ionomer to carbon ratio and catalyst type, on the hydrogen crossover rate is presented. The corresponding cathode mass transfer coefficient values are analyzed. In addition, the proton exchange membrane in the cell is modified for the incorporation of a Pt recombination catalyst to reduce hydrogen crossover.[1] The ionomer degradation promoted by the involvement of the recombination catalyst is verified, and the use of a ceria-based radical scavenger is consequently proposed for mitigation. The research aims to explore the direction in designing the next-generation PEWE catalyst coated membranes.

[1] Zhang, Z.; Han, Z.; Testino, A.; Gubler, L. Platinum and Cerium-Zirconium Oxide Co-Doped Membrane for Mitigated H2 Crossover and Ionomer Degradation in PEWE. *J. Electrochem. Soc.* **2022**, 169 (10), 104501. DOI: 10.1149/1945-7111/ac94a3.

Mapping of conductance and electric defects at PEM MEAs using lock-in thermography and microstructural analysis of degradation effects

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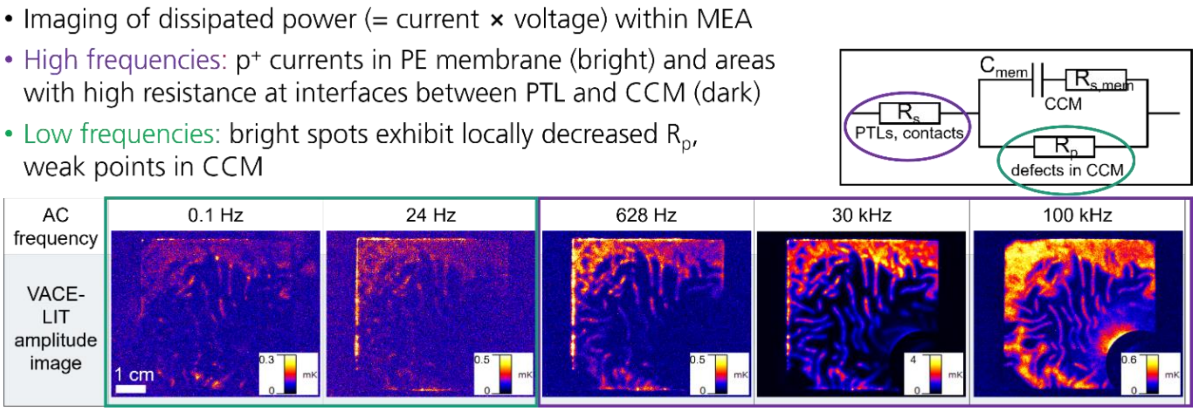
Electrical contacts between bipolar plates, porous transport layers (PTLs) and catalyst layers as well as ion conductivities of membranes are subject to degradation during operation of PEM and AEM water electrolyzers [1]. Lock-in thermography (LIT) provides the ability to map current flows and electrical losses laterally, and even with depth resolution, by detecting minute temperature differences in the millikelvin range [2]. Membrane electrode assemblies (MEAs) are sufficiently thin to detect heat sources with sub-mm spatial resolution. Due to the insulating properties of MEAs with ion exchange membranes at DC below V_{rev}, pulsed AC is required as excitation source for LIT. Our Variable frequency AC Excitation Lock-in Thermography (VACE-LIT) method allows to image the current paths through the MEA and thus the electrical conductivity at the interfaces and within the materials (see **Figure 1**) [3].

Detrimental increase of contact resistances during operation of PEM electrolyzers may occur due to surface oxidation of titanium fibres of PTLs. In a study, the degradation of contact resistance of Ti fleece PTLs was investigated using various electrical, surface analytical, and electron microscopy methods. The results will be correlated and discussed in this presentation.



- Imaging of dissipated power (= current × voltage) within MEA
- High frequencies: p^+ currents in PE membrane (bright) and areas with high resistance at interfaces between PTL and CCM (dark)
- Low frequencies: bright spots exhibit locally decreased R_p, weak points in CCM

Figure 1: *VACE-LIT images of a 5x5 cm² sized PEM MEA acquired at different AC frequencies (bottom) and addressed components of the equivalent circuit diagram (top right) [3]*

[1] S. Siracusano, S. Trocino, N. Briguglio, V. Baglio, A. S. Aricò, *Materials (Basel, Switzerland)*. **2018** *11*, DOI: 10.3390/ma11081368.
[2] O. Breitenstein, M. Langenkamp, *Lock-in Thermography*, Springer Berlin Heidelberg, Berlin, Heidelberg **2003**.
[3] V. Naumann, E. Grunwald, L. Giesenberg, W. Münchgesang, K. Witte-Bodnar, K. Ilse, pss RRL **2023** DOI: 10.1002/pssr.202300028, in press.

Metal-Organic Chemical Deposition as a Tool for Establishing a Fundamental Understanding Towards the Electrocatalysis of Oxide-Supported Ir-Based Materials for the Oxygen Evolution Reaction

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[b]*ICGM, University of Montpellier, CNRS, ENSCM, Montpellier, France*
[c]*Centre for Catalysis Research, Catalysis Institute, Department of Chemical Engineering, University of Cape Town, 7701, South Africa*

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The generation of green hydrogen by renewable, sustainable means is a crucial building block towards the realisation of a carbon-free energy economy. Proton exchange membrane water electrolysis (PEMWE) offers a promising route for the generation of clean hydrogen, using renewable energy, for both stationary and mobile energy storage applications, and as a feedstock for the chemical industry. As water electrolysis is an electrochemical redox reaction, cathodic hydrogen evolution cannot occur without an efficient, and rapid anodic oxygen evolution reaction (OER). While both iridium and ruthenium oxides are state-of-the-art OER catalysts in acidic environment, the latter undergoes dissolution under anodic OER conditions much more rapidly than the former, and this makes iridium oxide the most suitable catalytic material for electrolyser anodes. Several strategies have been explored to enhance iridium utilisation in OER catalysts, and of these, the use of cheap, stable support materials has been seen as a promising means to produce highly active, durable catalysts, by enhancement of the electrocatalytically active surface area[1-3].

The development of a metal-organic chemical deposition (MOCD) method as a tool to study oxide-supported iridium Ir-based OER catalysts is outlined and the learnings from the use of MOCD for the deposition of Ir-based nanoparticles on Sb-SnO_2 support are highlighted. At the start of the presentation, the formation of epitaxially anchored, rutile IrO_2 nanoparticles on Sb-SnO_2 support with a structural metal-support interaction, and high performance for the oxygen evolution is shown[1]. In the later portion of the talk, the usage of inert and oxidising reaction environments at low and high deposition temperatures is discussed. Here, the surprising observation of reductive Sb segregation and the formation of reduced iridium species at high temperature using MOCD is explained based on thermodynamics, and the physicochemical and electrochemical properties of the prepared catalysts are evaluated. The findings from this work highlight the considerations required for the development of model supported catalyst systems to study the OER, as well as the synthesis of doped oxide supports and the deposition of Ir-based catalysts.

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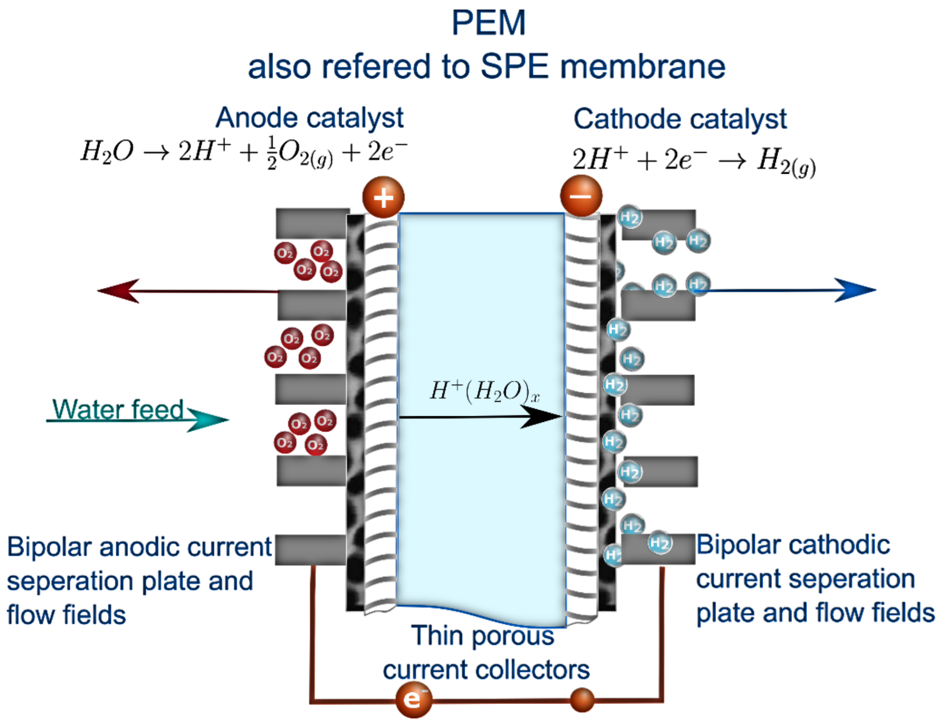
Wednesday 30th August – Session 16



Transfer of Wind Data to Electrolyzer Test Stand

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For the electrolytic production of hydrogen based on renewable energy sources, knowledge about the behavior of electrochemical reactors operated with intermittent energy must be raised. For this purpose, a probabilistic method has been developed to transform wind speed data to electrolyzer input current density. This provides a systematic approach for clustering wind speed characteristics according to their influence on PEM-WE operation.

The method uses measured wind velocities (10 min resolution for 3 years) and simulated current distributions (20 ms resolution for 10 min) as input. The latter distributions were generated based on 5 different simulated wind field velocities, each portrayed over 6 random seed submodels, and transformed by an electrical model. These current distributions rely on many assumptions, among these are wind field model, wind turbine model[1] and electrolytic cell resistance.

To correlate both input datasets, wind field velocities were analyzed in a descriptive as well as explorative (adapted from signal processing theory)[2] manner. Based on recurring characteristics, specific days were pulled from the 3-year population and used for rearranging the current density submodels into looped sequences representing standard days or weeks.

First results will be presented, utilizing data from the Adwen AD 8-180 wind turbine in Bremerhaven and a Greenlight E30/E40 test station. The outcome includes definitions of recurring wind characteristics, the impact of the current density submodel choice and time resolution on the test station. The common focus will tackle reproducibility's sticking points along with the key issue – validity.

This work is part of the hydrogen flagship project H_2Mare - joint project H_2Wind (03HY301D), funded by the German Federal Ministry of Education and Research.

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On the quantification of Ir dissolution in proton exchange membrane water electrolyzers

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Proton exchange membrane water electrolysis (PEMWE) is considered to play a key role in the new energy scenario by coupling the production of high-purity hydrogen with the renewable energy sources. However, the omnipresent challenges of this approach are the slow oxygen evolution reaction (OER) kinetics taking place on the anode and the necessity for critical raw materials as catalysts or related components. Reducing noble metal loading without compromising the electrolyzer durability is necessary for the implementation of PEMWE on a TW scale.[1]

Currently, aqueous electrolytes represent a model system for testing OER electrocatalyst performance, given the ease to examine their activity and stability when performing simplified half-cell tests.[2] However, dissolution-based catalyst stability evaluations performed in model systems do not represent the full-cell PEMWE conditions.[3] Venturing to determine the real catalyst dissolution rates in PEMWE, the activity and stability of anode catalyst layers (CLs) are evaluated in a specifically developed metal-free single cell electroyzer. Various accelerated stress tests (ASTs) mimicking intermittent operation were applied in order to promote anode catalyst degradation and consequential catalyst dissolution that is later quantified via ex-situ inductively coupled plasma mass spectroscopy (ICP-MS) analysis. The obtained results give new insights into catalyst degradation mechanisms in PEMWE, complement the previously obtained results in half-cell tests and propose a new approach towards catalyst stability studies in PEMWE.

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Water Electrolysis Research and Development by HySA Infrastructure CoC

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Proton-exchange membrane (PEM) water electrolysis (WE) technology is considered as promising hydrogen generation solution in the frame of the ongoing energy transition if the process of hydrogen generation by means of WE is linked to renewable energy sources, such as wind, solar, etc.

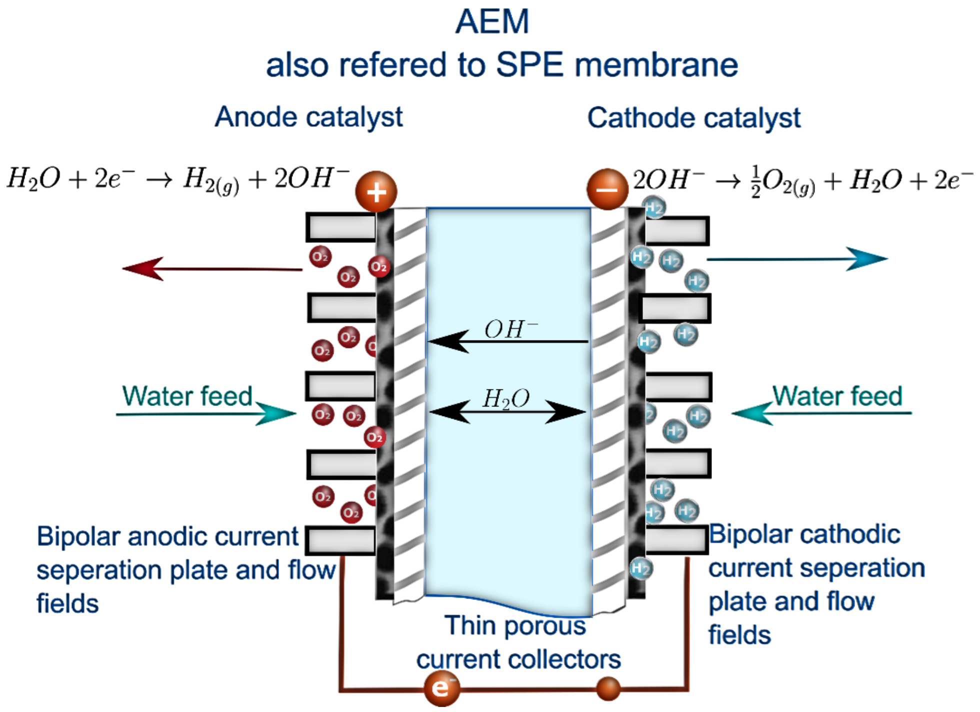
Among other existing water electrolysis technologies, such as alkaline, solid oxide, the technology based on proton-exchange membranes has received a great deal of interest in South Africa. One of the reasons is endowment of South Africa with its PGM resources, such as platinum (Pt) and iridium (Ir) that are used in PEM water electrolysis (WE) catalytic components. As it is known, PEMWE technology is very well suited to accommodate intermittency of energy supply associated with renewables. PEMWE technology can also deliver relatively high-pressure hydrogen gas of high purity. South Africa has also superior endowment of both onshore wind and solar. It is known thar renewable energy (RE) is one of the largest operational cost components in the production of green hydrogen. Other factors contributing to the interest in green hydrogen water electrolysis technology in South Africa that are not obvious, but important, include large tracts of sparsely populated land with little alternative use, which can be dedicated for RE production. South Africa also has a suitable geographical position with deep water ports for the potential export of large quantity of hydrogen and its derivatives such as ammonia.

Approximately 15 years ago South African Government approved national program HySA: Hydrogen South Africa that resulted in developing expertise and capacity to conduct research, development, and earlier commercial activities around green hydrogen production by means of water electrolysis. These activities include development of local IP at the components, stack and system levels. Recently, a number of “catalytic” projects have been identified in order to increase a demand in green hydrogen and stimulate investments.

This talk will provide an update on the R&D activities undertaken by HySA at NWU towards water electrolysis development.

Poster Presentations

Alkaline Anion Exchange Membrane (AEM)



Synthesis and characterization of NiMo/C as a HER catalyst for PGM-free AEM water electrolysis

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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 or be used for ammonia and steel production. The alkaline anion exchange membrane water electrolysis (AEMWE) combines the advantages of PEM electrolysis with the cheap materials of the alkaline electrolysis.

In this work NiMo and NiMo on different supporting materials were synthesized via a microwave assisted hydrothermal reaction with a subsequent H_2 reduction step.

The produced catalysts were compared in terms of electrochemical performance via rotating disc electrode (RDE, **Figure 1a**) and cell measurement (**Figure 1c**). Their elemental compositions were analysed by using ICP-OES and STEM-EDX (**Figure 1b**). The structure of the catalysts was analysed by SEM, TEM and XRD measurements.

Even though non-supported NiMo has the lowest overpotential of all the catalysts at 10 mA/cm^2 shown in Figure 1a the performance is significantly worse in a full MEA-setup (Figure 1c) indicating the importance of carbon supports for the cathode. The best NiMo catalyst in the form of NiMo/KetjenBlack600 was then sprayed on a membrane together with NiFe-LDH as the anode showing a current density of 2 A/cm^2 at 2.15 V in 1 M KOH. This is not on Pt-like levels yet, but a step into the right direction for PGM-free AEMWE.

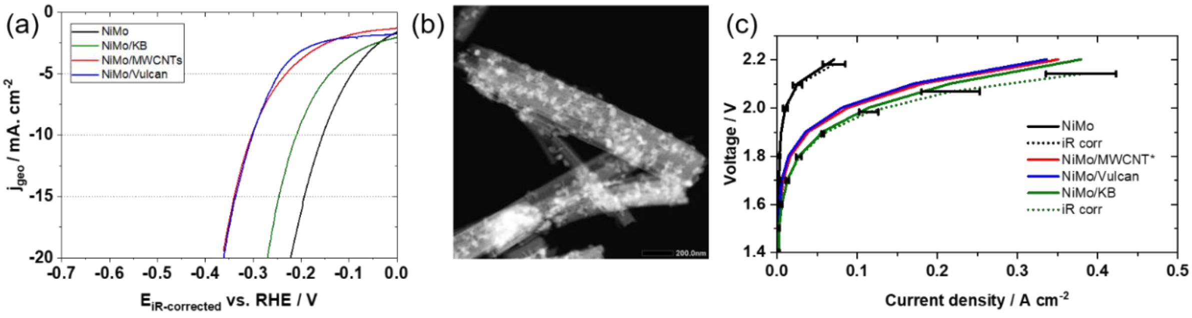

Figure 1*: (a) LSVs of pure NiMo and NiMo on different types of carbon support measured by rotating disk electrode (RDE). (b) STEM EDX picture of non-supported NiMo. (c) Full cell measurements of NiMo and NiMo/C cathode and Ni-felt anode.*

Electrochemical impedance spectroscopy study of an anion exchange membrane water electrolyzer

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Low-cost anion exchange membrane (AEM) water electrolysis is a promising technology for producing “green” high-purity hydrogen[1]. It integrates the benefits of both acidic polymer electrolyte membrane and classic alkaline electrolysis: inexpensive non-noble metal-based catalysts/stack materials[2] and a zero-gap cell architecture, typical for PEM electrolysis. Further development of AEM water electrolyzer components necessitates a deeper understanding of the electrolyzer behavior measured “in situ”.

The electrochemical impedance spectroscopy (EIS) approach proves to be a very effective tool that provides a non-invasive in-situ measurement of the electrochemical system’s impedance, including water electrolyzers. The most common approach is a complex nonlinear least-square fit approximation to a model function represented by an equivalent circuit model (ECM), which consists of electrical components, such as resistors, inductors, and capacitors, as well as generalized elements, e.g., constant phase element (CPE), Warburg, and others. This approach is rather attractive due to its simplicity instead of its drawbacks, such as the ambiguity and uncertainty in interpreting EIS data based on ECMs.

The presented study shows the detailed EIS study of AEM water electrolysis cells based on commercially available non-noble metal catalysts and AEMION™ (Ionomr, Canada) membrane. The ECM based on three R/CPE components (high-, mid-, and low-frequency arcs)[3] was used to unravel different contributions in the total EIS footprint of the AEM water electrolyzer. Characteristic frequencies of main EIS contributions are provided for the AEM water electrolyzer based on commercially available membranes and electrodes as a benchmark.

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Thermally processible anion exchange membranes for AEMWE at scale

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Anion exchange membrane water electrolysis (AEMWE) is a burgeoning technology that offers the most potential benefits to produce clean hydrogen and achieve the U.S. DOE target of $1 per kg hydrogen. Current commercial membranes all feature hydrocarbon backbones sans heteroatoms and chemically durable quaternary ammonium functional groups, thus providing good performance and durability. However, all the AEMs (anion exchange membrane) that are commercially available lack thermal characteristics necessary for hot-pressing electrodes.

Embedding electrodes into the membrane surfaces via hot-pressing is one of the key processing techniques used in proton exchange membrane water electrolyzers and fuel cells. This technique enables higher performance and durability owing to the improved interfacial contact, reduced cell resistance, and more efficient use of electrocatalysts, and it is also scalable. Therefore, it is critically important that AEMs be designed for thermal processing.

Polyethylene- and polypropylene-based AEM materials enable thermal processing due to their associated melting points being less than 160 °C. There have been several literature examples of polyolefin-based AEMs prepared mostly by Ziegler-Natta [1,2] or ROMP[3] reactions. These academic reports showcased excellent results in terms of membrane performance, however in all cases the reactions were inefficient with low mass recovery making them challenging for commercialization. Herein, we report polyethylene- and polypropylene-based AEMs prepared from Ziegler Natta polymerization. Our optimized catalyst system allows for greater comonomer utilization (≥ 50%), improved control and repeatability of the materials composition, and fast reaction kinetics, while utilizing low-cost monomers in a commercially scalable process. The base polymers are readily thermally processed into thin films with and without support material and the functionalized membranes enable clean catalyst layer decal transfer via hot-pressing. Lastly, we will demonstrate that the membranes developed at Giner have competitive performance and durability characteristics compared to the current commercially available AEMs.

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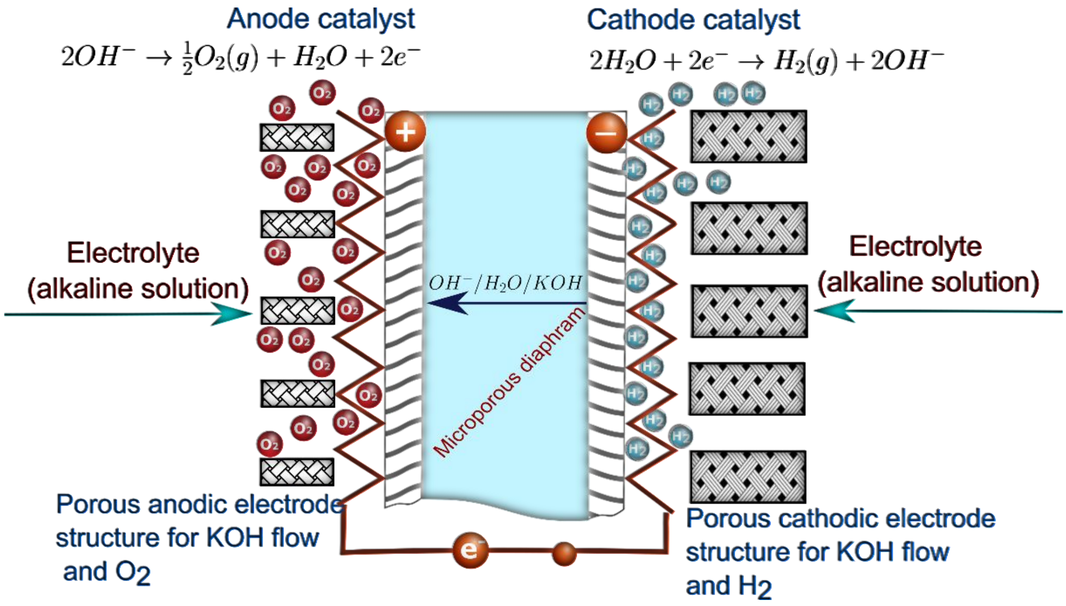
Alkaline Water Electrolysis (AWE)



Development Strategies for Diaphragms in Alkaline Water Electrolysis

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Electrolytically produced hydrogen is a keystone in the decarbonization of the industrial and energy sectors. Amongst the technologies for the electrolytic production of hydrogen, precious-metal free alkaline water electrolysis is the most mature and easiest to scale. However, alkaline water electrolysis faces performance shortcomings with regards to the other technologies.

A major component in alkaline water electrolysis limiting performance is the separator, which today on commercial scale is a diaphragm. The separator prevents the electrodes from short-circuiting while minimizing gas crossover. Several approaches to improve the performance of the separator include the development of novel membranes, reaching from ion-solvating membranes [1] to anion exchange membranes [2]. Concurrently to the complications on their synthesis, novel polymers face stability concerns. The polymer backbone may suffer from nucleophilic attack of the hydroxide-anion [2].

Besides the development of novel polymers, one promising approach to improve the separator lies within improving the diaphragm. Reducing the diaphragm thickness increases gas crossover, and thus faces limitations with regards to the operating pressure and temperature [3]. The major advantage of improving the diaphragm is its scalability and stability. The fast-growing hydrogen industry requires rapidly scalable, cost-competitive solutions. Hence, revisiting the well-established diaphragm strategies are the most promising fast-to-market routes.

We present strategies for the improvement of the diaphragm by choosing known alkaline-stable polymers and already industrially implemented production processes. The produced diaphragms are tested towards performance and stability at 80 ◦C in 30 w% KOH, with a focus on the conductivity, bubble point and hydrogen gas crossover. We see that, by revisiting the development-strategy of diaphragms, the performance of phase-inverted diaphragms in terms of conductivity and hydrogen gas crossover may be substantially improved.

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Improved cold-start behavior for alkaline electrolysis through electrolyte concentration heat storage

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Alkaline electrolysis (AEL) outperforms other state of the art electrolysis technologies, like polymer-electrolyte membrane (PEM), both in terms of capital and operational expenditure. It only relies on ubiquitous materials, has a high efficiency and the best long-term stability. However, problems lie in the dynamic behaviour and especially the gas contamination in the lower partial load range as well as slower cold start processes compared to PEM electrolysis.

Unfortunately, AEL is not as qualified for direct coupling with renewables, as for example PEM. One reason for this is that heating the stack to operating temperature is particularly time-consuming during a cold start process. Zhang et al.] show in their work that heating the electrolyte of an 250 kW alkaline electrolyser up to 68°C takes approximately 1.3 h. Since quick starts are needed in a renewable scenario, they conclude that an external heat source for starting the process would improve the flexibility of the electrolyser.

Better than an external heat source would, of course, be an internal heat source that could be used without drawing further energy. For this reason the content of this work is a theoretical concept of an innovative concentration heat storage, which can accelerate the cold start capability of alkaline electrolysis. Here, the strongly exothermic reaction of the liquid electrolyte KOH or NaOH when diluted with water is used. Furthermore, the general property of an electrolyser to concentrate the liquid electrolyte through the conversion of the water contained during operation.

The designed concept is based on concentrating the electrolyte up to a certain max. value (40 - 45 %) during stationary operation and diluting the highly concentrated electrolyte to a lower limit value, e.g. 20 %, when a cold start is required. Due to the exothermic reaction, the temperature of the electrolyte increases by approx. 20°C when diluting NaOH 40 % -> 20 %, for example. This temperature increase can be used for effective preheating.

Since the enthalpy of solution of KOH is higher compared to NaOH, even higher values can theoretically be achieved when diluting KOH. Thus, it is possible to increase the flexibility of alkaline electrolysis with this concept.

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Enhanced OER activity of sputtered Ni thin films due to iron in the electrolyte

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Numerous efforts are made to reduce the overpotential of the infamous, sluggish oxygen evolution reaction (OER) in alkaline water electrolysis (AWE). These efforts involve the development and study of OER electrocatalysts. Ni is an established electrocatalyst for this reaction and the effect of Fe on the activity of this electrocatalyst has been extensively studied for many years.[1,2,3] However, it is still not known what the active site is and whether it is iron in the bulk or on the surface of Ni that is responsible for the enhanced electrocatalytic activity. In this study, the effect of different concentrations of Fe in the electrolyte on the OER activity of different sputtered Ni electrocatalysts was investigated. Magnetron sputtering was employed to sputter Ni, NiO and NiNiO thin film electrocatalysts. The electrode surfaces were activated through repeated cycling and it was found that the Fe in the electrolyte deposited onto the surface of the Ni electrocatalysts during this process. The average overpotential at 10 mA cm-2 was 284 mV after cycling the sputtered thin films in KOH containing 1 mM Fe, which is 64 mV lower than in pure KOH. All Tafel slopes in the study are between 36 and 45 mV dec^{-1} indicating similar kinetics for the samples cycled in different Fe concentrations. Energy-dispersive X-ray spectroscopy (EDS) and X-ray photoelectron spectroscopy (XPS) results show that the Fe responsible for the enhanced activity is found on the surface and not in the bulk structure of the Ni electrocatalysts.

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Development of alkaline electrolyzers for green hydrogen at Stiesdal A/S

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The absence of any requirement of noble metals and high-temperature materials, make alkaline electrolyzers most demanding technology for industrial scale production of green fuel (i.e., hydrogen), if associated with renewable power sources (i.e., solar and wind), to mitigate the existing dependence on fossil fuels. Alkaline electrolysis process is a century old, but the production of scalable technologies is rather new. At Stiesdal Hydrogen, we develop and demonstrate full-scale commercial unit in “minimum viable product” configuration at commercially relevant power level. The team at Stiesdal focuses on rethinking the design of alkaline electrolyzers to leverage on already existing and well proven high throughput manufacturing processes, supply chains and low-cost yet efficient materials, we will cut the unit costs drastically. We focus our R&D activities towards investigating the possible activation of minimal viable material for alkaline electrolysis with least compromise in its lifespan, reducing or possibly eliminating all sorts of losses associated with the conventional design of alkaline electrolyzers (i.e., power, electrolyte, materials, etc.), and optimizing cell design by efficient selection of parameters (geometry, perforation, distancing, etc.). This presentation will focus on our low-cost alkaline electrolyzer, the HydroGen electrolyzer, for mass production and how this unit paves the way for low-cost green hydrogen enabling swift scaling into the GWs.

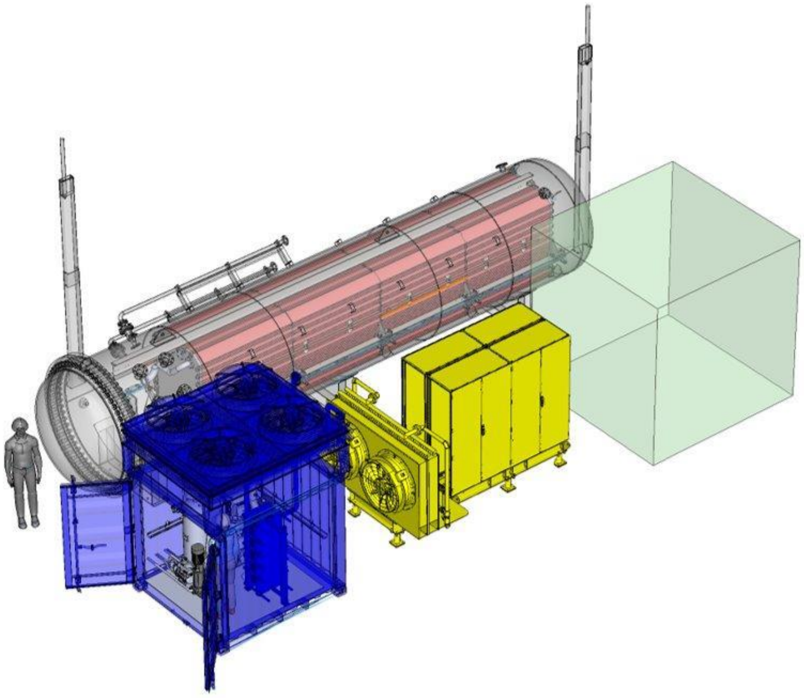

Figure: *Stiesdal 3MW Hydrogen Electrolyzer with power electronics*

The effects of water quality of different sources on the performance of electrolysis

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Electrolysis is a technology which uses renewable electricity to decompose water and produce green hydrogen. The commercially available electrolyzers have strict requirement for the water purity (For PEMWE, strict water conductivity of ＜0.1 μS/cm is required. For commercially available AWE, the water conductivity should be less than 5 μS/cm), which limits the large-scale industry application of water electrolysis technology due to supply competition with the household needs. In this work instead of feeding ultra-pure water or deionized water to electrolyzer, impure water sources such as wastewater/seawater/brakish water etc. after treatment plant will be introduced as feedstock in the system to produce hydrogen. The work addresses both current and future issues of commercial electrolysis technologies, and therefore facilitates the development of PtX technologies, especially the impurity content effect in the feedstock on the performance of commercially available electrolyzers. The Electrochemical impedance spectroscopy (EIS) and polarization measurements will be carried out to characterize the performance of electrolyser under different operating conditions.

Elucidating the resistance of free bubbles in zero-gap alkaline water electrolysis

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Alkaline electrolyzers have a higher internal ohmic resistance compared to other water electrolysis technologies, even with a zero-gap configuration. The expected ohmic resistance of the Zirfon diaphragm cannot fully explain this phenomenon [1]. Bubble curtains can also contribute to the ohmic resistance. In this study, we investigated the role of free bubbles in increasing the ohmic resistance in a zero-gap configuration using Electrochemical Impedance Spectroscopy (EIS) and chronopotentiometry. We used different electrode geometries, namely uncoated and coated nickel perforated plates and 3D-structured electrodes. The electrode geometry is expected to influence the bubble curtain flow pattern, free bubble internal recirculation, and gas holdup in the electrolyzer.

We compared the high-frequency EIS resistance (R_{ohm}) at low and high current densities. At low current density, the effect of bubbles is expected to be reduced due to the limited gas formation, in contrast to high current density. The high-frequency resistances at 0.01 A.cm^{-2} and 0.8 A.cm^{-2} are presented in **Figure 1(a).** It shows that for the best-performing electrode geometries with the lowest ohmic resistance, the difference in ohmic resistance between low and high current is ~10%, which increases to ~30% for the poorer performing electrode materials. Therefore, the effect of free bubbles on the ohmic resistance seems relatively limited, possibly because the electrolyte conductivity between electrodes is not significantly affected by bubbles in a zero-gap design. **Figure 1(b)** illustrates the relationship between cell potential and ohmic resistance at 0.8 A.cm^{-2} for measurements using different electrode structures. The data generally confirms the expected trend that a higher ohmic resistance leads to a higher cell potential.

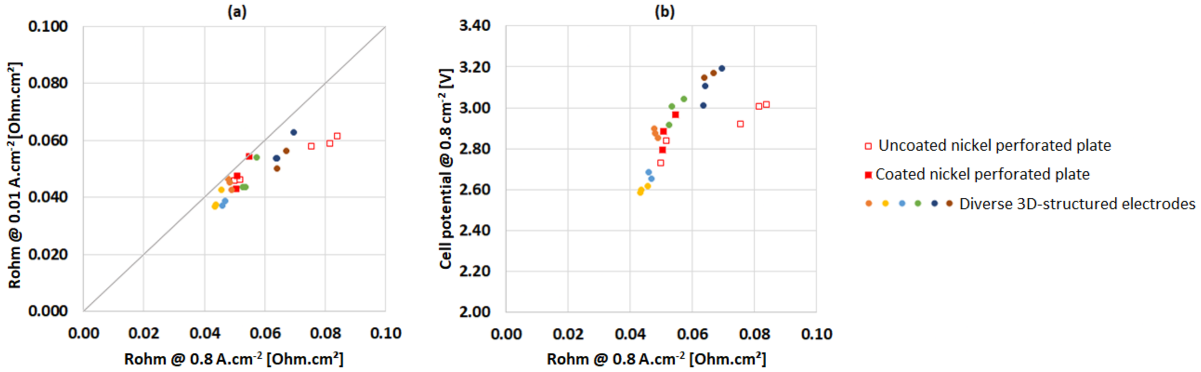

Figure 1: (a) High frequency resistance (32 kHz) at 0.01 A.cm^{-2} and 0.8 A.cm^{-2}; and (b) cell potential versus ohmic resistance at 0.8 A.cm^{-2} for different electrode geometries in a zero-gap electrolyzer. Conditions: ~28%wt KOH at 12 L.h^{-1}, ~25 °C.

[1] de Groot, M. T.; Vreman, A. W. Ohmic Resistance in Zero Gap Alkaline Electrolysis with a Zirfon Diaphragm. Electrochimica Acta. **2021**, 369, 137684. DOI: 10.1016/j.electacta.2020.137684.

Dynamic hydrogen bubble templated synthesis of Ni_xP_y-based electrocatalysts for alkaline oxygen evolution reaction

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The dynamic hydrogen bubble template (DHBT) is an emerging synthesis technique that can produce three-dimensional (3D) porous materials, which are highly desired in electrocatalytic applications. [1,2] This method bypasses the use of organic and inorganic templates by using H_2 gas evolved from the reaction as the template. Cathodic conditions during DHBT drive the simultaneous electrodeposition of the desired material and the production of H_2 gas. In this study, porous Ni_xP_y materials were synthesized through the DHBT method and were tested as catalysts for oxygen evolution reaction (OER) in alkaline conditions. The effect of the potential on the morphology and electrochemical performance of Ni_xP_y was studied by applying different constant potentials per sample during electrodeposition (-2, -3, and -4V vs Ag/AgCl). High potentials are needed to activate both the Ni^{2+} species reduction–phosphidation and H_2 evolution reactions. At low applied potential (– 2 V vs. Ag/AgCl), insufficient amounts of H_2 bubbles were produced. As the electrodeposition potential was increased, Ni_xP_y was produced on the surface, making it more HER active, thus increasing H_2 production rate. As a result, increasing the voltage to -4 V during DHBT synthesis changed the catalyst's morphology from bulk to 3D porous film (**Figure 1**) and doubled the electrochemically active surface area. The changes in morphology further affected the electrochemical properties of the developed Ni_xP_y films. The overpotential required to reach 10 mA cm^{-2} in 1 M KOH electrolyte increased in this order: 279 mV ($Ni_xP_{y\,(-4\,V)}$) < 282 mV ($Ni_xP_{y\,(-3\,V)}$) < 289 mV ($Ni_xP_{y\,(-2\,V)}$). The most active catalyst, $Ni_xP_{y\,(-4\,V)}$, exhibited good kinetics towards OER, with a low Tafel slope at 44 mV dec^{-1}. Overall, this work offers significant findings in selecting the appropriate electrodeposition potential in designing and developing highly active OER catalysts through the DHBT method.

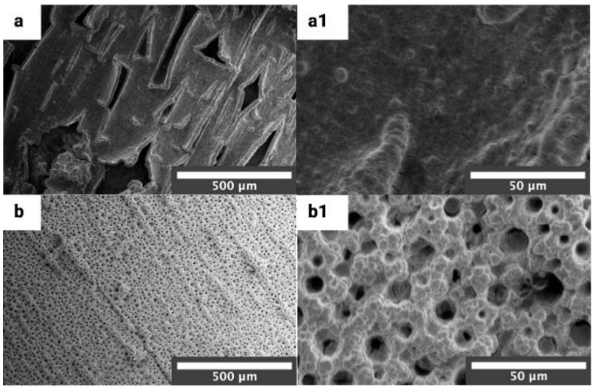

Figure 1. *SEM Images of the Ni_xP_y film produced at (a,a1) – 2 V vs. Ag/AgCl and (b,b1) -4 V vs. Ag/AgCl.*

[1] Plowman, B. J.; Jones, L. A.; Bhargava, S. K. Building with Bubbles: The Formation of High Surface Area Honeycomb-like Films via Hydrogen Bubble Templated Electrodeposition. *Chemical Communications* **2015**, *51* (21), 4331–4346. https://doi.org/10.1039/C4CC06638C.

[2] Oh, S., Kim, H., Kwon, Y., Kim, M., Cho, E., & Kwon, H. Porous Co–P foam as an efficient bifunctional electrocatalyst for hydrogen and oxygen evolution reactions. *Journal of Materials Chemistry A* **2016**, *4*(47), 18272-18277. https://doi.org/10.1039/C6TA06761A.

Computational Approaches to Alkaline Anion Exchange Membranes and Electrolysis

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Different computational approaches have made it possible to model catalytic processes and material properties at different length scales; from microscopic to mesoscopic to macroscopic hence, the suitability of these computational approaches in investigating material properties, chemical processes and different phenomena in alkaline anion exchange-based membrane fuel cells (AAEMFC). AAEMFCs have been heralded as possible challengers of proton exchange membrane fuel cells that have dominated the fuel cell space. This is because AAEMFCs create opportunities for cost reduction, mainly due to the switch in operating conditions from an acidic to an alkaline environment/medium. [1,2]. Thus, to improve and optimize the operation and properties of AAEMFCs, modelling at different length scales is essential. In this work, we give a scoping review of how computational approaches have been used to investigate material properties and chemical processes in AAEMFCs. We zoom in on how different modelling length scales have been applied; The microscopic scale entails the ab initio and quantum mechanical modelling of alkaline AEMs. The mesoscopic scale entails using molecular dynamics simulations and other techniques to assess the alkaline electrolyte diffusion in AEMs, OH– transport and chemical degradation in AEMs, ion exchange capacity of an AEM, as well as morphological microstructures. We observe that there are still more opportunities to deploy computational approaches in generating fundamental insights into material properties, chemical reactions, and processes of AAEMFCs.

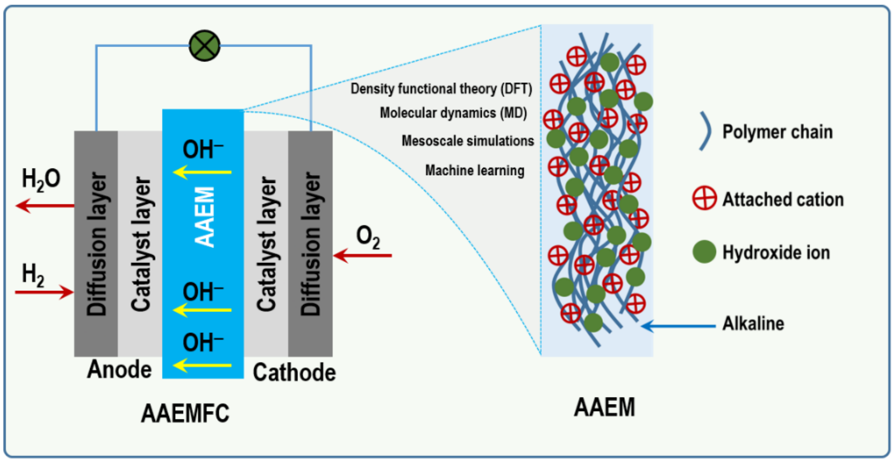

***Figure 1**: Schema for AAEMFC and AAEM as well as the different modelling length scales.*

[1] Ouma, C. N. M., Obodo, K. O., & Bessarabov, D. (2022). *Membranes*, 12(11), 1051.
[2] Vincent, I., Kruger, A., & Bessarabov, D. (2017). *International Journal of Hydrogen Energy*, 42(16), 10752-10761.

Improving Alkaline Water Electrolysis Efficiency Using an Asymmetrical Electrode Cell Design

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Hydrogen is an energy carrier with potential applications in various industries. Alkaline electrolysis is a commonly used method for hydrogen production; however, its energy cost remains relatively high compared to other methods. In this paper, we present a simple and scalable method that significantly improves the energy efficiency of alkaline electrolysis. Our approach involves mitigating interfacial pH changes by using a cell design with a different cell design, introducing the electrode asymmetry. We tested the method using a multivariate approach in both laboratory and industrial current density conditions and validated the results with numerical simulations. Our results demonstrate a clear improvement (11.6%) in energy efficiency, providing an important contribution to the field of sustainable energy production. Figure 1 shows the improvement by the decrease in the cell potential as the Area Quotient (A_Q) raise. Our findings have important implications for the development of cost-effective and sustainable hydrogen production methods.

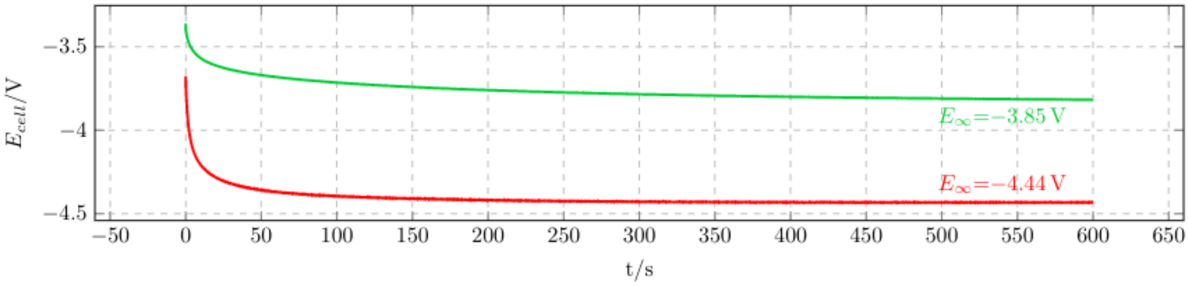

Figure. *Chronopotentiometry with different cell configuration. [KOH]= 6 mol/L;* j_{WE}*=400 mA/cm*^{2}

Mechanical alloying of Ni-based catalysts for alkaline water electrolysis

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Alkaline water electrolysis (AWE) is a mature technology and currently undergoing large scale industrialization. Electrodes based on nickel coated steel plates are robust and economical. However, the technology generally operate with low current densities, leading to research in catalyst synthesis, electrode modification, and stack design. Highly efficient, durable, and low-cost catalyst powders, which can be quickly coated on the conventional perforated electrodes is therefore of great interest.

Mechanical alloying was studied to produce Ni-based alloys with high yield. Results show that, for instance, 3-hour milling at 500 RPM, is sufficient to form highly crystalline Ni_2Al_3 alloy as a Raney nickel precursor powder. The found milling profile is applicable for other catalyst compositions with high product yield (≥80%).

The produced catalysts were characterized by XRD, SEM and EDX, and applied to electrodes by airbrushing. Following an activation procedure, the catalysts were evaluated in half cell electrochemical measurements.

The project is performed in close collaboration with the company Stiesdal Hydrogen A/S.

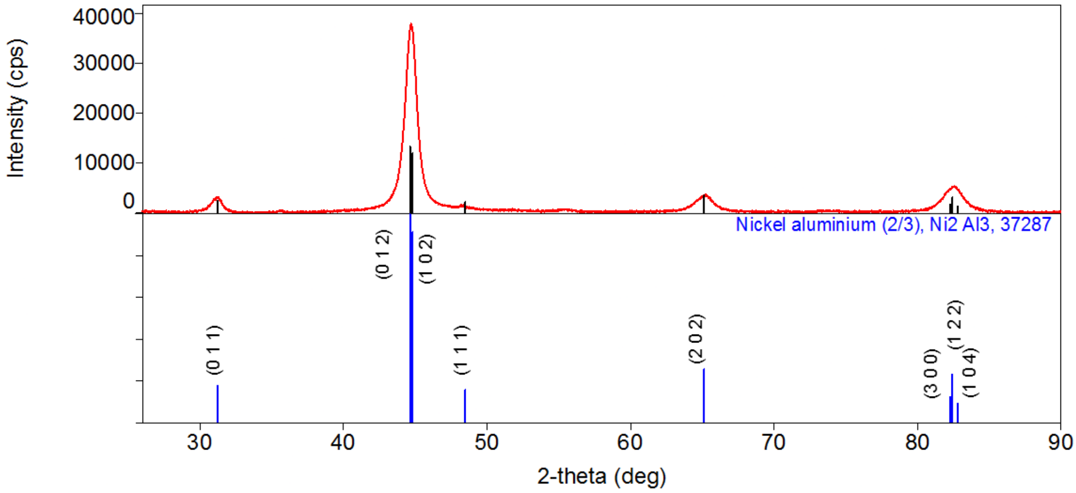

***Figure 1**: XRD result of Ni_2Al_3 alloy synthesized by high-energy ball milling.*

Magnetron sputtering of NiFe electrocatalysts for enhanced OER activity in alkaline media

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Anion Exchange Membrane (AEM) water electrolysis is a promising technology gaining increased interest in the quest for environmentally friendly and sustainable energy sources [1]. It has the potential to operate at higher current densities than traditional alkaline water electrolysis (AWE) but at lower cost than polymer electrolyte membrane (PEM) electrolysis by replacing PGM-based catalysts with Ni-based non-noble catalysts. Highly active, durable and scalable non-PGM catalysts still need to be developed even though promising options are available in literature. Ni, in combination with Fe has been shown many times to be highly active for the sluggish oxygen evolution reaction (OER) at the anode of a AEM water electrolyser. However, consensus still needs to be reached on the role Fe plays in enhancing the catalytic activity of Ni [2].

The aim of this investigation was to gain insight into the role of Fe in the enhancement of the OER by using magnetron sputtering to prepare binder-free thin films of Ni and NiFe. Two types of catalysts were prepared, i.e. (i) co-sputtering Fe with Ni and (ii) incorporation of electrolytic Fe into sputtered pure Ni. The purpose was to show whether bulk Fe present from the start or surface/bulk Fe incorporated from the electrolyte influences the OER activity differently. The lowest overpotentials reached was ~330 mV for the co-sputtered NiFe (23 % Fe) and ~310 for 0.1 mM Fe-spiked KOH at 10 mA.cm^{-2}. The presence of Fe shifted the Ni redox peaks to higher values and also suppressed the NiOOH peak. In-situ Raman measurements confirmed the presence of NiOOH at potentials above 1.45 V for Ni and 3 % co-sputtered Fe and the absence of NiOOH peaks for higher compositions of Fe. For co-sputtered NiFe catalyts, enhanced activity was achieved from the start and potential cycling had no further influence on the OER activity. Therefore, this work shows that even though better activity was achieved when co-depositing Fe from the electrolyte, the co-sputtered catalysts were more active from the start without the need for extended potential cycling. This could have implications for catalyst preparation as a promising method to prepare highly active binder-free thin films that doesn't need extensive pre-treatment or in-situ activation.

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[2] Anantharaj, S., S. Kundu, and S. Noda, *"The Fe Effect": A review unveiling the critical roles of Fe in enhancing OER activity of Ni and Co based catalysts.* Nano Energy, 2021. **80**.

Machine learning guided optimization of nano-structured Ni electrodes for alkaline water electrolysis

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The market for alkaline electrolysers is projected to grow massively. While systems in the MW scale are already marketed, cheap and efficient mass-manufacturing methods for making electrodes are still being explored, and improvements in efficiency are still sought after.

One option for electrode manufacturing is electroplating. Electroplating is versatile, already widely industrialized, and offers a wide parameter space in which to optimize coating performance either via tuning of the chemical composition or the morphology. Even single-element coatings offer a large variety of morphological tuning, simply by varying process parameters. However, optimization within a multi-dimensional parameter space can be a tedious and time-consuming effort.

We have explored the optimization of high surface area nickel coatings for the hydrogen evolution reaction (HER), within a fixed chemical space, and selected process parameter space. Using machine learning (ML) methods with a human-in-the-loop we have optimized pure nickel coatings. With the overvoltage at 10 mA cm^{-2} as the figure of merit, we have achieved improvements of ca 200 mV as compared to plain substrates, and ca 100 mV compared to a manual optimization. The optimization process is illustrated in **Figure 1**, and have been realized with minimal experimental efforts and only few iterations. Optimized electrodes show remarkable HER activity, and the results pave the way for being applied on more complex coating systems.

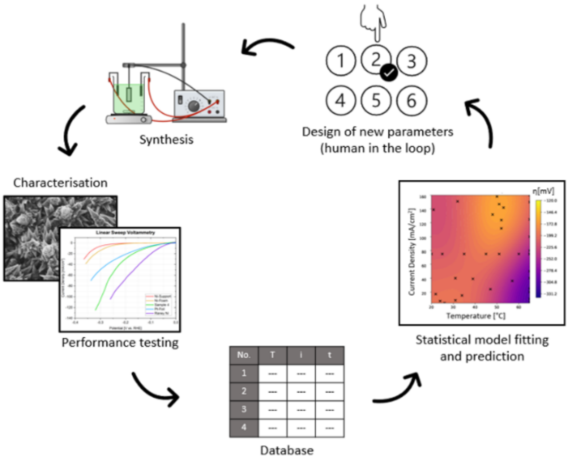

***Figure 1**: Iterative feedback loop between ML predictions and experimental work.*

Prospects for Alkaline Exchange Membrane (AEM) Electrolysis

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Alkaline exchange membrane electrolysis (AEMEL) has emerged as a promising novel route toward potential cost reductions of hydrogen production. The AEMEL technology allows to preserve simultaneously the advantages of a membrane water electrolyser, as well as the low-cost materials, both electrodes' catalysts, and structural materials, derived from the alkaline environment. Given the promise and potential, however, there is a strong need to mature the technology readiness level of AEMEL. Its technological challenges are mainly embedded in developing innovative low-cost alkaline Membrane-Electrode Assemblies (MEAs), Stacks and Modules, capable to deliver overall device performance and durability that allow direct competition with current competitor electrolyser technologies. In this talk, an overview on HydroLite's recent advancements in harnessing nanotechnology to enhance the performance of alkaline exchange membrane (AEM) electrolysers for green hydrogen generation will be outlined, with specific emphasis on the design-to-cost, innovation, and development of nano-structured components for improved and enhanced performance of Alkaline Membrane-Electrode Assemblies.

Effects of water quality on alkaline water electrolysis performance.

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The development of renewable energy is a key element to reach carbon neutrality by 2050. Offshore wind turbines are increasingly used, even far from the coast. However, the cost of electrical transmission infrastructure becomes more and more important with distance and power [1]. A solution to limit the transportation cost related to offshore wind turbines is to transport energy in chemical rather than electrical form using hydrogen [1]. Furthermore, the latter can also be used to limit the intermittency of renewable energy by allowing energy storage. The transport of chemical energy can be achieved in several ways, by ship after densification and storage, by pipelines or by conversion of produced hydrogen into e-fuels using existing infrastructure.

However, an important challenge arises with the use of water electrolysis offshore: the only source of water easily available is seawater, which contains many trace elements besides water. Some of these elements are contaminants for the electrodes or separator and will therefore reduce the lifetime of the electrolyser and its efficiency.

There are two development paths for the use of seawater for water electrolysis: developing new catalysts that are compatible with these impurities, or using seawater pre-treatment. The latter allows the employment of state-of-the-art electrolysers but requires studying the effect of trace impurities present after seawater treatment on the performance of water electrolysers.

Since alkaline water electrolysis is well-known to be less sensitive to water quality than polymer electrolyte membrane (PEM) electrolysis [2], the first is the one being investigated in this work. Our study focuses on the determination of the faradic efficiency in the presence of different trace elements in the 1-1000 ppm range, starting from 1 M KOH electrolyte. Firstly, the two most prevalent anions in seawater, namely chlorides and sulphates, are investigated using KCl and K_2SO_4 salts. Secondly, with respect to cations, Na^+ is the most prevalent cation in seawater, but it is usually already present in the KOH pellets used to prepare the alkaline electrolyte. Therefore, our study will focus on the second most prevalent cation in seawater, namely Mg^{2+}.

[1] Ibrahim, O. S.; Singlitico, A.; Proskovics, R.; McDonagh, S.; Desmond, C.; Murphy, J. D. Dedicated Large-Scale Floating Offshore Wind to Hydrogen: Assessing Design Variables in Proposed Typologies. *Renew. Sustain. Energy Rev.* **2022**, *160*, 112310.

[2] Khan, M. A.; Al-Attas, T.; Roy, S.; Rahman, M. M.; Ghaffour, N.; Thangadurai, V.; Larter, S.; Hu, J.; Ajayan, P. M.; Kibria, M. G. Seawater Electrolysis for Hydrogen Production: A Solution Looking for a Problem. *Energy Environ. Sci.* **2021**, *14*, 4831–4839.

Other topics

Less is More: Variable Catalyst Loading for Improved CO_2 Electroreduction

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The use of gas diffusion electrodes that supply gaseous CO_2 directly to the catalyst layer has greatly improved the performance of electrochemical CO_2 conversion. However, reports of high current densities and Faradaic efficiencies primarily come from small lab scale electrolysers. The difference in scales means that many limitations that manifest only for larger electrolysers are not captured in lab scale setups We develop a computational model of a large scale flow electrolyser and compare its performance to a model of a lab scale electrolyser. We find that the scalability of the system is inhibited by large flow-wise inhomogeneities in the local reaction environment, due to increasing catalyst layer pH and concentration boundary layer thicknesses.[1] Furthermore, we investigate mitigation methods by which this reaction inhomogeneity can be reduced, and discuss their corresponding strengths and drawbacks. In doing so, we isolate a counter-intuitive method by which the selective removal of catalyst from the catalyst layer can greatly improve Faradaic efficiency and reaction homogeneity, while using significantly less total catalyst. A simplified product cost metric is then utilised to functionally optimise the local catalyst loading analytically and numerically for a diverse selection of profiles and restrictions. Finally, we implement the catalyst loading optimisation strategies into the prior computational model of the large scale flow electrolyser and discuss how effectively this method mitigates upscaling issues.

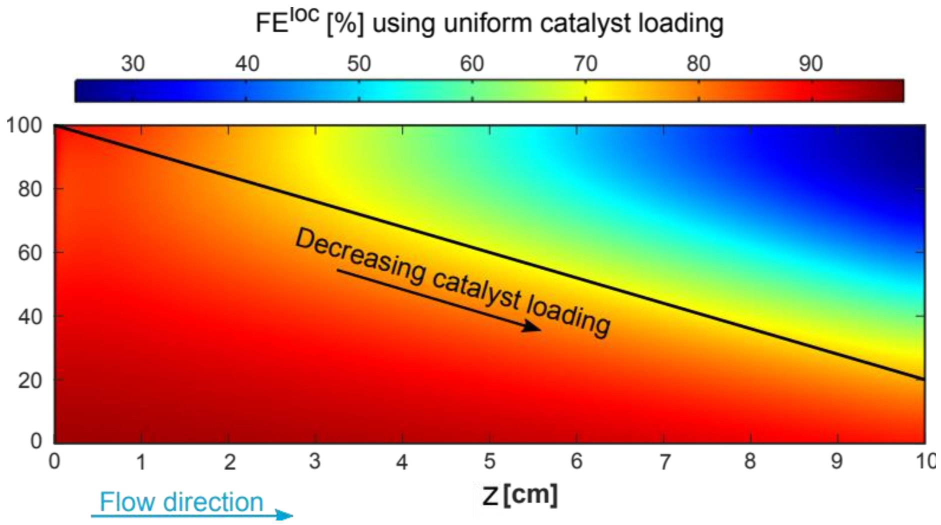

Figure 5: *The local Faradaic efficiency in the catalyst layer, shown in colour, decreases in the downstream direction. By selectively reducing the available catalyst, this loss of Faradaic efficiency can be minimised, ensuring that there is always a balance between availability of reactant and reaction sites.*

[1] Joseph W. Blake, Vojtěch Konderla, Lorenz M. Baumgartner, David A. Vermaas, Johan T. Padding, and J. W. Haverkort, *ACS Sustainable Chemistry & Engineering* **2023** *11* (7), 2840-2852, DOI: 10.1021/acssuschemeng.2c06129

Electrolytic Hydrogen as a Partial Replacement of Carbonaceous Reductants during Ferrous Ore Smelting

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The removal of oxygen from stable metal oxides is mainly done using fossil carbonaceous reductants, which release a significant quantity of $CO_2(g)$ as the primary by-product. A global drive to mitigate anthropogenic gaseous carbon (C) release necessitates a decreased dependence on C as the main reductant in various smelting industries, e.g., iron-, chromium-, manganese-, and titanium-ores to name a few. Hydrogen (H_2) has been identified as a candidate for CO_2 abatement in metallurgy, as its interaction with metal oxides yields H_2O as the byproduct.

The use of H_2 in steel production is relatively well understood as the reduction of Fe-oxides by H_2 is thermodynamically favorable. Identifying the potential of H_2 during the pre-reduction of Fe-oxide-containing ores has yet to receive significant attention in the metallurgical community. As appose to C, the thermodynamic activity of H_2 as a reductant decreases with an increase in reaction temperature. Therefore, the use of gaseous H_2 is essentially limited to pre-reduction (defined as the high-temperature treatment of ores before traditional smelting). The primary aim of pre-reduction is the metallization of intrinsic Fe-oxides ($Fe^{3+}\rightarrow Fe^{2+}\rightarrow Fe^{0}$),[1] decomposition of ore-bound carbonate,[2] and lowering the oxidation state of higher metal oxides (e.g., $Mn^{4+}\rightarrow Mn^{3+}\rightarrow Mn^{2+}$).[3] Though, the purpose of pre-reduction will depend on the ore type, as well as its composition.

The use of electrolytic H_2 in metallurgy is a potentially limitless take-off market. If smelters can produce their H_2 on-site, from renewable sources, gaseous C emissions can be curtailed significantly. Moreso, the availability of high-quality reductants is less readily available,[4] which further expedites the attractiveness of employing H_2 as a reductant. The use of H_2 can only be considered, from an economical point of view, if H_2 can be produced at a reasonable cost – which makes the development and upscaling of water electrolysis capabilities and capacities of major importance on a global scale.

[1] Davies, J.; Paktunc, D.; Ramos-Hernandez, J. J.; Tangstad, M.; Ringdalen, E.; Beukes, J. P.; Bessarabov, D. G.; Du Preez, S. P., The Use of Hydrogen as a Potential Reductant in the Chromite Smelting Industry. *Minerals* **2022,** *12* (5), 534.

[2] Davies, J.; Tangstad, M.; Schanche, T.; du Preez, S. P., Pre-reduction of United Manganese of Kalahari Ore in CO/CO2, H2/H2O, and H2 Atmospheres. *Metallurgical and Materials Transactions B* **2023**, 1-21.

[3] Tangstad, M.; Schanche, T.; du Preez, S. P., Use of H2 in Mn-Ferroalloy Production. In *Advances in Pyrometallurgy: Developing Low Carbon Pathways*, Springer: 2023; pp 35-53.

[4] Erwee, M.; Swanepoel, S.; Reynolds, Q., The importance of controlling the chemistry of pre-oxidized chromite pellets for Submerged Arc Furnace FeCr smelting: a study on furnace Si control. *Available at SSRN 3926683* **2021**.

High Entropy Alloys Based Macro- and Mesoporous Catalysts

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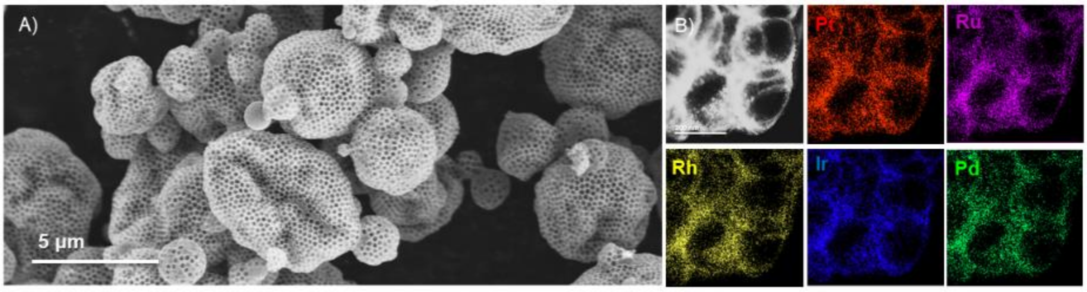
High entropy alloys (HEAs) have rapidly gained importance in the field of catalysis and electrocatalysis, due to their high chemical and thermal stability and to the virtually unlimited types of active sites accessible, stemming from the high configurational entropy.[1] In this communication,[2] we introduce the first low temperature approach for the synthesis of macro- and mesoporous HEA particles composed of Pd, Pt, Ir, Rh and Ru. By spray-drying a solution containing dissolved metal salts and latex beads, hybrid particles composed of latex beads embedded in an inorganic salts matrix are formed due evaporation induced self-assembly (EISA). Porous, fully reduced HEA-based particles are obtained by annealing the hybrid particles at temperatures as low as 350°C under inert atmosphere. The porous particles exhibit elevated specific surface area, ranging between 100 and 150 g m^{-3}, the highest value reported so far for this kind of materials and good catalytic activity towards the CO oxidation reaction. *In situ* scanning transmission electron microscopy proved that the porous structure is stable up to 800°C.



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[2] M. L. De Marco, W. Baaziz, S. Sharna, F. Devred, C. Poleunis, A. Chevillot-Biraud, S. Nowak, R. Haddad, M. Odziomek, C. Boissiere,`D. P. Debecker, O. Ersen, J. Peron, M. Faustini, ***ACS Nano*****, 16,** 15837-15849 (2022)

Efficient Design of Flow-Based Water Electrolyzers for Hydrogen Production through Numerical Modeling and Experimental Testing

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Flow-based water electrolyzers (FBEs) are among the novel designs that have the potential to produce hydrogen at a comparable price to hydrogen produced from fossil fuels [1]. An FBE utilizes a liquid electrolyte as a medium for ion conduction and the electrolyte flow for the separation of gaseous products [2]. By removing the membrane, water electrolyzers become more cost-effective, durable, and stable under varying loads. This project aims to develop new FBE designs for highly efficient hydrogen production at large scales.

Developing an efficient FBE design involves careful consideration of the flow channel geometry and operating conditions. To evaluate the performance of different geometries in terms of gas cross-over and efficiency, a numerical model has been created to simulate bubble generation and flow as shown in **Figure 1**. The model can also help increase the active surface area of the electrolyzer. Once a design is suggested by the numerical model, it will be tested experimentally to assess its performance in real-world situations.

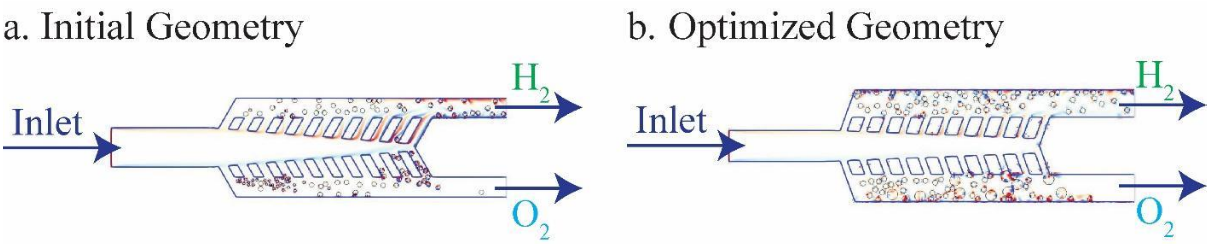

Figure 1. a) *The initial design of a sample FBE: the electrolyte enters the device in the middle channel and goes through smaller canals into the outer channels. The products are being generated in the outer channels. In this geometry, bubbles can be seen in the middle channel which creates gas crossover.* ***b)*** *The modified geometry: The design and operating parameters of the electrolyzer are modified in order to reduce the gas crossover. No gas crossover happens in the new geometry.*

[1] Hadikhani, P., S.M.H. Hashemi, S.A. Schenk, and D. Psaltis, *A membrane-less electrolyzer with porous walls for high throughput and pure hydrogen production.* Sustainable Energy & Fuels, 2021. **5**(9): p. 2419-2432.

[2] Hashemi, S.M.H., P. Karnakov, P. Hadikhani, E. Chinello, S. Litvinov, C. Moser, P. Koumoutsakos, and D. Psaltis, *A versatile and membrane-less electrochemical reactor for the electrolysis of water and brine.* Energy & Environmental Science, 2019. **12**(5): p. 1592-1604.

A Flexible Simulation Tool for Water Electrolysis on system level

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The onsite production of green hydrogen via electrolysis becomes ever more important for future industry defossilization. In many possible use cases of water electrolysis, a comparison of the different available system technologies depending on the conditions at the planned site would be useful to enable an informed decision on which technology would be best, alkaline (AEL), proton exchange membrane (PEMEL) or solid oxide (SOEL) water electrolysis.

To this end, an open-source python-based modeling tool is developed to enable the user through an easy-to-use graphical interface to configure and simulate electrolysis systems in a steady state, including all necessary balance of plant components for the three technologies. It also provides a techno-economical comparison between the three technologies, considering specific user requirements using integrated electrolyzer system designs or user-defined ones. Additionally, the tool enables the user to easily adapt or replace the models for specific components as well as integrate user-defined stack models into the system. Also, the increase in system efficiency due to improved stack or BoP-components can be easily estimated to investigate promising development options.

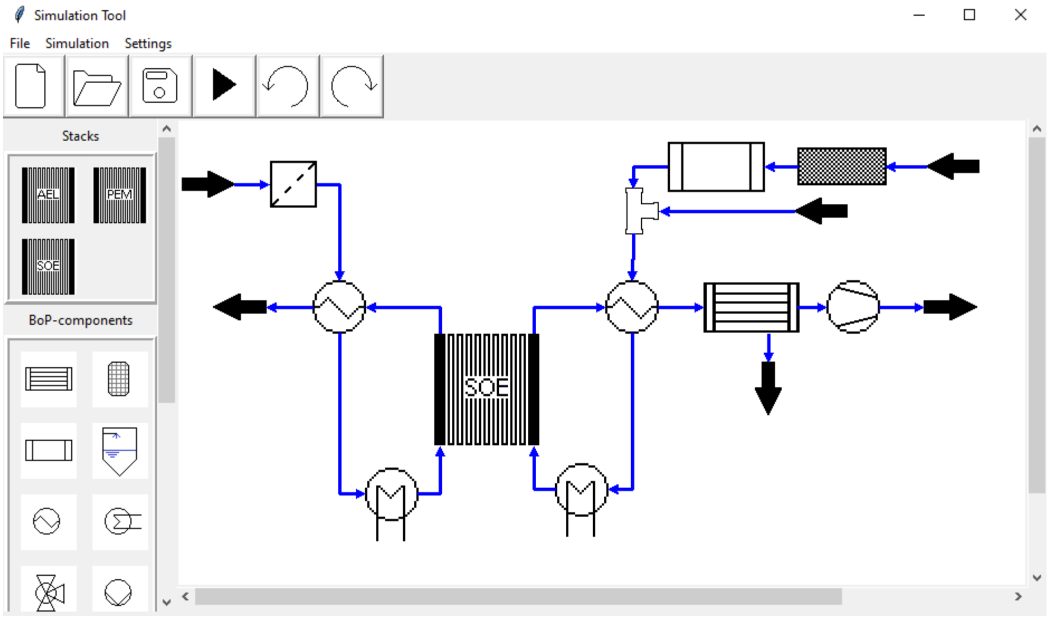

Figure 1: The graphical interface of the electrolysis system design tool showing a simplified solid oxide water electrolysis (SOEL) system

Addressing Safety for Electrolytic Hydrogen Production Using Catalytic Hydrogen Recombination Technology

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High-purity standards are required for hydrogen (H_2) used as a fuel in a number of applications such as in low-temperature hydrogen fuel cells, or as a chemical feedstock for ammonia production, etc. Water electrolysis is considered an environmentally friendly and sustainable technology for H_2 production.[1] However, H_2 obtained using water electrolysis contains a finite number of impurities such as, for example, oxygen. The amount of oxygen will depend on what type of electrolysis technology is used. Accidental leak of hydrogen within compact electrolysis cabinets also poses a critical safety concern and should be controlled to below a certain level (flammability limit of H_2 in air 4–75 vol%).[2] Therefore, suitable oxygen removal technologies need to be developed to guarantee the safe operation of the electrolyzer and to ensure that high-purity H2 is produced.[3]

Catalytic hydrogen recombination (CHR) technologies (e.g., passive autocatalytic recombiner, PAR) play an important role in safety control assurance and have been widely employed in nuclear power plants.[2] CHR technology has also been considered for oxygen removal in water electrolysis, however, the integration of such a process is rarely documented.[4] External CHR-based oxygen removal unit combined with the electrolyzer will not only provide safety control but allow additional hydrogen purification. In this respect, both processes can be done without any external power source and, hence, without being affected by external factors, such as intermittent electricity supply. Nevertheless, CHR technology for water electrolysis, specifically catalyst and process development, is still in the basic stage and requires further attention from engineers and scientists.

In this research work, the development of Pt–X bimetallic catalyst for a CHR-based oxygen removal unit is proposed. The catalyst was tested in an in-house-developed experimental setup to evaluate the catalyst's performance. The catalyst demonstrated good start-up characteristics (fast initiation time and low initiation temperature), stability (no deactivation), and durability (>500 h) during CHR tests. Thus, the developed Pt–X catalyst can be considered for further integration into an oxygen removal unit and tested in combination with an electrolyzer.

[1] Hermesmann, M.; Müller, T. E., Green, Turquoise, Blue, or Grey? Environmentally friendly Hydrogen Production in Transforming Energy Systems. Progress in Energy and Combustion Science 2022, 90, 100996.
[2] Kozhukhova, A. E.; du Preez, S. P.; Bessarabov, D. G., Catalytic hydrogen combustion for domestic and safety applications: A critical review of catalyst materials and technologies. Energies 2021, 14 (16), 4897.
[3] Kim, T.; Song, Y.; Kang, J.; Kim, S. K.; Kim, S., A review of recent advances in hydrogen purification for selective removal of oxygen: Deoxo catalysts and reactor systems. International Journal of Hydrogen Energy 2022, 47 (59), 24817-24834.
[4] Ligen, Y.; Vrubel, H.; Girault, H., Energy efficient hydrogen drying and purification for fuel cell vehicles. International Journal of Hydrogen Energy 2020, 45 (18), 10639-10647.

An Open-Source Modeling Tool for Alkaline (AEL), Proton Exchange Membrane (PEMEL), and Solid Oxide (SOEL) Water Electrolysis Systems

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The demand for green hydrogen necessitates efficient and cost-effective large-scale water electrolysis through appropriate system dimensioning and material selection. Mathematical-physical models optimize the efficiency and economy of these complex systems, but published models usually focus on only one electrolysis technology, limiting cross-technology considerations. In addition, these models typically address specific issues like cell design or operating conditions, further restricting generalization to other contexts.

The newly introduced open-source modeling tool in Python enables users to select and dimension application-specific electrolysis technologies and integrate electrolyzers into new and existing plants (see **Figure 1**). Moreover, this tool facilitates the identification of development and savings potential through improved design of materials, cell components, and operating strategies. The core of the tool includes the steady-state zero-dimensioned stack models of alkaline (AEL), proton exchange membrane (PEMEL), and solid oxide (SOEL) water electrolysis. The stacks comprise repetitive experimentally validated single-cell models and enable the determination of different stacks' performance, gas purity, and temperature for customizable operating conditions. The models consider loss mechanisms and heat losses, providing a comprehensive system analysis. Harmonized model formulations ensure result comparability. The graphical user interface allows for individual design and integration of Balance of Plant components (BoP), making system analysis accessible to end-users not directly involved in electrolysis technology.

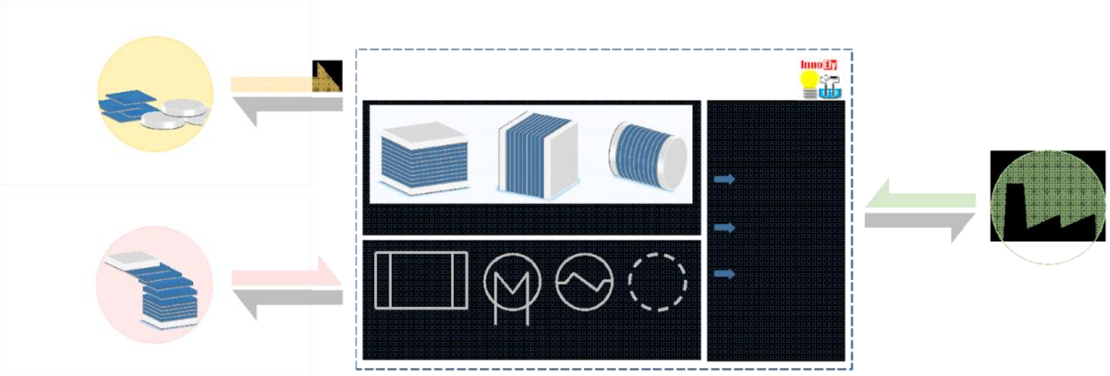

***Figure 1**: An overview of the open-source modeling tool for different electrolysis technologies and systems with considerations for various stakeholders in the field*

Multi-objective adjoint optimization tool for electro-chemical systems applied to membrane-less electrolyzer

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One promising design for producing hydrogen to shift the global economy towards a low-carbon future is the membrane-less water electrolyzer. This design removes the membrane, resulting in a significant decrease in capital cost, facilitating large-scale production of water electrolyzers, providing a longer lifetime for the device and ensuring more stable electrochemical performance. These electrolyzers can operate at elevated temperatures and pressures resulting in more efficient hydrogen production and lower hydrogen compression energy requirement.

One major design challenge for membrane-less electrolyzers is achieving a high hydrogen purity while maintaining its efficiency. To address this issue, current contribution presents a multi-objective optimization tool based on adjoint sensitivity analysis using Computational Fluid Dynamics (CFD) to model a simplified electrolysis cell. The tool allows the optimization for multiple design variables like the flow topology or the catalyst distribution for contradictory objectives such as efficiency and purity. In the conference contribution we will present the details of simulation setup and optimization tool and also report on the preliminary results of the optimization application to a generic membrane-less electrolyzer.

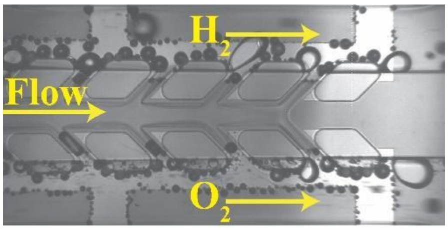

***Figure 1:** Experimental setup*

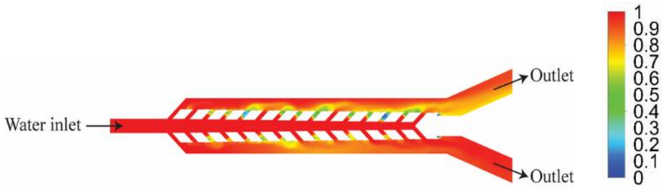

***Figure 2**: Volume fraction of water*

[1] Y. Kametani et al. "A new framework for design and validation of complex heat transfer surfaces based on adjoint optimization and rapid prototyping technologies." *Journal of Thermal Science and Technology* 15.2 (2020)

[2] E. M. Papoutsis-Kiachagias & K. C. Giannakoglou "Continuous adjoint methods for turbulent flows, applied to shape and topology optimization: industrial applications." *Archives of Computational Methods in Engineering* 23.2 (2016)

[3] P. Hadikhani et al. "A membrane-less electrolyzer with porous walls for high throughput and pure hydrogen production." *Sustainable Energy & Fuels* 5.9 (2021): 2419-2432.

Sustainable water sources for Electrolysis in PtX

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Power-to-X (PtX) is gaining increasing attention across the world as a promising technology for the production of renewable fuels and chemicals. PtX involves the conversion renewable electricity through water electrolysis into hydrogen, which can then be used as a chemical feedstock or fuel. However, considerable volumes of water are needed to produce renewable hydrogen, which can make it difficult for PtX technologies to be sustainable in regions with water scarcity. This work gives an overview of current studies on sustainable water sources for electrolysis in PtX. It discusses various water sources, including brackish water, wastewater, and seawater, where their benefits and drawbacks are explored, along with their techno-economic feasibility. The potential of coupling electrolysis and PtX technologies with renewable energy-powered desalination and wastewater treatment systems has also been discussed. These integrated systems can not only provide sustainable water sources for electrolysis and PtX but also contribute to solving the global water scarcity challenge. An overview of sustainable resources for PtX is given in the **figure 1**.

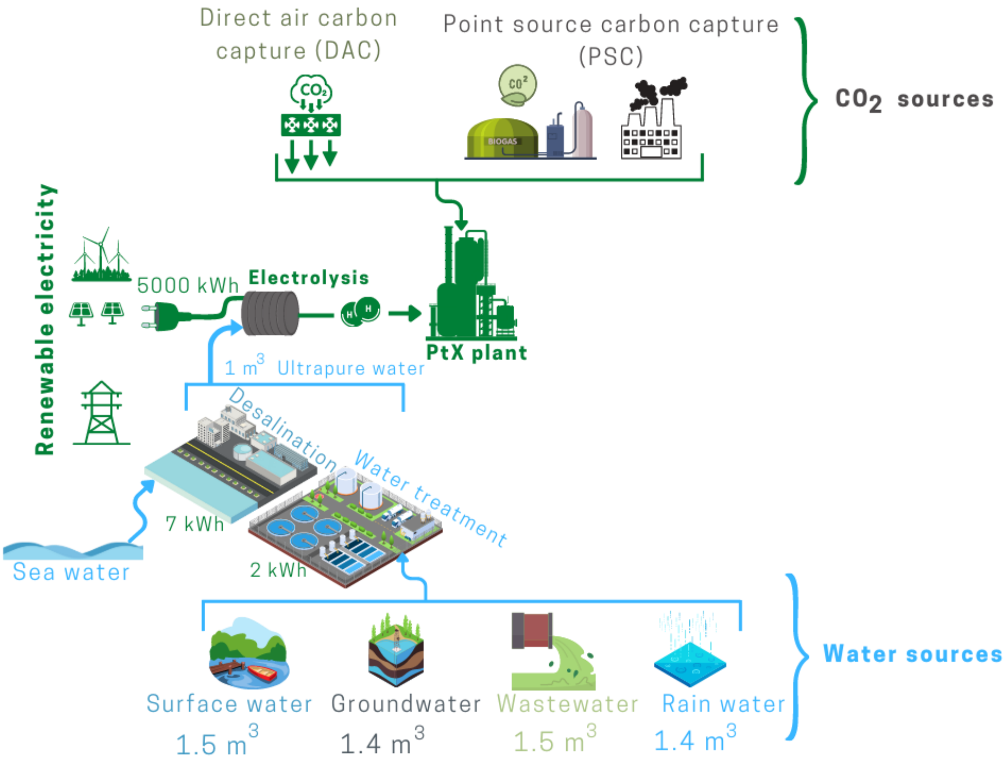

***Figure 1.** Overview of sustainable resources for power-to-X (PtX) systems.*

Proton-conducting ceramic electrolyzers for high efficiency green hydrogen production

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Green hydrogen is an important vector to decarbonize some of the hard to abate sectors, including our chemical industries. In order to cost-effectively do so, the cost of green hydrogen should reach the target price of 1 – 2 $/kg. At present, green hydrogen is still too expensive for such applications to make economic sense. The electrolyzer efficiency and capital cost of such electrolyzer systems have a direct impact on the final cost of green hydrogen. New innovative techniques are needed to improve the electrolyzer efficiency and decrease the capital costs of such systems.

Thermodynamically, steam electrolysis requires less energy to make green hydrogen compared to water electrolysis. In addition, these high-temperature systems can operate at near 100% electrical efficiency. Therefore, such systems would be ideal for applications where waste steam is available, like in the case of most chemical industries. Currently, solid oxide based high-temperature electrolyzer (SOEC) systems are being developed for such applications. These SOEC systems make use of an oxide conducting ceramic and operate at about 850 ºC. However, these high-temperature conditions require special and expensive materials for stack sealing and stack construction, making these systems capital intensive. In addition, steam needs to be fed into the SOEC system also on the hydrogen side, resulting in “wet hydrogen” and a higher post drying load. This will decrease the system efficiency and hence is not ideal.

HyET E-Trol is developing a novel intermediate temperature proton conducting ceramic based electrolyzer (PCEC) to solve some of the issues with respect to the high-temperature SOEC systems. These PCEC systems operate at around 500-600 ºC and can provide the same electrical efficiency as SOEC systems. PCEC system also requires a lower activation energy, due to their inherent nature, and hence are more compact compared to their SOEC counterpart. The lower working temperature also makes it possible to work with cheaper materials for the sealing and the stack, and hence is a more cost effective solution. Steam is fed into the anode end of the PCEC systems, hence the hydrogen produced in the cathode side is drier, decreasing the drying load and increasing the system efficiency. In this talk, the progress with regards to the development of PCEC systems and its scale-up plans will be presented.

Fleet-based performance model and degradation estimation

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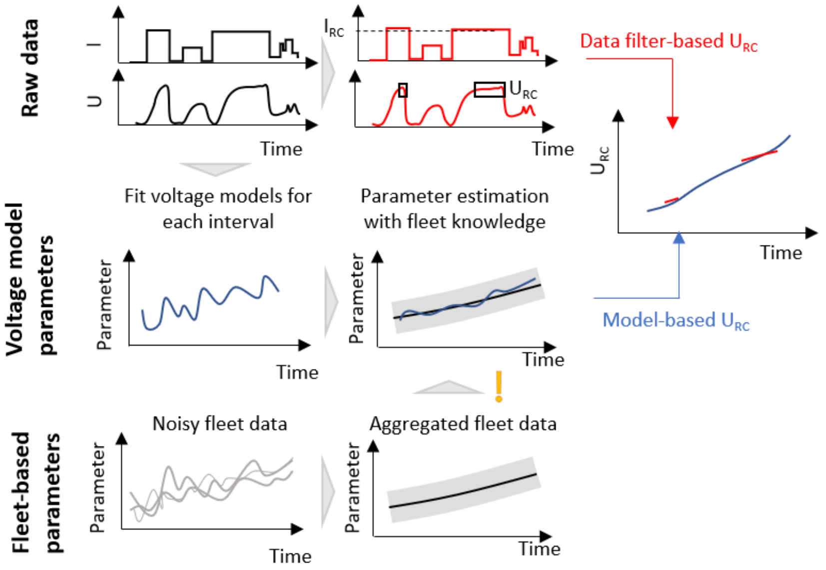
Quantifying degradation for industrial electrolyzers operating in the field is challenging because (1) it is unpractical to run standardized tests regularly and (2) degradation-related measurements such as voltage vary with operating conditions (e.g., current and temperature). One approach is to convert the measured voltage to a reference condition ("U_{RC}") using simplified, parametrized models for the observed cell voltage. Then, we can use this model to predict voltage under reference condition and use it as degradation indicator. However, identifying parameters for the voltage model is not always straightforward. If the data coverage is limited (e.g., when an electrolyzer is operated with constant current, the coverage of the current data is very limited), the identified parameter might be biased [1]. With biased parameter, the predicted U_{RC} is not trustworthy.

Fleet knowledge can be leveraged to tackle this problem. As illustrated in **Figure 1**, one can aggregate historical data of multiple similar electrolyzers ("fleet") to obtain "fleet knowledge" on how a parameter evolves. Then, one can utilize the fleet knowledge with Bayesian approach [2] to estimate parameters of an electrolyzer. As a result, one can obtain stable model parameters and U_{RC} that shows a clear degradation trend.



This method has been validated with >10 industrial electrolyzers in the field with ~2 years of operation. The next step is to investigate the suitability of this method on electrolyzers with slightly different designs and thus different degradation trajectory.

[1] Asudeh, A.; Jin, Z.; Jagadish, H. V. Assessing and Remedying Coverage for a Given Dataset. In *2019 IEEE 35th International Conference on Data Engineering (ICDE)*. DOI: 10.1109/ICDE.2019.00056

[2] Bishop, C.M. Probability Distribution, In *Pattern Recognition and Machine Learning*; Springer, 2006.

Using treated wastewater as a source of water electrolysis

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Affiliation: [a] Aalborg University, AAU Energy

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Currently low-emissions hydrogen production from renewable resources is still to be developed. Water electrolysis is currently one of the best choices of the pure hydrogen production. But 9 L ultrapure water is consumed to produce only 1 kg hydrogen, which is not sustainable and environmentally friendly for a long run. Thus, in this work, a brand-new water source will be introduced into the water electrolysis process, and then boosting the water electrolysis to some extent by expanding the usable water sources. The wastewater will be desalinated by the membrane technology of membrane distillation (MD). The water quality after the treatment will be tested. Then the treated wastewater will undergo the PEM water electrolysis. Hydrogen production rate, Faradaic efficiency and turnover frequency will be calculated to describe the reaction rate and efficiency of the electrolysis process. Meanwhile to test and verify the potential damages on the electrolyzer, polarization curves and electrochemical impedance spectroscopy will be conducted before and after the electrolysis. We will conclude whether treated wastewater is a good source for water electrolysis by comparing performance and some economic factors.

Mechanical Properties of tubular Proton-Conducting Ceramic Cells and Effect of Ageing and Operating Conditions

Federico Palmerinia, Peyman Khajavia, Henrik Lund Frandsena, Peter Vang Hendriksena, Dustin Beeaffb, Ragnar Kiebacha

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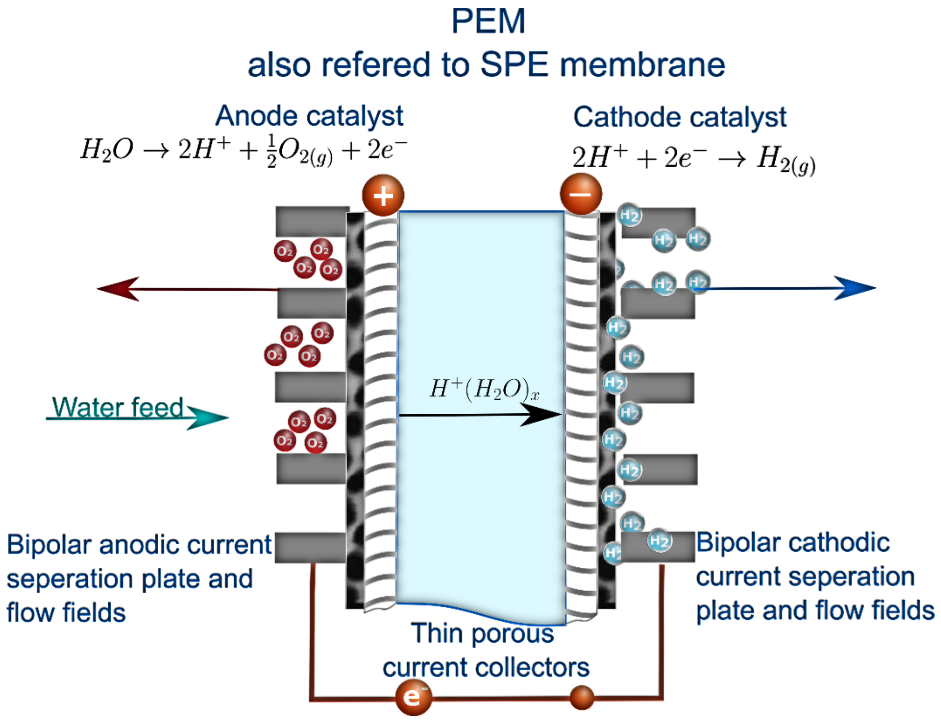
Proton-conducting ceramic cells represent a promising technology to enable a large variety of electrochemical processes, but numerous challenges hinder further development and subsequent commercialization.

Among them, thorough characterization of the mechanical properties is of fundamental importance to improve the robustness and long-term reliability of these devices. In fuel electrode supported designs, the Ni-BCZY support represents the principal structural component. However, other components such as the electrolyte can significantly affect the structural integrity of the device. In this study, mechanical characterization of tubular Ni-BCZY27/BCZY18 half-cells has been carried out through a high throughput four-point bending methodology. The objective of the study was to investigate the elastic behaviour of the components. Moreover, we carried out tests involving the exposure of the specimens to a variety of operating conditions, both in the short and long term, to assess the effects on the characteristic strength, elastic modulus, fracture mode, and chemical and morphological properties of the half-cells. The impact of the high temperatures and gas composition on the reliability of the components is discussed.

This work has been supported by the WINNER project. WINNER has received funding from the Fuel Cell and Hydrogen 2 Joint Undertaking under Grant Agreement No (101007165). This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation programme, Hydrogen Europe and Hydrogen Europe Research.

Proton Exchange Membrane (PEM)



Test station development for the characterization of PEM water electrolysis at elevated temperature operation

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[a]Forschungszentrum Jülich GmbH, Helmholtz-Institute Erlangen-Nuremberg for Renewable Energy (IEK-11), Germany; [b]Friedrich-Alexander University Erlangen-Nuremberg, Germany

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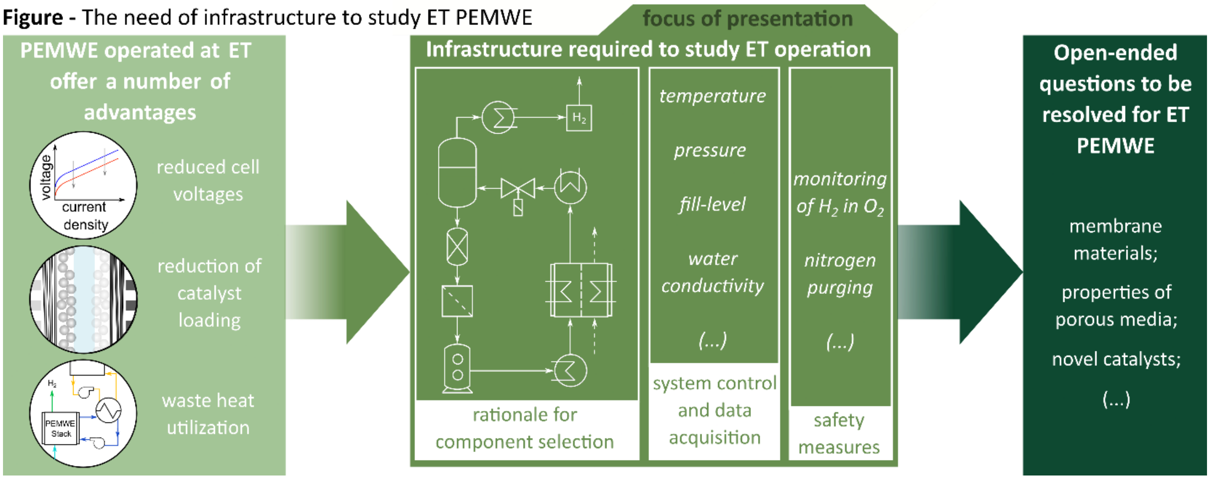
Polymer Electrolyte Membrane Water Electrolyzers (PEMWE) are typically operated between 50°C and 80°C, but in pursuit of improved efficiency and lower hydrogen production costs, operating at elevated temperature (ET) above 90°C has been identified as a way to make green hydrogen more competitive.[1] The harsher operating conditions, however, call for the need of specialized test setups, which meet the higher thermal energy requirements whilst ensuring temperature stability. Moreover, these setups need to allow for increased pressure to operate with liquid water above 100 °C and in all cases maintain a safe testing environment.

A design for a test station providing these attributes is presented, whereby we share the details behind (i) the provision of the reactant to the cell at the required operating conditions; (ii) the separation and handling of the product gases; (iii) the incorporated safety measures; and (iv) the methods adopted to monitor and control the system in parallel to logging the required data.

It is expected that sharing the design of an ET test station encourages interest in this emerging field, facilitates the build-up of test stations and hence accelerates the investigation of operating PEMWE at ET to assess its potential for efficient green hydrogen production.

Figure - The need of infrastructure to study ET PEMWE



[1] Zhang, W.; Liu, M.; Gu, X.; Shi, Y.; Deng, Z.; Cai, N. Water Electrolysis toward Elevated Temperature: Advances, Challenges and Frontiers. *Chem. Rev.* **2023**, Article ASAP. DOI: 10.1021/acs.chemrev.2c00573 (accessed 2023-02-16)

Lifting the Lids on Reference Electrodes in PEMWE: Previous Approaches and Current Application

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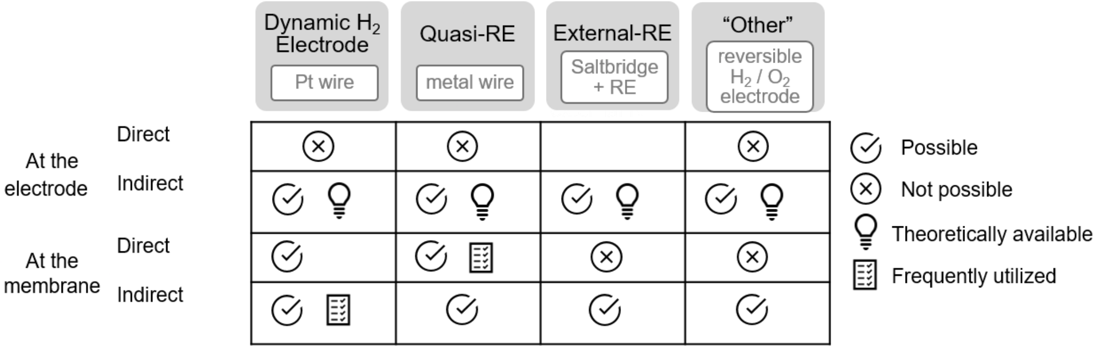
The authors of this contribution have undertaken a comprehensive review of reference electrodes (REs) used in PEM Water Electrolysis (PEMWE) research. The importance of REs cannot be understated as they are instrumental in determining the potential within the system and in separating the two electrodes. Examining the electrodes' characteristics yields insights into their individual performance and can e.g. help to assess new catalyst layer designs, their interplay with the adjacent porous transport layer or understand the complex and multi-faceted mechanisms of degradation [1].

Previous research on REs has generated a significant amount of information and detailed data for each reference electrode setup. However, this information is currently distributed across various publications. As a result, the present review compresses this information into a single, comprehensive resource. The following key aspects are illuminated in the context of the corresponding concept: a clear and thorough explanation of the concept, a review of the historical background and evolution of the concept, an exploration of the various ways in which the concept can be applied in research fields, including examples, a discussion of the strengths and limitations and recommendations for future research or practical applications. The purpose of the work is to provide guidance to researchers in the field, enabling them to effectively tailor the reference electrode to meet the specific demands and contexts of their research.

***Table 1:** Combination of the different types of RE and positions with (theoretically) possible, impossible, and already implemented combinations.*



		Dynamic H_2 Electrode Pt wire	Quasi-RE metal wire	External-RE Saltbridge + RE	"Other" reversible H_2 / O_2 electrode
At the electrode	Direct	⊗	⊗		⊗
	Indirect	✓ 💡	✓ 💡	✓ 💡	✓ 💡
At the membrane	Direct	✓	✓ 📋	⊗	⊗
	Indirect	✓ 📋	✓	✓	✓

✓ Possible
⊗ Not possible
💡 Theoretically available
📋 Frequently utilized

[1] Kuhnert, E.; Hacker, V.; Bodner, M. A Review of Accelerated Stress Tests for Enhancing MEA Durability in PEM Water Electrolysis Cells. *International Journal of Energy Research* **2023**, *2023*, 1–23. DOI: 10.1155/2023/3183108

Towards Understanding the Influence of the Ionomer in PEMWE Anodes Consisting of Various Ir-Based OER Catalysts

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[b]HySA/Catalysis Centre of Competence, Catalysis Institute, University of Cape Town, 7701, South Africa

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This project was a joint undertaking between the Institute for Electrical Power Systems at Leibniz University Hanover, and HySA/Catalysis at the University of Cape Town, where the research was intended to enhance the technology readiness level of catalyst-coated membranes (CCMs) for proton exchange membrane water electrolysis (PEMWE) applications. In this study, novel ultrasonic spray coating was utilized to prepare a library of CCMs containing oxygen evolution reaction catalysts of varying electronic properties, consisting of Ir black, rutile iridium oxide, and an in-house synthesised catalyst which was a mixture of Ir metal, rutile, and amorphous iridium oxides. The anodic ionomer loading in these CCMs was differed in an ultra-low range to deconvolute the influence of proton and electronic conductivity on the overall performance of the prepared PEMWE CCMs.

The CCMs in **Figure 1** a) and b) comprise of commercially available OER catalysts. The results demonstrate that IrO_2 CCMs show a tendency towards 12 wt% as the optimal ionomer content, in agreement with previous findings using the Mayer-Rod coating technique[1]. Meanwhile, IrB CCMs exhibit an optimal ionomer content range of 12-18 wt%. For the mixed metal-oxide catalyst CCM shown in **Figure 1** c), the performance is best at lowest ionomer contents, possibly offering a compromise between sufficient electric and protonic conductivity.

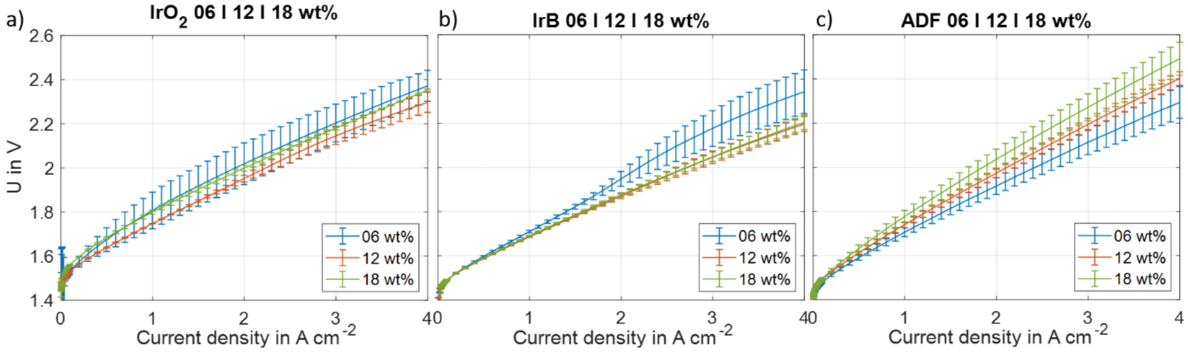

***Figure 1:** Current-voltage characteristics at 60 °C for different ionomer weight percentages with **a)** rutile iridium oxide, **b)** iridium black, and **c)** mixed metal-oxide in-house synthesised catalyst.*

Supported by additional information from cross-section SEM analysis of the CCMs before and after testing, the results show an optimal ionomer content for each iridium catalyst type, depending on proton and electron transport resistance, mass transport, and catalytic activity. The findings contribute to the development of efficient and cost-effective hydrogen production technology.

[1] Bernt, M.; Gasteiger, H. A. Influence of Ionomer Content in IrO 2 /TiO 2 Electrodes on PEM Water Electrolyzer Performance. J. Electrochem. Soc. 2016, 163 (11), F3179-F3189. DOI: 10.1149/2.0231611jes.

Hydrogen crossover measurements of proton exchange membranes for water electrolysis with *in-operando* conditions

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[a]Hahn-Schickard, Georges-Koehler-Allee 103, 79110 Freiburg, Germany;
[b]Electrochemical Energy Systems, IMTEK – Department of Microsystems Engineering, University of Freiburg, Georges-Koehler-Allee 103, 79110 Freiburg, Germany;
[c]University of Freiburg, Institute and FIT – Freiburg Center for Interactive Materials and Bioinspired Technologies, Georges-Köhler-Allee 105, 79110 Freiburg, Germany

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Gas crossover in proton exchange membrane water electrolysers presents both, an efficiency and safety challenge for the implementation of large-scale electrolysers [*1*]. Many studies determine gas crossover in a fuel cell environment with a fuel cell testbench, which proved to deliver reliable results when evaluating Nafion and Hydrocarbon membranes [*2*]. However, substantial differences between the fuel cell setup and an actual electrolysis cell remain, especially the liquid water instead of humidified gas and cell compression. In this work, a method to determine gas crossover is presented, which mimics electrolyser cell conditions along with direct high frequency resistance (HFR) measurements. Both values are presented as a figure of merit, i.e. membrane selectivity, which aids in the ranking of different proton exchange membranes for water electrolysis (**Figure 1**). This figure of merit is dependent on thickness, ion exchange capacity and polymer side chain length.

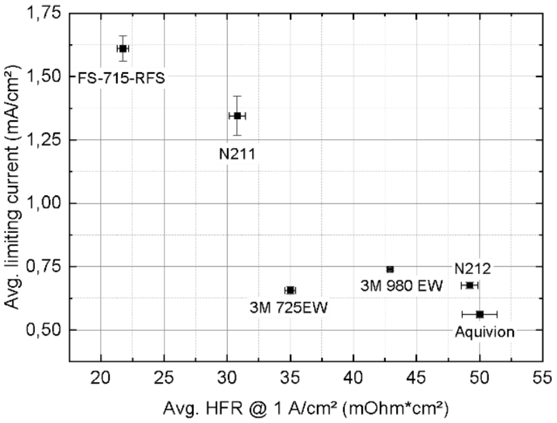

***Figure 1** Average limiting currents of H_2 cross-over and high frequency resistances for various commercial membranes.*

[1] Janssen, H. Safety-related studies on hydrogen production in high-pressure electrolysers. *International Journal of Hydrogen Energy [Online]* **2004,** *29* (7), 759–770.

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Ruthenium-based pyrochlores as anode materials in PEM water electrolyzers

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The need for green hydrogen production is increasing as oil and gas prices increase, coupled with the uncertainty pertaining to the availability of these fossil fuels. PEM water electrolysis holds many advantages as an electrolysis technology, including portability, modularity and the ease of coupling to intermittent, renewable energies. However, its reliance on rare and expensive Ir as an anode electrocatalyst hampers the upscaling of this technology. Therefore, this work seeks to research an alternative anodic electrocatalyst to replace some of the Ir. Phase pure ruthenium-based pyrochlore electrocatalysts have been prepared by a citrate sol-gel method [1] and have been physically characterized by XRD and S(T)EM. Furthermore, this electrocatalyst has been subjected to ex-situ electrochemical characterization in a three-electrode setup and will be characterized in a custom-made half cell design. Linear-sweep voltammetry results of the Y2Ru2O7 electrocatalyst indicate an overpotential of 300 mV at a current density of 10 mA cm-2. This result agrees well with what has previously been reported for this electrocatalyst [2] and indicates that this material shows promise as an OER electrocatalyst. However, it has previously been reported that these electrocatalysts have insufficient conductivity [1,3]. Therefore, different dopants are added in the pyrochlore A-site to generate oxygen vacancies and alter the electronic structure to increase the conductivity. Conductivity is assessed through diffuse reflectance spectroscopy and Tauc plots provide information about the changes in the band-gap upon doping. In addition, in-situ conductivity is assessed with an in-situ conductivity probe.[4] Promising compositions will be subjected to single cell tests. It is expected that doping Y2Ru2O7 will successfully increase the conductivity of the electrocatalysts and lead to promising alternatives for Ir in PEM water electrolyzers.

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Techno-economic analysis for waste heat utilization of a power-to-gas plant based on PEM electrolysis

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The power-to-gas (PtG) concept is a key technology for successful sector coupling in future energy systems. An outstanding example of how these coupled energy systems work, is currently being realized at Wunsiedel Energy Park in northern Bavaria. One of Germany's largest PtG plants based on a polymer-electrolyte-membrane (PEM) electrolysis with 8.75 MW electrical power has been in operation there since September 2022. A key aspect is the integration into the existing municipal energy infrastructure, which consists of various cogeneration plants, a sewage treatment plant, and one of Bavaria's largest battery energy storages (BES) with a capacity of 10.2 MWh.

Optimal integration of this PtG plant is essential to ensure an economically viable plant operation. For this purpose, a holistic system approach is applied, using the main product hydrogen and the two by-products, oxygen and thermal energy. In this study, the focus is on efficient waste heat utilization in the adjacent sewage treatment plant to improve the overall efficiency of the PtG plant and decrease the heat production costs of the sewage treatment plant. To determine the waste heat production of the PtG plant, a simulation model is developed in MATLAB/Simulink. The PEM electrolysis represents the main component of the model and is implemented by a combination of a thermal, a mass transfer and an electrochemical model. These submodels are interdependent and, therefore, necessary to calculate the heat generation during the water splitting process. In addition to the electrolysis model, the balance of plant and, thus, the heat generation in the downstream drying and compression units are also part of the simulation model.

Two scenarios are defined for the waste heat utilization in the adjacent sewage treatment plant. The temperature level of the cooling water return flow of the PtG plant is at a relatively low value of 51 °C. Since the sewage treatment plant operates at a flow temperature of approximately 95 °C, the waste heat cannot be used directly for drying the sewage sludge. Therefore, in the first scenario, the waste heat only preheats the air of the conventional heat generation plant, which consists of a combination of wood gasifiers and cogeneration plants. In the second scenario, a high-temperature heat pump is integrated downstream of the PtG plant. This allows the temperature level of the waste heat to be raised to the corresponding flow temperature of the sewage treatment plant. Thus, the waste heat can be used directly in the drying process. Simulation results show that the efficiency of the PtG plant can be significantly increased by using the waste heat. In addition, the heat production costs of the sewage treatment plant can be reduced due to the lower use of fuel compared to the conventional heat generation.

Electrolysis Stacks: Methods and Tools for Experimental Characterization

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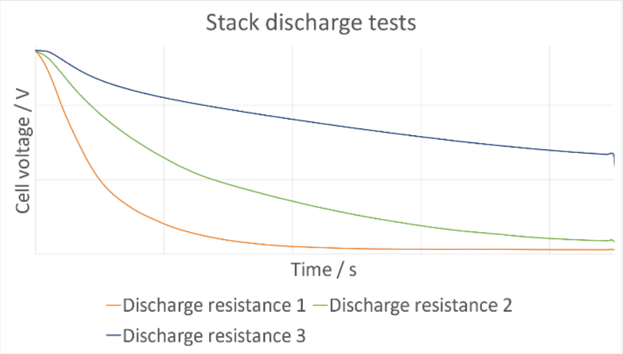
Energy conversion via water electrolysis is an important cornerstone for a renewable energy system. Different electrolysis technologies play out various advantages depending on the application, with proton exchange membrane (PEM) electrolysis being one promising technology for the implementation for dynamic operation. Today, test methods for electrolysis stacks mainly focus on performance and degradation studies rather than a holistic characterization of the stack. Performance characterization primarily include the measurement of polarization curves, the correlation between current and voltage, on single cell or stack level. While the measured voltage is the sum of all resistances occurring within the cell or stack at a certain current density, the differentiation of various loss effects is hardly possible.

More information on appearing resistances can be gathered by measuring the response of the stack to a DC base load superimposed by an AC signal. This response allows the analysis of the stack impedance at different frequencies, hence called electrochemical impedance spectroscopy (EIS). EIS gives more insight into performance limiting mechanisms within the stack. Additionally, determining the discharge rate after the stack is turned off, is important for safe operation and mitigation of degradation (Figure 1). However, these methods solely incorporate the electrical domain of the stack and do not include product gases or process water. Measuring the produced hydrogen gas quality during operation allows for a deep insight into occurring degradation processes. Detected impurities can indicate accelerated aging on the cathode side. Water analysis is the corresponding counterpart on the anode side. As the circulating process water is continuously filtered for high purity, the filter elements accumulate degradation products of the stack. Analysis of these filters is a valuable source of data, not only at the test bed but also for commercially available systems.



The different measurement methods presented and their combination allow a detailed investigation of the processes occurring in an electrolysis stack. Comprehensive testing of a stack with these methods and the investigation of processes and limitations are crucial for improvement. The stack, as central element of an electrolysis system, must be well understood for successful integration of the system into a renewable energy system.

High-pressure PEM Water Electrolysis Stack and System Characterization

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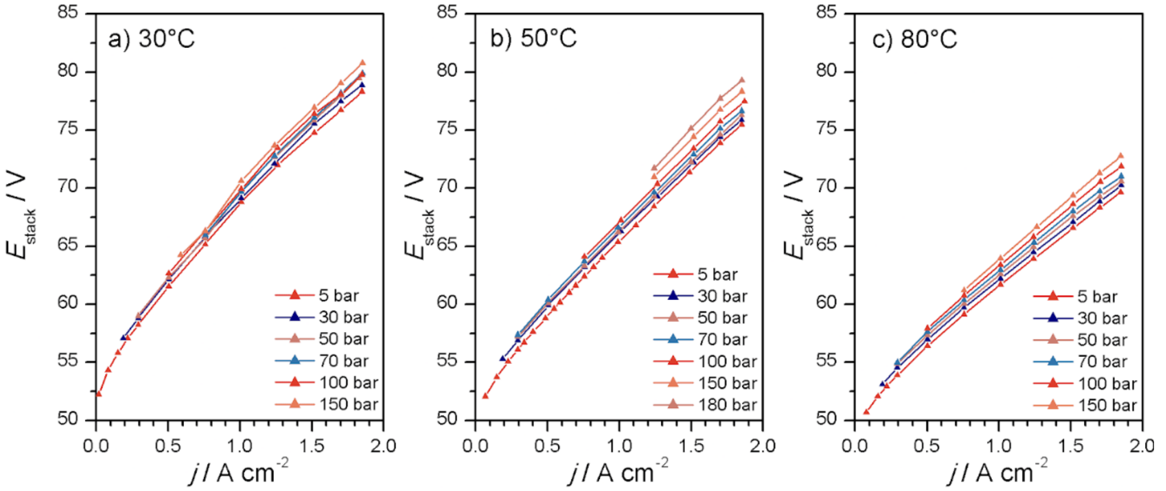
The pathway to reach the cost targets for green hydrogen includes implementing automated manufacturing methods, reducing PGM loading, reducing membrane thickness, and increasing operating temperature. Increasing the operating pressure is another strategy that may contribute to bring down the hydrogen production costs. Our work [1] shows that it is possible to achieve economically viable solutions with electrolyser systems operating up to 200 bar, making downstream mechanical compressors redundant for applications such as ammonia production, e-fuel production, and injection into the natural gas grid. The implementation of advanced materials and operation however comes with significant challenges related to long-term durability and the high defect sensitivity of the cells. These risks must be addressed through accelerated tests and in-situ characterization to fast-track the technology development.

Institute for Energy Technology (IFE) has built a flexible PEM water electrolysis system platform for testing of small-scale prototype electrolyzers up to 33 kW and 200 bar differential pressure. A software has been developed in-house for running multi-sine electrochemical Impedance Spectroscopy (EIS) on all cells in the stack simultaneously, altogether making this one-of-a-kind test facility well suited to study performance and lifespan of next-generation stacks and systems by employing accelerated stress test (AST) protocols and real-life operating conditions. In this work, we present the result from the characterization of a small-scale (2 Nm3/h) prototype stack up to 180 bar. EIS was used to study the cells' performances and durability, and to characterize the failure mechanism of aged cells.



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Development of Highly Active and Durable Low Loading PEMWE Catalyst Layers

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Polymer electrolyte membrane water electrolysis (PEMWE) technology is currently emerging as a feasible alternative for large scale hydrogen production using electricity generated from renewable energy sources. However, insufficient catalyst (IrO_2/$IrRuO_x$) stability at the anode due to complex oxygen evolution reaction (OER) mechanism, requires the use of high loading catalyst layers (ca. 3 $mg_{Ir}\cdot cm^{-2}$) to ensure an appropriate performance and durability over extended periods in operation. The utilisation of such loadings will essentially hinder the widespread adaptation of the PEMWE technology due to Ir scarcity and high cost. For this technology to have breakthrough at a terawatt scale, the Ir loading must be reduced to ca. 0.05 $mg_{Ir}\cdot cm^{-2}$. However, the integration of ultra-low loading catalyst layers into electrolyser cells still remains a challenge.

In this work, we evaluate catalyst nanostructuring as an approach to produce highly active and durable low loading catalyst layers for PEMWE. Catalyst layers based on Ir-nanoframes and Ir-Ni polyhedral nanoparticles were fabricated and characterised in-situ to determine the electrochemical performance and stability under accelerated stress test (AST) protocols. The layers based on Ir-nanoframes and Ir-Ni showed an exceptional electrochemical performance and stability compared to catalyst layers based on the commercial catalyst, Ir-black. Further, the post-mortem analysis showed a higher degree of Ir-dissolution and precipitation in the membrane for CCMs based on Ir-black. These results strongly suggests that nanostructuring could be one of the most effective strategies to simultaneously improve PEMWE efficiency and stability, and ultimately reduce the Ir catalyst loading.

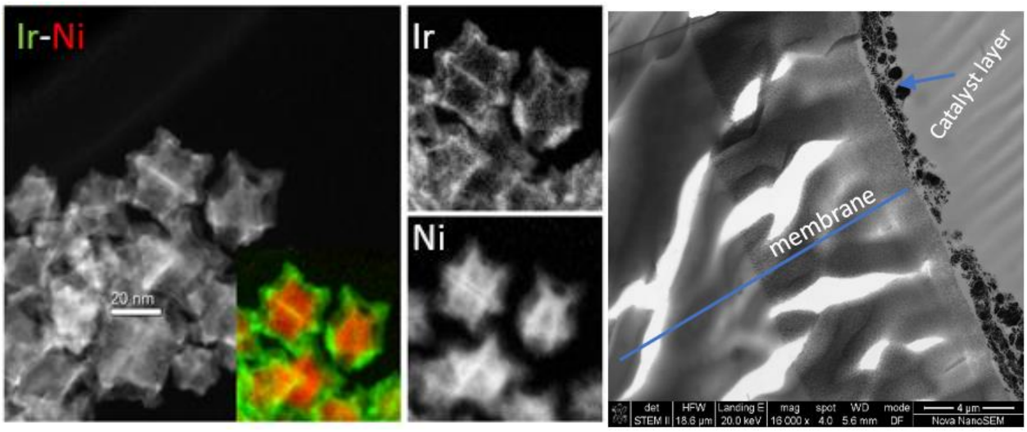

Figure: *HAADF-STEM images of synthesised Ir-Ni nanostructures (left), and the cross section of Ir-black CCM after testing, showing Ir precipitation in the membrane (right)*

Supported iridium-based electrocatalysts for PEM water electrolyzers

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The polymer electrolyte membrane (PEM) water electrolysis is gaining large attention as an environmental-friendly way to produce “green” hydrogen. However, it is costly due to the usage of noble metals to produce anode and cathode electrocatalysts. To make PEM water electrolysis economically feasible, the noble metals loading needs to be reduced. Promising solution is to use supported electrocatalysts [1]. Support materials provide many sites for the catalytically active nanoparticles to settle during their synthesis, resulting in an even nanoparticles distribution and increased active surface area. Nanostructured carbon materials with good conductivity and large surface area are always preferred to support noble metal nanoparticles, and the functional groups of nanostructured carbon materials can further enhance the immobilization of nanoparticles [2].

Iridium and its oxides remain the best option for a corrosion-stable and active OER catalysts that can withstand the harsh environment of a PEM anode. The main challenge now is to decrease the iridium loading on the anode increasing at the same time its electrocatalytic activity and long-term corrosion stability.

The present study is focused on carbon-supported catalysts for applications in PEM water electrolyzer and «reversible» fuel cell. The effect of the electrocatalyst support on the performance of the PEM water electrolyzer was studied. The obtained catalysts were implemented at the anodes of the PEM water electrolyzer, and they were characterized using different techniques, including electrochemical impedance spectroscopy and transmission electron microscopy.

Acknowledgements

The work was carried out at the National Research Center "Kurchatov Institute" in the framework of the implementation of Order No. 89 01/20/2023 under item 3p.2.5. "Development of new electrocatalytic materials with improved properties for PEM electrochemical devices".

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Interleaved buck converter for PEM water electrolyzer using integrated MOSFET with current sensing compensation

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The realisation of a multi-phase interleaved buck converter is presented for use in a water electrolyzer. A highly efficient, yet cost effective realization is desired in industry to produce hydrogen from reusable energy sources. The MOSFET with integrated drivers and current sensing, which is mass produced for the CPU and GPU market, may help to fulfil this goal. In [1] an analysis is given of the different interleaved DC/DC step-down topologies for use in proton exchange membrane electrolyzer applications. The interleaved buck converter utilizing the integrated MOSFET is presented here to confirm its benefits. The integrated MOSFET reduces the cost and the number of discrete components by combining them into a single package. Other benefits include built-in current measurement, temperature compensation and fast over-current protection in case of a short-circuit in the load. In this work the current measurement accuracy of the integrated MOSFET is improved using a multinomial fit compensation in the microcontroller. This in turn improves the hydrogen flow estimation accuracy using Faraday's law of electrolysis, since it relies on the current measurement accuracy. The proposed converter is modular and can be stacked in series to achieve a higher output voltage as required for more cells in a stack. The resulting converter achieves a peak efficiency of 96% with a load of 200W.

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CFD modelling of an accidental hydrogen release in desktop PEM electrolyser enclosure

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Traditional fossil fuel energy supplies are being depleted and do not cover global energy demand. Renewable energy is the main solution to address this problem. Hydrogen (H_2) satisfies most of the characteristics of a perfect renewable energy carrier. The process of producing H_2 by using electrolysis is one of the promising technologies in the foreseeing future. In combination with solar-PV or wind energy, H_2 production has the potential to develop a sustainable energy cycle [1]. However, the safety aspect of H_2 usage remains to be investigated. Hydrogen mixture in a confined environment can accidentally ignite or even detonate as a result of H_2 release from equipment. An accidental H_2 release can occur in the fittings, tubes, hydrogen tank, and electrolysis cell [2]. Therefore, the risk of H_2 release caused by equipment failure needs to be investigated. In the proposed study, possible scenarios of H_2 release from electrolysis cell into the desktop PEM electrolyser enclosure were numerically studied. A 3D CFD simulation of an in-house developed PEM electrolyser (HySA Infrastructure, South Africa) was performed in STAR-CCM+ code (Siemens) using RANS model with k-ε turbulence. The studied scenario observes a fitting failure of the electrolysis cell resulting in H_2 leak. Hydrogen distribution profiles were calculated for two different mass flow rates of release scenario.

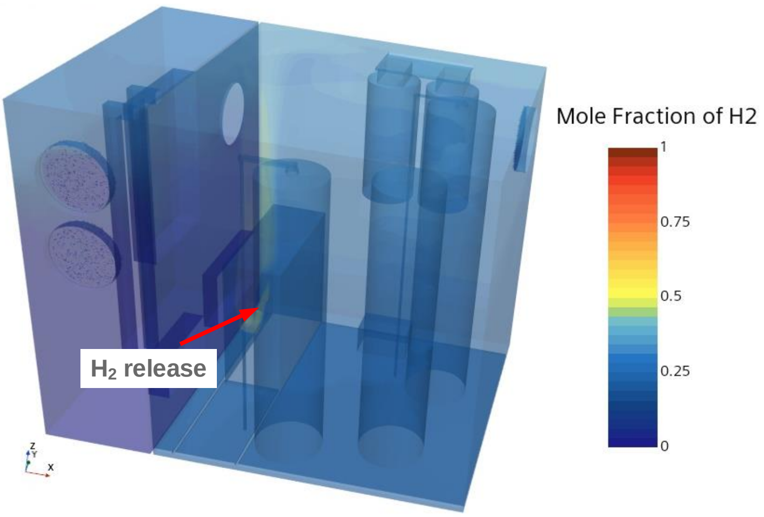

Figure 1. *3D geometry of calculation domain designed in STAR-CCM+.*

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Development and localisation of portable lab-scale Proton Exchange Membrane (PEM) based hydrogen generators within South Africa

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Nitrogen, Hydrogen, and Helium can be used within gas chromatography (GC) as a carrier gas.[1] For GC analyses, Helium is commonly used as it provides the best efficiency and reasonable analysis times. However, Helium is expensive and becoming limited in supply.[2] Hydrogen poses to be a good alternative as it provides quick analysis times, lower cost, and can be produced on-site[3] to be used as both carrier gas and for usage in flame ionisation detectors (FID). Lab-scale hydrogen generators are mainly based on PEM (proton-exchange membrane) water electrolysis (WE) technology. Lab H_2 generators produce high purity hydrogen and use platinum and iridium electro-catalysts. South Africa has largest deposits of PGM (platinum group metals) and therefore it is important to develop locally related technologies to produce these generators and later scale them up for large volumes of hydrogen for other applications.[4] Therefore, a need was identified by HySA Infrastructure Centre to develop cost-competitive generators, locally manufactured, which produce high purity hydrogen for laboratory use. At HySA Infrastructure Centre, a portable lab-scale H_2 generator, namely the HyGEN, was designed and developed with in-house and locally sourced parts as listed below:

- Multicell PEM short stack
- PEM catalyst coated membranes (CCM’s)
- DC power converter (HyBuck) for powering the PEM short stack
- Input-output (IO) controller for control and monitoring of the hardware
- Raspberry Pi based computer utilised to run the main software
- Touch screen user interface

The HyGEN has the following features:

- Two modes of operation:
    - Flow mode: H_2 is produced at constant flow rate (max = 418.3 mL/min),
    - Pressure mode: H_2 can be pressurised to a maximum pressure of 10 bar
- H_2 output:
    - Wet
    - Dry (purity > 99.999 %)
- Power consumption: 250 W

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Benchmarking catalysts for water electrolysis technology for hydrogen production

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The effect of greenhouse gas (GHG) emissions of this century is expected to become more pronounced, and as a result, there is widespread agreement that carbon dioxide emissions should be cut through a variety of strategies. The main emphasis has been on creating energy sources that are both renewable and environmentally friendly. However, renewable energy sources like wind and solar power have a major drawback in that they are not continuously available, necessitating the development of effective energy storage solutions. Hydrogen is regarded as a clean energy carrier which has great potential in solving the challenges associated with GHG.[1] One possible remedy to this problem is to produce hydrogen via Proton Exchange Membrane Water Electrolysis (PEMWE) process using renewable energy sources. In this process, oxygen is produced when water is oxidized at the anode, and hydrogen is released at the cathode.[2] PEMWE employs platinum electrocatalyst at the cathode for hydrogen evolution reaction (HER) and iridium-based electrocatalysts at the anode for oxygen evolution reaction (OER).[3] HySA Infrastructure has developed proprietary methods of synthesizing the noble metal nanoparticle electrocatalysts for PEMWE with particle size of less than 5 nm and high degree of dispersion. Electrochemical techniques such as cyclic voltammetry, linear sweep voltammetry, chronoamperometry, chropotentiometry, etc. are used to determine electrochemically active surface area, mass activity, stability, etc. of the in-house synthesized electrocatalysts. Characterisation of the electrocatalysts is obtained from Scanning Electron Microscopy – Energy Dispersive X-ray (SEM-EDX), Transmission Electron Microscopy (TEM), Brunauer, Emmett and Teller (BET), Powder X-ray Diffraction (PXRD), X-ray photoelectron Spectroscopy (XPS).

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Coupled multiscale simulation of two-phase flow in porous transport layer with oxygen evolution reaction for PEM electrolyzers

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This study introduces a numerical tool for simulating the two-phase flow through a porous transport layer (PTL). The approach employs a hybrid-scale multiphase solver, developed by Carrillo et al. [1], that brings together Volume-of-Fluid (VoF), Immersed Boundary Method (IBM), Darcy's law and adaptive mesh refinement (AMR) [2] to model transport phenomena in small-scale geometries [3].

In the first step the approach is tested in a two-dimensional simulation of air flow injected through a PTL represented by five rows of staggered cylinders (**Figure 1**). The results depicted in **Figure 2** show a flow pattern similar to the preferential pathways reported in [4]. The hybrid-scale approach is confirmed to be a promising technique for a cost-effective simulation of two-phase transport processes in porous structures showing a good agreement with the reference body-fitted VoF and VoF-IBM-resolved simulations (**Figure 3**) of the same porous geometry.

In our conference contribution we will present the results of a simulation, where the multiscale approach is extended to a simplified configuration of the PEM electrolyzer anode side including the PTL region, the two-phase flow through the bipolar plate and the oxygen evolution reaction modelled through the Butler-Volmer-approach.

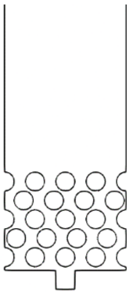

Figure 1: *Comp. Domain*

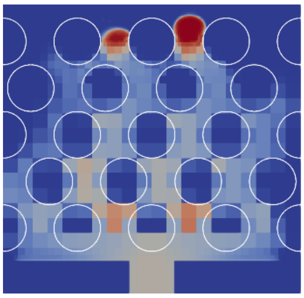

Figure 2: *Multiscale simulation*

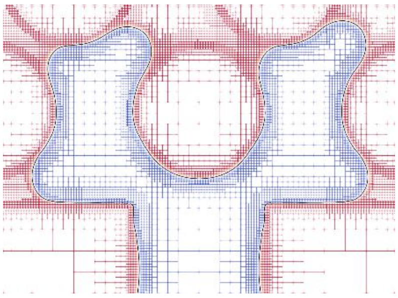

Figure 3: *Immersed boundary with VoF*

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Development, testing and comparison of mid-term test routines for partial load and direct dynamic operation of PEM stacks

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The development of reproducible, significant, transferable, and independent test protocols as a suitable data source for the evaluation, analysis and further development of water electrolysis systems, components and materials is a central challenge in the transformation to a hydrogen-based economy. This is especially true for the (direct) coupling with renewable energies, which require alternating partial load and dynamic operation.

The main topic of the present work is the identification and development of scalable mid-term test protocols with varying load for PEM stack components and materials rating in a direct coupling with wind turbines. Test bench limitations such as temporal and dynamic resolution and control as well as computing capacity are particularly considered.

For this purpose, empirical and synthetic test profiles as well as their combinations from the literature and in-house development are compared theoretically and experimentally. The effects on performance as well as the significance and limitations of the expected results are discussed.

This work is part of the hydrogen flagship project H_2Mare - joint project H_2Wind (03HY301D), funded by the German Federal Ministry of Education and Research.

Enhanced system design to reduce the SO_2 crossover to the cathode at SO_2 Depolarized Electrolyser (SDE)

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Green hydrogen is needed as an energy carrier in the energy transition away from fossil energy sources. For this reason, large quantities of renewable energy-based hydrogen will be required in the near future. Most of this will be produced by PEM water electrolyser technology, which has the disadvantage of requiring high overvoltage to break the water molecule into hydrogen and oxygen gas products. If SO_2 is added to the anode, the reaction changes and SO_2 is oxidized to sulphuric acid, but simultaneously protons are created that can transport via a proton conductive membrane to the cathode to produce hydrogen. This reaction has the advantage of significantly lower standard conditions potential $E° \sim 0.17$ V compared to conventional water electrolysis. This has two implications: a larger amount of hydrogen can be produced with the same quantity of renewable energy, and as the potential of the anode is lower, the material requirements are less demanding. However, as SO_2 is introduced to the system and can carry over to the cathode, it will be reduced to elemental Sulphur or H_2S gas. Both SO_2 and H_2S would then be contaminants for the produced hydrogen.[1] Nevertheless, a large quantity of green hydrogen is being planned to be used in metallurgical or chemical processes that might already contain these gases. Therefore, this technology has not been studied that much and therefore, there is a possibility of making significant improvements.

This work presents a new SDE electrolyte circulation strategy that will lower the sulfur-based contaminant formation at the cathode. Additionally, we will study the SDE operational parameters to find optimal conditions for the SDE that differ strongly from the optimal conditions used in the conventional PEM water electrolyser. In previous studies, the SDE has been operated at a very low pH, leading to the formation of S and H_2S that could be prevented by operating at higher pH, as shown in the thermodynamic analysis in **Figure 1**. The idea would be to determine optimal operating conditions for the SDE to prevent the formation of undesirable products. We discuss new instrumentation that we use for cathode gas contaminant detection. All these efforts will maximize the hydrogen gas output.

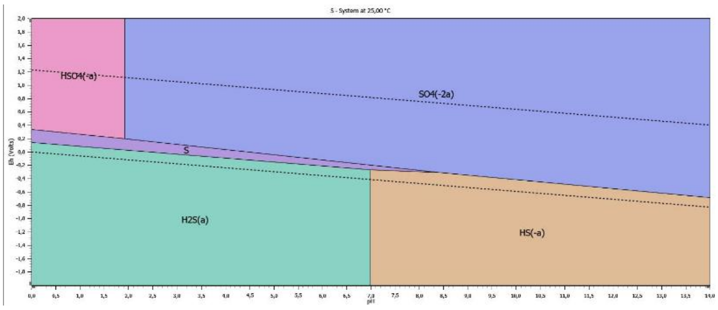

Figure 1: *Thermodynamic calculations of possible products in S-H_2O system at 25 °C in SDE (drawn using HSC Chemistry 10 program)*

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Multi-Scale Computational Modelling Techniques of Electrocatalysts for Oxygen Evolution Reaction

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Electrolytic hydrogen production is a promising option for relatively small to medium flows of hydrogen and is also useful for high-purity hydrogen required in niche applications. Recent advances in electrolysis have made it possible to design, build, and demonstrate large-scale plants for hydrogen production based on both PEM (proton-exchange membrane) as well as alkaline technologies. The utilization of various computational approaches has enabled the modeling of catalytic processes and material properties at the multi-scale level, as illustrated in **Figure 1** in PEM water electrolysis systems. These computational methods are well-suited for investigating material properties, chemical processes, and various phenomena applicable to electrocatalyst for water electrolysis. At the microscopic scale, atomistic and molecular modeling are utilized, while at the mesoscopic scale, molecular and coarse-grained modeling are employed. Finally, at the macroscopic scale, coarse-grained and continuum modeling are used. We explore multi-scale computational modelling techniques applicable to electrocatalysts in the oxygen evolution reaction (OER), with particular emphasis on iridium and its oxides. [1,2] Furthermore, we address the modelling of the reaction mechanism of the OER in both acidic and alkaline media. The study showed that multiscale computational modeling can play a critical role in advancing our understanding of electrolytic hydrogen and concludes with a discussion of opportunities and challenges that arise from ab initio modelling, using density functional theory.

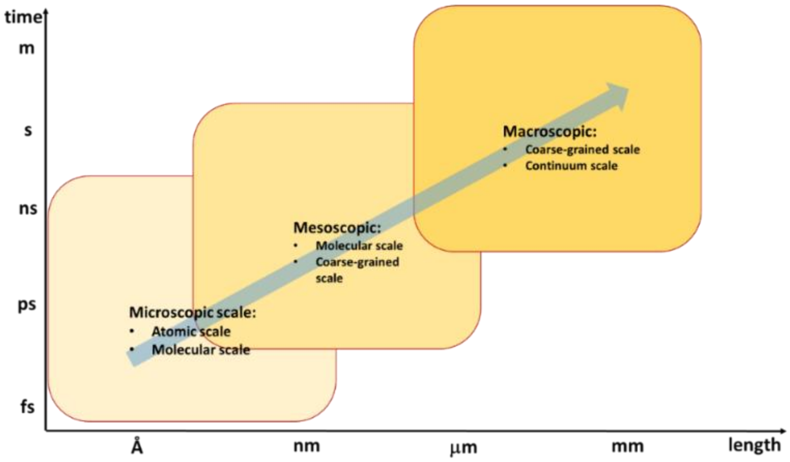

***Figure 1**. Schematic of multiscale modelling methods at different length scales.*

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Performance and durability of anode gas diffusion electrodes in PEM water electrolyzer

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Polymer electrolyte membrane (PEM) electrolysis technology offers ideal prospects for green hydrogen generation, e.g., rapid dynamic response time, large operational current density range, high efficiency, the possibility to operate at significantly differential pressure, either coupling with renewable energy sources or grid stabilization.[1]

The market access of this technology is mainly hindered by its high capital and operational costs which is due to the usage of expensive materials, which should resist harsh operational conditions, being the most severe at the anode (oxygen evolution at high anodic potential, acidic media). The degradation of PEM water electrolyzer components is among the most important challenges.[2]

Time-efficient evaluation of the durability of novel PEMWE stack components is possible by using the accelerated stress test (AST) protocols. According to recent reports [2], the main degradation mechanisms are associated with anode catalyst dissolution, membrane chemical decomposition, and the formation of semiconducting oxides on the metal components. However, there are still no widely-accepted protocols in the community, so its development is of high priority.

The presented study shows our recent advances related to the development of the AST for PEM water electrolyzer in comparison with the basic durability test – constant operation of the cell at an increased voltage (2.4 V). The electrolyzer aging is discussed in terms of ohmic resistance, charge transfer resistance, and Tafel behavior. The cell voltage breakdown based on the recently developed approach [3] is provided.

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Transient model of Wind powered PEMWE system

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Hydrogen has emerged as a promising energy carrier in hard to abate sectors in the context of a sustainable energy future. PEM water electrolysis is an emerging electrochemical method for producing hydrogen from water. The performance of the PEM water electrolyser system is influenced by various factors, including the power supply, operating conditions, balance of plant component sizing, configuration, control strategy and the system design parameters. Renewable energy sources, such as wind turbines, can be integrated with PEM water electrolysis to produce green hydrogen. However, wind turbine power and solar photovoltaics are characterized by fluctuations and intermittency, which can have a significant impact on the performance of the PEM water electrolysis system. The power generated by a wind turbines park can vary rapidly, leading to changes in the voltage and current supplied to the PEM water electrolyser. Such fluctuations can affect the efficiency, durability, and safety of the PEM water electrolysis system. Therefore, understanding the dynamics of the system is essential for optimising its performance and enhancing its reliability.

In this study, we have developed a model of a PEM water electrolyser system using OpenModelica, an open-source software tool for modeling and simulation. The model incorporates the dynamic behaviour of the system, including the response of the electrolyser to changes in the power supplied by a wind park. We used the model to investigate the effect of wind turbine power fluctuations on the performance of the PEM water electrolysis system. The model was validated using actual data from a European Union project. The data consisted of measurements of the power supplied by a wind turbine and the resulting hydrogen production by a PEM water electrolysis system. The model was calibrated using the data and validated by comparing the simulated results with the actual measurements. The validation demonstrated that the model accurately predicts the performance of the PEM water electrolysis system. Our results agree with literature that the system responds to changes in power supply by adjusting its operating conditions, which can affect its efficiency and durability. The model can be used to optimise the operating conditions of the system and enhance its performance under dynamic conditions. In conclusion, this study highlights the importance of considering dynamic effects in the design and operation of PEMWE. The findings of this study have implications for the development of sustainable energy systems that integrate multiple renewable sources.

Dynamic operation of PEM electrolyzers for cheaper green hydrogen - a critical review

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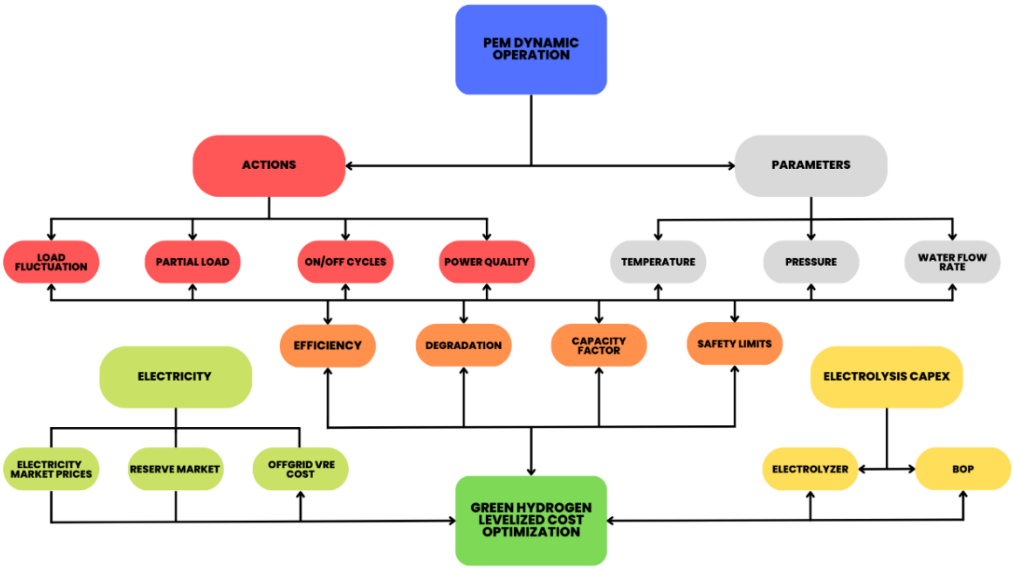
As more and more variable renewable energy sources are being connected to the electricity grid, the grid's volatility increases. The production of green hydrogen is seen as a promising energy storage and balancing solution to tackle this issue. Green hydrogen is also essential for decarbonizing hard-to-electrify sectors and its demand is increasing every year. The dynamic operation of Polymer Electrolyte Membrane (PEM) electrolyzers can utilize intermittent renewable electricity, improve electricity grid flexibility, and produce green hydrogen with lower costs than constant operation. In addition, dynamic operation can bring benefits in the form of extra revenue from the electricity reserve market. However, Dynamic operation affects the efficiency, degradation, capacity factor, and capital cost of PEM electrolyzers. Optimizing dynamic operation of PEM electrolyzers is a complex process, since different variables influence each other and affect the levelized cost of the produced green hydrogen. In this poster, we present a critical review about the main variables influencing the optimization of PEM electrolysis with respect to the levelized cost of green hydrogen, as shown in **Figure 1.** Moreover, actions taken by operator/optimizer during the PEM electrolyzer's dynamic operation are investigated and their influence on various performance indicators of PEM electrolysis are analyzed. We conclude that a holistic approach to the optimization of PEM electrolyzer dynamic operation that considers different interconnected variables will be needed to fill in current gaps in literature.



Introducing Iridium Nanosheet Catalysts on Titanium Oxide for Oxygen Evolution Reaction in PEMWE

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Polymer electrolyte membrane water electrolysis (PEMWE), a technology that produces hydrogen by electrolyzing water, has been gaining attention as a promising solution to overcome the intermittent production of renewable energy. However, the usage of iridium (Ir) for oxygen evolution reaction (OER) in the anode electrode poses a significant challenge in the commercialization of PEMWE. To address this challenge, researchers have been looking for ways to reduce the usage of iridium by developing a catalyst with higher performance than the iridium nanoparticle catalyst used as a commercial catalyst. One of the strategies is introducing support materials that can increase the active area of the catalyst. While carbon-based supports are commonly used in other applications, they are not suitable for OER environments due to their susceptibility to high voltage and strong acid conditions. Instead, a metal oxide support with high corrosion resistance, such as titanium oxide (TiO_2), is preferred. However, catalysts loaded on TiO_2 with nanoparticles face an electrical contact problem because of the low electrical conductivity of TiO_2, which results in a degradation in activity. While many studies have reported doping methods to increase the conductivity of TiO_2, there are also reports that these methods reduce the durability of support. Therefore, a new approach to synthesizing a better structure of catalysts is needed to utilize the metal oxide support.

In this study, we present a new approach to synthesizing an Ir nanosheet (NS) catalyst supported on TiO_2 (Ir NS/TiO_2). The Ir NSs were synthesized by a simple method, directly annealing a mixture of Ir precursor and alkali salt. The Ir NSs were then supported on TiO_2 to act as a reaction site and an electron path to compensate for the low electrical conductivity of TiO_2. The Ir NS/TiO_2 catalyst demonstrated superior OER activity and stability under acidic conditions. In addition, this catalyst exhibits superior performance when used as an anode in full cell. These results suggest that Ir NS/TiO_2 could be utilized to reduce the amount of precious metal catalyst in PEMWE and increase the stability of OER-supported catalysts. This method can pave the way for the development of new catalysts for PEMWE that are more efficient and cost-effective, ultimately making hydrogen production more sustainable and accessible.

Reliability and qualification of gasket materials for PEM electrolysis

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Gaskets are secondary components of an electrolysis cell meaning that they are not directly involved in electrochemical processes. Nevertheless, they play an essential role in separating the anode and cathode compartments, preventing leakage and mixing of product of gases and contribute to compensate the tolerances of various components. Therefore, the gasket materials should have adequate mechanical resistance to compression and thermal stress, should be hydrophobic and chemically and electrochemically stable, and should have low permeability for gases.

Four types of commercially available elastomer materials, i.e. fluorine elastomer, ethylene-propylene-diene monomer and nitrile butadiene rubbers with and without an inorganic support material, were subject to stability tests at low pH value over 72 h in different acidic environments (H_2SO_4, H_2SO_4 with additional O_2 loading, HF and HNO_3) at 80°C. After these exposure tests, the samples were investigated using thermogravimetry, tensile testing and gas permeation using He to qualify for their applicability as gasket materials. Furthermore, the obtained H_2SO_4 solution was tested using ICP-MS to detect ions released from the elastomer.

Exemplary results are shown in Fig. 1. It was demonstrated that nitrile butadiene rubber with the support material for higher pressure applications shows significant changes in its composition and a significantly higher ion release compared to the gasket material types without such a supporting material. In addition, this material also shows significantly higher gas permeation compared to materials without a support which are probably related to voids and defects in the gasket material. Furthermore, the experiments revealed that the fluorine elastomer shows the least release of ions although significant differences in its mechanical behavior were determined (not shown here). The relative change of He permeation is much smaller compared to the supported nitrile butadiene and similar compared to the other materials tested, which altogether makes the fluorine elastomer rubber the most promising candidate for usage in electrolysis cells out of the tested materials.

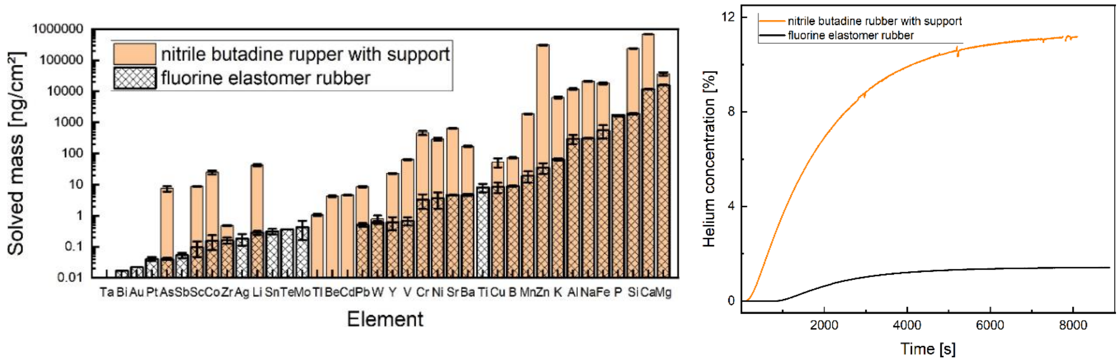

***Figure 1**: Exemplary results of ICP-MS and gas permeation measurements of a fluorine elastomer rubber and nitrile butadine rubber with an inorganic support after stability testing.*

About the structural optimization of catalyst layers for PEM electrolysis

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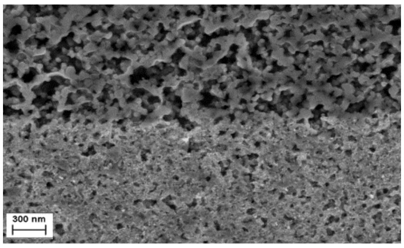
In view of the desired energy transition and the increasing demand for energy storage systems with regard to renewable energies, hydrogen is an efficient and environmentally friendly energy carrier which can be stored and used without greenhouse gas or any harmful emissions. The polymer electrolyte membrane (PEM) water electrolysis offers the possibility to store energy from for example wind and solar energy sources by producing regenerative, green hydrogen.[1]

The energy-converting reactions take place at the heart of the PEM stack, the catalyst coated membrane (CCM). The CCM consists of a perfluorosulfonic acid (PFSA) membrane, for instance Nafion™ membrane, which is coated on both sides with microporous catalyst layers. The efficiency of the system is based on the reaction at the triple phase boundaries within the CCM and is therefore significantly influenced by the porous microstructure of the catalyst layers, as it has a decisive influence on the electrochemical accessible surface and the supply and removal of the reactants.[2,3]

The materials and production of the CCMs, contribute decisively to the still high costs of the system. Thus, different approaches for the cost reduction target the optimization of the catalyst layer itself and its processing. In the present study, the focus is on one hand on the drying of the wet-applied catalyst ink as a decisive step in the formation of the microstructure of a (nano-)particulate layer.[4,5] The selection of a suitable drying process, for instance, can reduce defect formation in the layer and further improve the microstructure. In this respect, effects of the mixture evaporation of the alcohol-water solvent mixture used in the inks must be taken into account, as the composition of the ink changes during the film solidification (selective evaporation). On the other hand, the structural composition of the catalyst layer is additionally optimised. The approach chosen here aims at tailoring the microstructure of the catalyst layer through the use of multilayers, consisting of several layers each with adjusted microstructural properties. The focus is on the formation of porosity gradients (**figure 1**) and the distribution of components within the catalyst layer to enhance the mass transport of the reactants and reduce cross over effects and material costs.



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PEMWE COMPONENTS COATINGS & CATALYSTS : Developing Durable and High-performance coatings & catalysts

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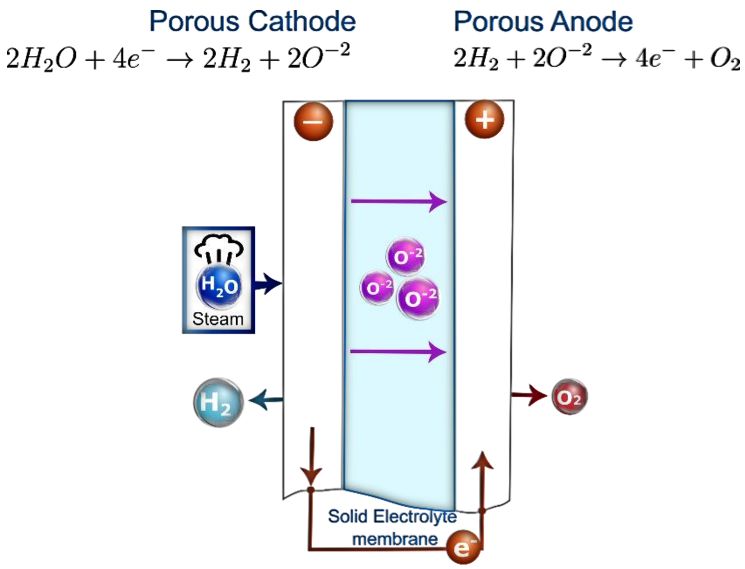
Green hydrogen is widely accepted as a critical part of advancing the energy transition. However, for it to become a reality the technology used to generate it, such as PEM Electrolysers, must demonstrate both performance and affordability. TFP Hydrogen's specialised coatings play an important role in enabling this; they enhance the performance, efficiency, and durability of PEM electrolysers to effectively reduce the lifetime cost of green hydrogen production. Utilizing a wide range of PGM coatings for titanium components including porous transport layers (PTLs) employed in PEM water electrolysers for Green hydrogen production. The developed coatings provide high corrosion resistance, lower interfacial contact resistance (reducing hydriding and embrittlement which increases ohmic resistance and can lead to mechanical failure) and lifetime for more than 10,000s of hours. Furthermore, the catalysts synthesised accelerate the electrolysis of the water at the anode and recombination of protons and electrons to form hydrogen at the cathode. High efficiency Iridium , Ruthenium oxides ($IrO2$, $RuO2$, $IrRuO2$), PtIr/C, anode catalysts are used in CCMs which enable the system to operate at a low voltage. Additionally, enhanced HER (NiMo/C) & OER (NiFeOx) catalysts are also synthesised to meet the recent advances and developments in anion exchange membrane (AEM) electrolysis.

Solid Oxide Electrolysis (SOE)



Effects of Solid Oxide Electrolysis Operation on Ni-YSZ Electrochemical and Microstructural Evolution

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Ni-YSZ fuel electrodes are widely used in electrode-supported SOECs but Ni depletion and disconnection near the electrode/electrolyte interface is often observed to cause performance degradation. This talk will present experimental studies of Ni-YSZ microstructural evolution during electrolysis, focused on a novel Ni-YSZ supported symmetric cell geometry. A range of Ni-YSZ microstructures are life tested under various operating conditions (temperature, current density, and steam/hydrogen ratio). The results show a substantial impact of gas diffusion in the thick Ni-YSZ supports, with Ni evolution most pronounced in regions that reach high steam content. Results from analytical calculations and a phase-field simulation of Ni migration, based on a spatial gradient in Ni/YSZ surface tension caused by electro-wetting, are present. Both surface diffusion and capillary driven evaporation and condensation are explored as possible transport mechanisms. The phase-field model employs the Ni-YSZ 3D microstructure as the initial condition and a large-scale numerical simulation predicts the directional Ni migration.

Doped ceria with exsolved Fe^0 nanoparticles as Sr-free cathode for CO$_2$ electrolysis in SOECs at reduced temperatures

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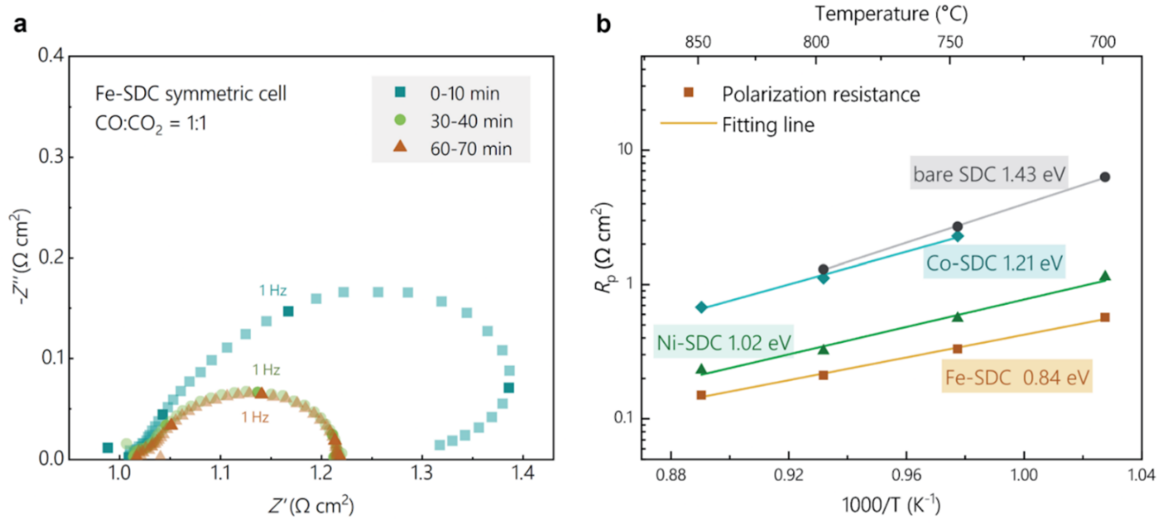
Solid oxide electrolysis cell (SOEC) is capable of electrolyzing CO$_2$ efficiently, which is a potential technology to realize “carbon neutral”. The efficiency of SOEC is mainly limited by CO$_2$ reduction reaction at the cathode. As an effective method to optimize the performance, transition metal doping and exsolution can construct metal-oxide interfaces, while increasing oxygen vacancy concentration at the oxide surface, thus facilitate CO$_2$ adsorption and dissociation. In order to construct stable heterojunction interfaces, transition metal decorated $Sm_{0.2}Ce_{0.8}O_{2-\delta}$ (SDC) as cathode for CO$_2$ electrolysis. The concept of Sr-free cathode with heterojunctions for CO$_2$ electrolysis is proposed. In this way, the application of *in-situ* exsolution is expanded to below 700 °C. Different from perovskites, ceria-based oxides do not contain alkaline earth elements. Thus, metal exsolution does not lead to phase transition of the parent oxide. Transition metals including Fe, Co and Ni can be respectively doped into SDC in air, and partially reduced to metal under CO-CO$_2$ mixtures. Under cathodic working conditions, Fe is partly exsolved as nanoparticles with diameter of 5 nm – 30 nm, anchored and monodispersed at the oxide surface, while exsolved Ni and Co agglomerated into large clusters. With doped ceria as parent phase, the sequence of catalytic activity of M-SDC is Fe-SDC > Ni-SDC > Co-SDC. Under the atmosphere of c(CO):c(CO$_2$)=1:1 and 700 °C, the polarization resistance of Fe-SDC is only 0.57 Ω cm^2, oxygen surface exchange coefficient is 1.68 × 10^{-3} cm s^{-1}, and the current density of single cell 1.5 V is 0.66 A cm^{-2}. Such performance is comparable or even higher than perovskite-based material measured at 800 °C. The application of Fe-SDC largely reduces operation temperature of CO$_2$ electrolysis without sacrificing the cathodic performance.



Fuel-side degradation of interconnect candidate ferritic-martensitic steels and Ni-based alloys for SOEC/SOFC

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Metallic interconnects are an essential component for the SOEC/SOFC stack setup. Interconnect materials require not only high electronic conductivity and creep resistance, but also excellent thermal conductivity and mechanical stability. On the fuel side of the cell, they must retain such properties above 825°C at high percentages of hydrogen and water steam. In this work, the degradation mechanisms, and their impact on the lifetime of the whole stack are being studied. Hydrogen diffusion through ferritic stainless steel can lead to internal oxidation of the materials in working mode and hydrogen embrittlement when the stack is shutdown. Besides the degradation caused by hydrogen, the materials have to be stable in the oxidizing atmosphere on the fuel side. In addition to oxidation effects on the surface of the material, the interdiffusion of nickel and other elements can lead to changes in microstructure and mechanical properties over long-term exposures. Within this framework, the following experiments aim at taking a closer look at the degradation of selected candidate materials for SOEC interconnects. Six ferritic materials with varying amounts of chromium and three Ni-based alloys are tested regarding their stability in hydrogen/water vapor environment. After exposure times of 300, 700 and 1000 hours in different hydrogen/water vapor atmospheres and various temperatures (700 – 900°C) in a 90 H_2-10 H_2O (vol.%) atmosphere, the interconnect materials are characterized with regards to scale growth, interdiffusion effects and mechanical properties. Thermal desorption analysis (TDA) and hot melt extraction were applied to detect absorbed/trapped hydrogen in ppm concentration and compared to the as-received materials. Furthermore, the results are compared to those of samples electrochemically pre-charged with hydrogen. Finally, a material ranking is suggested for the use as interconnect material in a SOEC/SOFC systems.

A Modified Hydrothermal Method for the Preparation of Nano-sized, Rutile-type IrO_2 Crystallites with Exceptional Activity and Stability Towards the Oxygen Evolution Reaction

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[b] *ICGM, University of Montpellier, CNRS, ENSCM, Montpellier, France;*
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Electrochemical water splitting by proton exchange membrane water electrolysis is an attractive means for producing carbon-free hydrogen when powered by renewable energy. However, the sluggish kinetics of the anodic oxygen evolution reaction (OER) requires the use of expensive platinum group metals. Iridium oxides are considered the state-of-the-art OER catalysts owing to their activity and more importantly, their exceptional stability during OER. Iridium oxides are synthesized with a crystalline or amorphous structure where the latter is more active but less stable than the crystalline analogue. Methods that produce rutile-type, nano-sized IrO_2 crystallites have been identified as highly promising for OER catalysis[1] owing to the combination of high activity and stability offered by the crystalline structure and small particles. Crystalline iridium oxides cannot be prepared without the use of thermal treatment either as an inherent part of the synthesis[2,3], or a post-synthesis heat treatment[4]. The use of high temperatures (>350°C) leads to particle growth, agglomeration and subsequently, lower activity[5]. Therefore, low temperatures should be used to reduce the effects of heat treatment.

In this work, a novel synthesis method directly yielding crystalline iridium oxide was developed. The modified hydrothermal method involves a low temperature (300 °C) calcination in the presence of an oxidant followed by a hydrothermal treatment to grow small (*ca.* 2 nm) crystalline IrO_2 nanoparticles. The prepared IrO_2 catalyst demonstrated good activity towards oxygen evolution. Most importantly, the catalyst displayed exceptional stability in comparison to a commercial benchmark characterised as a highly active amorphous Ir/IrOx catalyst. This useful method demonstrates that crystalline iridium oxide can be as active as amorphous iridium oxides.

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Optimizing the Partial Electrooxidation of Methane Using Supported C/γ-MnO_2 in Different Electrochemical Setups

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The current energy transition from fossil to renewable sources requests solutions for managing emissions in a scenario where large methane reservoirs are still available. Electrochemical studies focused on the partial oxidation of methane have drawn attention as an alternative to reduce the greenhouse effect caused by its burning and emission into the atmosphere.[1] This approach is useful to reduce the overpotential for H_2 electrochemical production since CH_4 oxidation potential is below OER, but also can add value to methane by its direct conversion to chemicals with added value, such as methanol, ethanol, carbon monoxide, and others. However, this transformation is complex due to its stable chemical structure, which requires high temperatures and pressures to break apart the bonds.[2] Noble-metal-based materials are the most frequently reported electrocatalysts for methane oxidation,[3] but their costs make the large-scale utilization unfeasible. Therefore, here we propose a cheap and easy electrode preparation for methane oxidation under different electrochemical setups. These setups are capable to increase the performance and methanol selectivity by the reflowing of the headspace gases into the electrolyte and the stirring. The catalyst electrodes composed of Ni/C/γ-MnO_2 demonstrate substantial activity for methanol, ethanol, and acetone production at low potentials of 0.8V vs. Ag/AgCl. The best performance setup is for the system under stirring, which shows methanol production above 40 $mmol.g^{-1}.h^{-1}$ with Faradic efficiency of 38.5%, and a current of 26 $mA.cm^{-2}$, and consistent H_2 evolution in Pt counterelectrode. Moreover, the electrode shows good stability over time and high current values even after being subject to reuse tests and reactions over 5 h.

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e-XPlore: A High-Pressure Solid Oxide Cell Electrolyser in a Sea Container for offshore Power-to-X Applications

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Green hydrogen and synthesis gases are one of the main energy carriers in our attempts to combat global warming and to fulfill the transition of our fossil fuel-based society and industrial activities to carbon neutral alternatives. One of the promising technologies for the production of these gases is the high temperature electrolysis with solid oxide cells (SOCs). At the German Aerospace Center's (DLR) Institute of Engineering Thermodynamics we experimentally investigate how SOC stacks[1] and modules[2] (up to 120 kW input) and use transient system simulations[3] to develop operation strategies. Particularly when syngas is needed by downstream processes at elevated pressures, it can be advantageous to pressurize the electrolysis as well. Therefore, DLR is building up a transportable test environment called e-Xplore[4] for an experimental analysis of a pressured electrolysis system. It comprises a system built in a 40 foot-sea container with an SOC module in a pressure vessel and includes almost all the required auxiliary components for nearly self-sufficient operation, such as cooling water, air supply, climate system, gas heaters, controls and safety system. The system only requires tap water, renewable electricity and some gases like hydrogen and nitrogen for heat-up or emergency cases. Steam electrolysis and co-electrolysis can be performed for hydrogen and syngas production with pressures up to 25 bar, an operating temperature of ca. 900 °C, and with a maximum electrical power input of 10 kW. This system supplies the synthesis gas for downstream processes, such as Fischer-Tropsch-synthesis to produce synthetic fuels within a Power-to-X context. This presentation will showcase the latest updates of planning and engineering of this system, as well as the relevant technical challenges. Operation strategies for different operating points will also be discussed. Furthermore, the off-shore application near a wind farm in the German North Sea as part of the H2Mare[5] project will be presented.

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In-situ Growth of Palladium Nanoparticles on A-site Layered Double Perovskite $PrBaMn_2O_{5+\delta}$

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The technique of exsolution, which involves the growth of nanoparticles in situ through phase separation under reducing conditions from an oxide lattice, has proven to be an effective method for the commercial use of noble metals. It overcomes the limitations of conventional deposition techniques by forming embedded nanoparticles in the host lattice. This has led to its use in addressing the drawbacks of solid oxide fuel cell (SOFC) electrode materials. The exsolution of active metals, such as Ni, Co, Ru, and Pd, from perovskite oxides has been successful in increasing the electrochemical performance of SOFC anode materials by providing catalytic sites for electrochemical reactions. A-site layered double perovskites, such as PrBaMn2O5+δ (PBMO), have shown remarkable mixed conductivity and stability in carbon and sulfur containing fuels.[1] The electrochemical performance and catalytic activity of PBMO towards fuel oxidation have been further improved by exsoling Ni and Co metal nanoparticles.[1,2] However, there has been little to no research on the exsolution of noble metals such as Pd from A-site layered double perovskites, which could significantly enhance the catalytic activity of SOFC anode materials.[3]

This study focuses on the exsolution of Pd nanoparticles from A-site layered PBMO through reduction. The Pd-doped material was synthesized using a two-step method, followed by characterization using various techniques. The crystal structure of the material was analyzed by X-ray diffraction and confirmed the formation of a tetragonal double perovskite with the appearance of metallic palladium. Thermogravimetric analysis was used to observe the phase change to the double perovskite. The presence of exsolved Pd nanoparticles was confirmed through transmission electron microscopy and STEM-EDX mapping. The oxidation states were analyzed using X-ray photoelectron spectroscopy, which revealed a change in oxidation state from cationic palladium before reduction to metallic palladium upon exsolution. Further investigations aim to understand the effect of palladium exsolution on the electrochemical performance due to its promising properties as an anode material for SOFCs.

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SOEC as enabler of highly efficient hydrogen production

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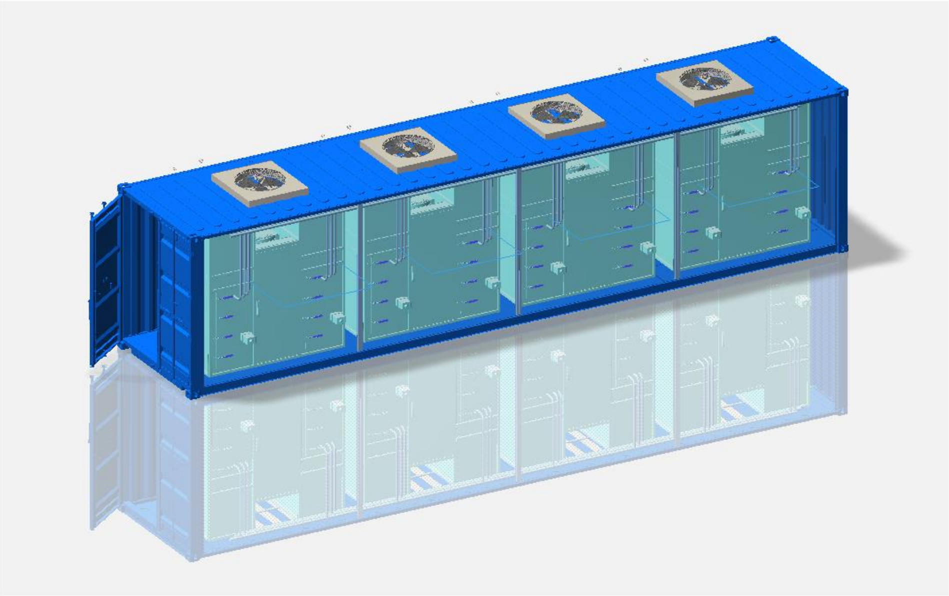
Production of green hydrogen from renewable sources shows a promising pathway for the long-term de-fossilisation, now adopted by many countries in their national strategic vision. Green hydrogen production via electrolysis shows the lowest carbon footprint among the H_2 production pathways. Several Electrolyser technologies are available, which differ in technical parameters and maturity. In 2030 SOEC H_2 production cost is estimated to be 15-25% lower compared to PEM electrolysis. SOEC is still in R&D phase with some pilot plants in the 100kW range in operation. With its working temperature between 600 and 800°C, SOEC has the potential to reach highest efficiencies due to thermodynamic characteristics with lower electricity demand at elevated temperatures for the splitting process of molecules like water into hydrogen and oxygen. Further advantages of this technology include the usage of non-precious catalysts at higher temperatures, the ability to operate the stacks reversibly and the possibility to convert carbonaceous feed gases directly and in combination with water (power-to-x). AVL with various partners is developing industrial scale 1MW SOEC modules where the first systems will be deployed already in 2023. A design study of such a modular 1MW system is shown in the figure below. The overall plant will reach about 80% efficiency of hydrogen production based on liquid water input and up to 88% based on steam input.



SOEC represents a particularly interesting technology to improve the production efficiency of hydrogen and e-fuels. This oral presentation will discuss the technology advantages and potentials for improvement.

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Solid Oxide Electrolysis for In Situ Resource Utilization six years after delivering MOXIE flight hardware.

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OxEon Energy was formed this week in 2017, days after completing the delivery of a production run of flight qualified CO_2 electrolysis stacks for the Mars2020 mission Perseverance Rover. The OxEon team developed the Solid Oxide Electrolysis (SOXE) stack inside MOXIE (Mars OXygen ISRU Experiment) that on Mars 20 April 2021 achieved the first demonstration of fuel production by electrolysis on another planet. MOXIE has continued intermittent operations on Mars the past two years, and as it approaches the end of the run opportunities allocated to it by mission planners, MOXIE continues to meet performance goals.

When OxEon was started as a new independent company the primary objective was to setup a SOEC (Solid Oxide Electrolysis Cell) development, manufacturing, and test facility. The OxEon team worked with Plansee (and US affiliate GTP) to capture lessons learned from the Mars project in the design of a full scale commercial SOEC stack. This new stack design, designated as the Eon 7130 electrolyzer (Figure 1 left), was put into prototype production in 2018 by OxEon and GTP. Initial stack builds have all demonstrated the hermetic seals and repeated thermal cycle capability shown at the smaller stack scale for the Mars project.

Dozens of Eon 7130 electrolyzer stacks have been produced and demonstrated dry CO_2 electrolysis, as well as steam, or steam-CO_2 co-electrolysis operation. These stacks have been subjected to multiple thermal cycles and accumulated multi-thousand hours of operation. A 30 kW Eon 7130 reversible solid oxide electrolyzer/fuel cell (rSOC) system comprising twelve 65-cell stacks is being readied for testing at the Idaho National Laboratory in Q1 of 2023 following demonstrations of OxEon 5 kW and 14 kW steam electrolysis stacks at INL in 2019 and 2022 respectively. A 20 kW reversible rSOC system is being prepared for a private customer in the US.

Follow-on work with NASA has led to the development of a redox tolerant cathode (electrolysis) material capable of surviving full oxidation by steam or CO_2, being restored to functionality simply by applying a voltage. NASA also supported work demonstrating both Lunar In Situ Resource Utilization (ISRU) for processing water ice from the permanently shadowed regions, and Mars ISRU (CH_4 and O_2 propellant production Figure 1) systems. These required design, production, and demonstration of an ISRU design variant of the Eon 7130 stack having internal oxygen ports and a fully sealed anode (oxygen evolution) perimeter. An overview of OxEon's activities and results are presented.

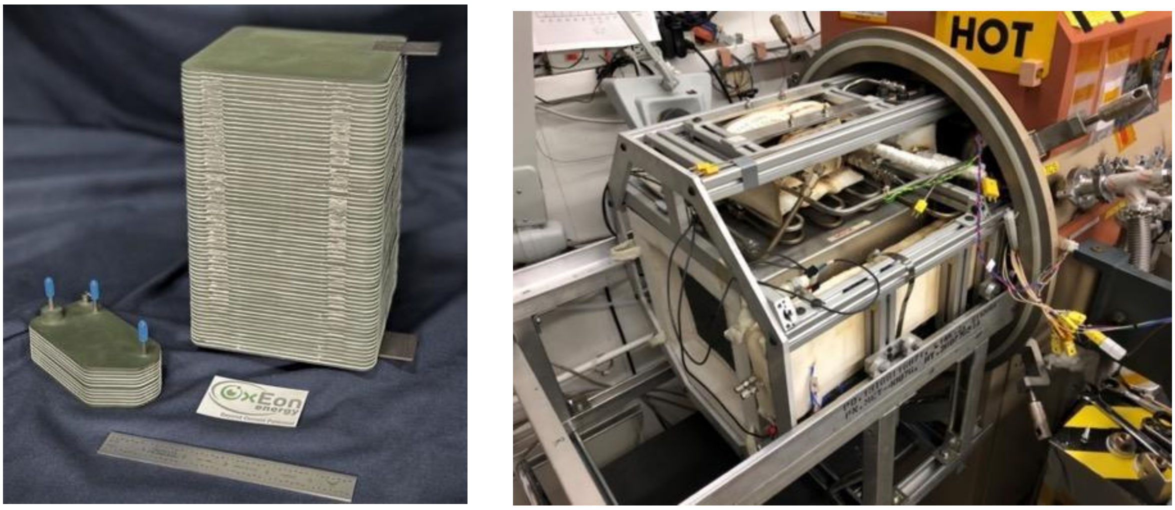

Figure 1. Eon 7130 Electrolysis stack (left) and OxEon Mars ISRU propellant system (right)

Current switching device development to characterise and monitor a proton exchange membrane water electrolyser

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High hydrogen purity, low gas cross overs, high product efficiencies and accelerated load response times has been the incentive for escalating interests and research conducted on proton exchange membrane (PEM) water electrolysis. It is regarded as one of the most prominent methods for hydrogen production during integration with zero-carbon electricity sources. Furthermore, meticulous characterization techniques have been developed to provide intricate insight on the analysis of the physical, chemical and electrochemical processes that occurs during operation. This research project will focus on two of these techniques namely electrochemical impedance spectroscopy (EIS) and the current interrupt (CI) method. EIS is a powerful tool that measures the relationship between the current and applied voltage across a specified range of frequencies. It provides sufficient information on the individual contributions towards the total impedance within an electrochemical system being monitored. However, this method utilizes quite complex and bulky testing equipment and analysis software that makes the technique quite expensive to use. Thus, it is imperative to implement a method that utilizes less expensive and complex testing- and analyses equipment that will successfully characterize a PEM water electrolyser delivering results that is in close correlation to that of EIS. Therefore, the CI method is further investigated by designing, modelling and implementing a PEM water electrolyser system that will imitate the CI technique both in the simulation and practical environment. The successful implementation of the CI method will later assist HySA Infrastructure in the characterization of PEM electrolyser short stacks which can lead to great market related impacts. The specific focus areas of this research project entail:

- Test bench station design and implementation for practical PEM water electrolyser testing.
- Design and model a PEM electrolyser system in simulation.
- Build a current switching board for current interrupt method practical implementation.
- Build monitoring circuit board and algorithm for PEM water electrolyser cell online monitoring.

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Dynamic measurements of clamping pressure distribution in a PEM water electrolysis cell and its validation by EIS

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Renewable energy surplus can be stored as chemically bound energy through water electrolysis, particularly Polymer Electrolyte Membrane (PEM) electrolysis. This dynamic process yields high purity hydrogen and oxygen, offering a significant opportunity for large-scale CO2-free electricity storage. [1, 2]

A PEM electrolysis cell is a mechanical assembly comprise of a PEM, anode and cathode catalyst layers, porous transport layers (PTLs), monopolar/bipolar plates, and two end plates. The assembly of these components is a sandwich configuration, the torque application results in uniform distribution of pressure by the end plates, facilitating continuous contact between the component and its surroundings, which ensures the right electric contact among all of them. Assembly pressure in a cell has a major effect on the performance optimizing. Because of, maintaining the contact pressure between the components provides sealing and the pressure distribution between cell components, and as such it results to the decrease in contact resistance between interfaces.[3]

The literature study revealed several studies on the clamping pressure effect on the performance, however, there is lack of studies which consider the effect of cell/stack pressure distribution across active area on the performance. The pressure distribution across the active area of a water electrolysis cell will be studied by employing pressure mapping sensor technology to characterize pressure distribution, and electrochemical impedance spectrometry will be used to characterise the performance of the stack. The study will lead to a better understanding of the relation between pressure distribution across the active area and the performance of the cell.

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High efficiency green hydrogen production through electron spin polarization.

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Photoelectrochemical water splitting (PWS) is one possible method for producing sustainable green hydrogen for useful electricity. The overpotential associated with the oxygen evolution reaction (OER) during water-splitting is a significant barrier in the commercialization of this technology[1]. Thus, this work explores the role played by chiral based Titanium dioxide (TiO_2) photoelectrodes as devices to optimize the hydrogen evolution process. Recent studies support the principle postured by the chiral induced spin selectivity (CISS) effect as an effective phenomenon for water splitting [2-4]. Theoretically, the absence of a spin controlling mechanism would result in the formation of hydrogen peroxide (H_2O_2) instead of the desirable triplet oxygen[5].The photoelectrodes were prepared by electrodeposition of TiO_2 nanoparticles onto doped tin oxide conducting glass and chiral molecules were allowed to self-assemble on the surface of the thin film. We expect a significant reduction in the generation of H_2O_2 which limits the efficiency of the overall water splitting process. Findings from this work show confidence that chiral electrodes have an improved electrocatalytic behaviour based on the observed early hydrogen onset potentials compared to the achiral and bare TiO_2 electrodes. Verdicts from this research are a proof of concept that controlled electron spin polarization is an important phenomenon in PWS.

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How to use QR codes

This abstract book explores the exciting potential of QR codes to enhance the reader's experience. QR codes, or Quick Response codes, are digital barcodes -they're used throughout the book to make accessing websites and online resources easier. Instead of typing a long web address, simply scan the code with your smartphone or tablet, and you'll be taken directly to relevant web pages such as the sponsors, ICE and Sun city international.

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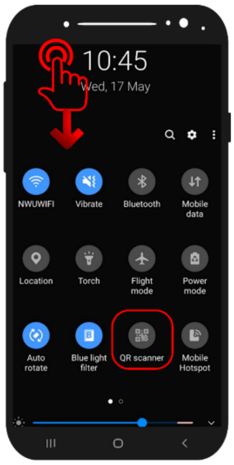
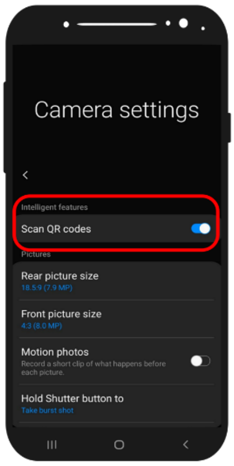
Using the Drop Down Menu

- This is the drop down menu where the Wi-Fi, Bluetooth, location and flashlight is located.
- Select the QR scanner.



Using the Camera App

- Make sure QR code scanner is enabled by going to camera settings.
- Open the Camera app, set to rear facing camera.



Camera settings

Intelligent features

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Rear picture size
18.5:9 (7.9 MP)

Front picture size
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Motion photos ○
Record a short clip of what happens before each picture.

Hold Shutter button to
Take burst shot

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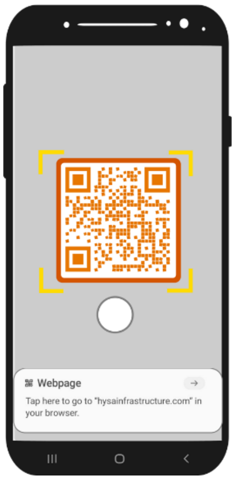

Webpage

Tap here to go to "hysainfrastructure.com" in your browser.

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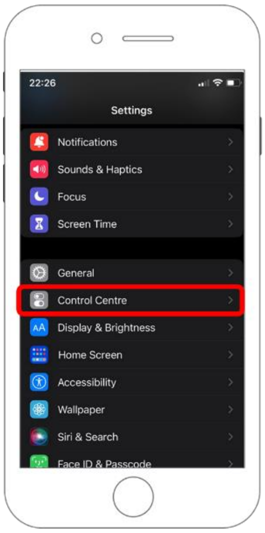
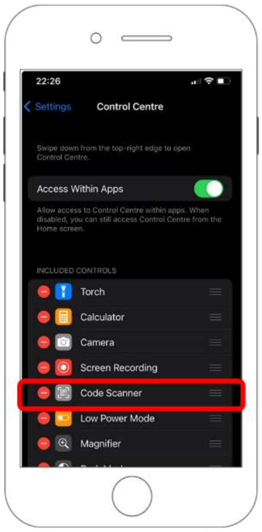
3. Go back to the Control Centre, select the QR Code reader, and focus your screen on the QR Code.





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Access Within Apps

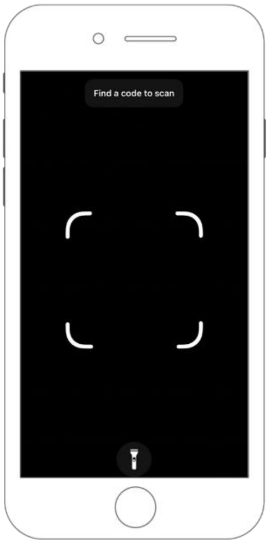
Allow access to Control Centre within apps. When disabled, you can still access Control Centre from the Home screen.

Using the Camera App

1. If the QR scanner is already on the drop down menu. (← refer to the Control Centre setting if not added)
2. Select the QR Scanner.

Scanning The Code (Also works using Camera)

- Open iPhone camera,, switch to rear view camera.
- Steadily pointy towards the QR Code for 2-3 seconds.
- If your device recognizes the QR code, a notification will show.
- Tap the notification to open the link associated with the QR code.



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