

Advanced Liquid Alkaline Water Electrolysis Experts Meeting

Summary Report - January 2022

Hydrogen and Fuel Cell Technologies Office

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Preface

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Acknowledgments

The Hydrogen and Fuel Cell Technologies Office (HFTO) acknowledges and thanks all of the experts for presenting valuable information and sharing their knowledge. HFTO thanks the moderators and scribes for their preparation and leadership in breakout sessions, and the organizing team for their effort in planning and executing the meeting. HFTO also thanks the participants of the meeting for their engagement in valuable discussion and for providing informative feedback.

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Nomenclature or List of Acronyms

ANL	Argonne National Laboratory
AST	Accelerated stress tests
BOP	Balance of plant
CAPEX	Capital expenditures
DOE	Department of Energy
DFMA	Design For Manufacturing and Assembly
EERE	Office of Energy Efficiency and Renewable Energy
EIS	Electrochemical impedance spectroscopy
H2NEW	Hydrogen from Next-generation Electrolyzers of Water
HFTO	Hydrogen and Fuel Cell Technologies Office
LANL	Los Alamos National Lab
LA	Liquid alkaline
LTE	Low temperature electrolysis
NREL	National Renewable Energy Laboratory
O-SOEC	Oxide-ion conducting solid oxide electrolysis cell
PEM	Proton exchange membrane
PTL	Porous transport layer
R&D	Research & development
RDE	Rotating disk electrode
SEM	Scanning electron microscopy
TEA	Technoeconomic analysis

Executive Summary

The U.S. Department of Energy (DOE) recognizes the decarbonization potential of hydrogen as a chemical and fuel, and recently launched the Hydrogen Shot initiative to reduce the cost of clean hydrogen to \$1 per kilogram of hydrogen produced by 2031.¹ Production of clean hydrogen by liquid alkaline (LA) electrolyzers is a promising pathway to achieve that goal given their commercial maturity. On January 26-27, 2022 the DOE Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen and Fuel Cell Technologies Office (HFTO) co-hosted an experts meeting with the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium on Advanced Liquid Alkaline Water Electrolysis. The primary goal of the meeting was to convene electrolysis experts in order to:

- Build a detailed picture of the status and challenges of commercially-available LA water electrolyzers and opportunities for developing next-generation LA electrolyzer technology
- Prioritize R&D opportunities to overcome current limitations and challenges
- Help shape HFTO's strategy for LA electrolyzer research and development

Over 130 people attended the meeting, representing a range of organizations including industry, national laboratories, universities, and government (Figure 1). The first day of the meeting featured presentations from industry and national lab experts to give an overview of the state of the LA electrolyzer field. The second day of the meeting was dedicated to small group, in-depth discussions on particular topics. For each topic, the goal was to identify and prioritize R&D strategies that could lead to significant advancements for LA electrolyzers in order to achieve the Hydrogen Shot target.

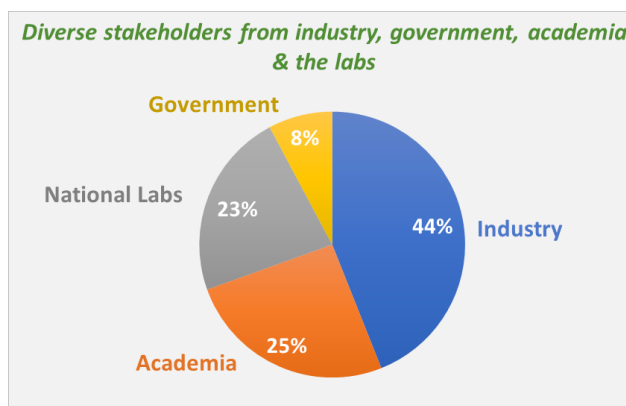


Figure 1. Attendance report by industry.

Throughout the workshop, attendees pointed to limitations of traditional LA electrolyzers, which have been commercially available for decades. Among the most prominently discussed limitations were low operating current density at a high efficiency and a lack of intermittent operability. Inability to operate at higher or differential pressures was also mentioned. Overcoming such limitations will be key in achieving the Hydrogen Shot target and deploying LA electrolyzers for a wide-range of applications in the future that may require variable operation tied to renewable energy generation. Commercial LA cells and stacks can have very long lifetimes; however, the impact of advanced materials, cell/stack designs, and dynamic operating conditions on durability remain research gaps.

Key R&D opportunities to develop advanced, next-generation LA electrolyzers to overcome the limitations mentioned above include: developing new materials, improving component interfaces, and designing novel cells and stacks. More fundamental diagnostic studies to correlate performance with material and interfacial properties and to understand degradation mechanisms are needed. Such studies will inform material development efforts for novel cell and stack components. Separators and catalysts, in particular, were highlighted as historically underdeveloped materials with significant opportunity for advancement. Characterization and testing of materials should be conducted using standardized protocols under relevant operating conditions, including those anticipated for next-generation LA systems (e.g., intermittent operation,

¹ <https://www.energy.gov/eere/fuelcells/hydrogen-shot>

higher pressure). Also, once degradation mechanisms are identified for advanced materials and components, development of accelerated stress test (ASTs) protocols to effectively accelerate these degradation processes to allow for durability testing to be conducted over a matter of weeks or months instead of years is greatly needed to expedite inclusion of results in near-term commercial products.

Material development must consider not only intrinsic material properties, but also the interfaces between components. Interfaces and cell integration will become more critical with advanced cell designs and more dynamic operating conditions. Re-designing LA electrode and cell architectures with greater attention to component integration and interface engineering could result in higher current densities and enable intermittent operation. Advanced material and cell development must also consider manufacturability from the outset, including both scale-up of cell size and applicability to high volume manufacturing.

In order to design LA electrolyzers for intermittent operation, it was noted that there first is a need to define the target operating conditions. This also includes an evaluation of potential cost impacts on different operating strategies that takes into account ramp rate, minimum operating capacity (turn-down capability), and start-stop considerations. Then, creative solutions must be developed and investigated to overcome challenges such as managing shunt currents, handling a highly corrosive electrolyte, and mitigating gas crossover at low current densities. Materials, cells, and systems should be designed to overcome those challenges while following intermittent load profiles. Accelerated stress tests could be developed for materials, single cells, and systems to accelerate and understand the relevant degradation mechanisms occurring under such operating conditions. A national testing facility could also be established with the capability to test novel stacks developed by industry using standardized accelerated stress tests.

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1 Introduction & Background

As part of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), the Hydrogen and Fuel Cell Technologies Office (HFTO) is enabling the development of advanced hydrogen and fuel cell technologies across sectors through applied research and demonstration. Among other activities, HFTO organizes and supports meetings that convene stakeholders from the research community, industry, and government to guide research and development priorities for hydrogen technologies.

HFTO, in collaboration with the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium, hosted the Advanced Liquid Alkaline Water Electrolysis Experts Meeting on January 26-27, 2022. Due to travel restrictions, this meeting was held virtually. The objectives of this meeting were to:

- Learn about the current challenges of liquid alkaline (LA) electrolyzer technology
- Prioritize impactful research, development, and demonstration opportunities to accelerate next-generation technology development.

The input received from the experts will be used to guide research direction and help establish targets. The meeting included presentations from industrial and national laboratory experts, followed by breakout sessions for deep technical discussions. This report summarizes the outcomes and achievements of the meeting that will be used to guide future work supported by HFTO. Presentations from the meeting, along with this report, can be found at: <https://www.energy.gov/eere/fuelcells/advanced-liquid-alkaline-electrolysis-experts-meeting>

1.1 Hydrogen Shot: Accelerating the H2@Scale Vision

Hydrogen is an important chemical feedstock in the global economy today with large quantities consumed in industries such as ammonia production and oil refining. There is also a growing demand for hydrogen in other applications such as transportation (e.g., fuel cell heavy-duty vehicles), innovative industrial processes (e.g., steel production), and grid services (e.g., power generation, load balancing). Hydrogen for such applications can be produced from a diverse set of energy feedstocks, including renewable power and fossil fuels. This hydrogen ecosystem is reflected in the H2@Scale vision illustrated in Figure 2. Achieving the H2@Scale vision with clean hydrogen could decarbonize several sectors of the economy and supports the Biden Administration's goal to achieve a net zero emissions economy by 2050.²

In June 2021, the DOE launched the Hydrogen Energy EarthShot to further accelerate breakthroughs in clean hydrogen production technologies that result in a more abundant, affordable, and reliable domestic clean hydrogen supply.³ The Hydrogen Shot initiative supports the H2@Scale vision and sets a specific goal to achieve a cost of \$1 per kg of clean hydrogen produced by 2031. Water electrolysis is a key hydrogen production pathway to implement the H2@Scale vision and achieve the Hydrogen Shot \$1/kg clean hydrogen target.

² FACT SHEET: President Biden sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies, <https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/>

³ <https://www.energy.gov/eere/fuelcells/hydrogen-shot>

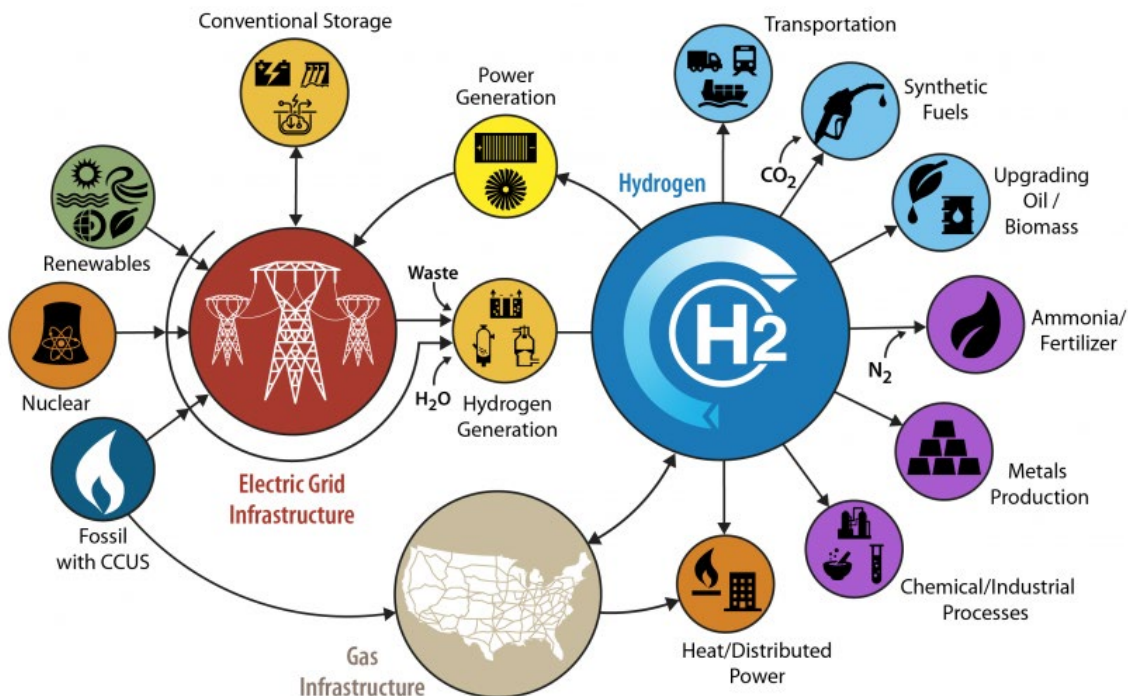


Figure 2. H2@Scale vision to enable decarbonization across multiple sectors of the economy.

1.2 Context: Ongoing HFTO Efforts for Electrolyzer Development

HFTO is helping to drive innovation in hydrogen production technologies to achieve the Hydrogen Shot goal. For more than a decade, HFTO has supported the development of several hydrogen production pathways, including water electrolysis. Water electrolysis (the process of using electricity to split water into hydrogen and oxygen gases) is a well-known technology for clean hydrogen production when utilizing renewable electricity. HFTO has established several consortia (led by national laboratories) to help lead research and development of low technology readiness level electrolyzer technologies.

The H2NEW consortium⁴ is addressing component integration and manufacturing challenges to enable more affordable and durable high-performing electrolyzers. The goal of H2NEW is to enable electrolytic hydrogen production at a cost of \$2/kg by 2026. While H2NEW has thus far focused on proton exchange membrane (PEM) and oxide-ion conducting solid oxide (O-SOEC) electrolyzers, the research and development (R&D) approach of the consortium could be applied to other electrolyzer technologies, such as LA electrolyzers.

1.3 Liquid Alkaline Electrolysis

LA electrolyzers are the oldest and most commercially mature electrolyzer technology. Originally developed to utilize low-cost hydroelectric power to produce hydrogen for ammonia production, these systems were designed to run under continuous, steady-state operating conditions. LA electrolyzers were large in scale (~100 MW) to meet the large hydrogen demand of industry, and large in physical footprint because of operation at low current densities to optimize system efficiency. While LA electrolyzers are being utilized today to produce

⁴ <https://h2new.energy.gov/>

hydrogen for more diverse applications, including transportation and power generation, they are still characterized by a large system footprint and the need to operate continuously.

Traditional LA electrolyzer cells utilize hot (80-90°C) concentrated alkaline electrolyte (e.g., 25% KOH) to transport ions between metal electrodes. Such caustic electrolytes have associated challenges, however, this electrolyte enables the use of low-cost electrode materials, such as Ni-based alloys and stainless steel. In between the electrodes is a solid, porous separator that is permeable to the liquid electrolyte and mitigates hydrogen and oxygen gas crossover between the separate electrode compartments. The distance between the electrodes and resistivity of the electrolyte (even if low) results in a parasitic ohmic resistance; operation at high current densities requires high voltages that can be uneconomical, decreasing efficiency, or detrimental to the electrodes' stability. Traditional LA electrolyzers operate at relatively low current densities (0.2-0.8 A/cm²) at voltages ranging from (1.4-3 V).⁵

To achieve the Hydrogen Shot goal of \$1/kg clean hydrogen produced with LA electrolyzers, significant advancements will be required. The current cost of hydrogen produced from LA electrolyzers ranges from \$3-5/kg⁶. Key innovations that can lead to substantial cost reductions include enabling stable operation at higher current densities, reducing system capital costs, and improving efficiency. Next-generation LA electrolyzers should also be re-designed to handle dynamic operation (e.g., load following solar power) to produce clean, low-carbon hydrogen by capitalizing on low cost electricity that is available intermittently. In this meeting, experts provided their perspective on what research, development, and demonstrations will result in the needed cost reductions to meet the Hydrogen Shot goal.

2 Expert Presentations

An introduction to the meeting was given by Dr. Ned Stetson, the Hydrogen Production Program Manager from HFTO, and Dr. Bryan Pivovar, the Director of H2NEW. Dr. Stetson discussed the priorities of the DOE Hydrogen Program, which include developing low-cost, clean hydrogen; low-cost, efficient, and safe hydrogen delivery and storage; end use applications at scale; workforce development; safety codes and standards; and environmental justice priorities. The H2@Scale initiative established by DOE provides a framework for making these priorities a reality. Dr. Pivovar discussed the current focus of H2NEW, which aims to provide scientific understanding of electrolyzer cell performance, cost, and durability trade-offs of PEM and O-SOEC electrolyzers. He highlighted how H2NEW's research approach could also apply to meet the needs of advanced LA electrolyzer development.

Following the introductory remarks, there were six expert presentations covering topics related to LA electrolyzer development. An overview of the presentation topics and speakers is found in Table 1. The presentations can also be found on the meeting website.⁷

⁵ "Green Hydrogen Cost Reduction: Scaling Up Electrolysers to Meet the 1.5 °C Climate Goal." IRENA (2020).

⁶ IRENA 2019; E3 report

⁷ <https://www.energy.gov/eere/fuelcells/advanced-liquid-alkaline-electrolysis-experts-meeting>

Table 1. Expert speakers, affiliations, and presentation titles.

Speakers	Affiliation	Presentation Title
Marcelo Carmo	Nel Hydrogen, USA	Introduction to Liquid Alkaline Electrolysis
Ed Revers	De Nora	Cell & Stack Components (Interfaces & Corrosion Challenges)
Joe Poindexter	Teledyne Energy Systems	System & Integration Challenges
Steven Kloos	AquaHydrex	Cell-level Challenges
Rangachary “Mukund” Mukundan	Los Alamos National Laboratory	Accelerated Stress Test Development
Brian James	Strategic Analysis, Inc.	Component & System Technoeconomic Analysis

2.1 Introduction to Liquid Alkaline Electrolysis

Dr. Marcelo Carmo, at the time of presentation, was the Director of Technology at Nel Hydrogen, USA. Previously he was the Director of the Institute of Climate and Energy Research (IEK-14) in Germany. He holds a Ph.D. in materials science from São Paulo University. He has co-authored more than 50 peer-reviewed publications, 4 book chapters, and coordinated and participated in several international collaborative R&D projects.

This presentation provided an introduction to LA electrolyzer technology, including a brief history of its development. LA electrolyzers have a long commercial history and have historically been used for ammonia production around the world using low-cost hydroelectricity. The typical size of such LA electrolyzers was on the order of 100-MW, although the largest facility in operation today is 25 MW in size. Dr. Carmo highlighted demand for hydrogen today is expanding to industries beyond ammonia production, demanding LA electrolyzers upwards of ~5 MW in size depending on the application. This historical perspective provided the rationale for how and why LA electrolyzer components and operating conditions were designed as such.

The presentation highlighted several areas for innovation, including separators, electrodes, porous transport layers (PTLs), and cell design for high pressure operation. New or improved separators for LA electrolyzers are key to decreasing the overall cell resistance. While thinner separators can also reduce resistance, mechanical stability is a challenge. More R&D on these materials is needed to identify potential replacements or improve the commonly-used Zirfon separator. Increasing the cell pressure is also desirable to reduce downstream compression costs, but is only possible with separator development to improve mechanical stability.

It was shown how novel electrode designs and catalysts have also led to improvements in activity. The current Ni-coated steel electrodes are very stable, and novel materials, electrode, and cell designs should not sacrifice stability. In fact, it was noted that stack degradation is so slow, that typically other equipment must be replaced before the stack, which has a lifetime of 20-30 yr. Dr. Carmo emphasized that LA electrolyzer development requires more effort in how materials and components are integrated, for example, in integrating catalyst layers with porous transport layers. He encouraged the research community to look to PEM electrolyzer electrode development for inspiration in component and cell design. Leveraging expertise from PEM electrolyzer development could lead to capital cost reduction, efficiency improvements, and even reduced footprint. Overall, this presentation touched on many of the topics that would be covered in more detail in later expert presentations and the breakout sessions.

2.2 Cell & Stack Components

Mr. Ed Revers is a Senior Scientist and Research Project Manager in the R&D-USA group of De Nora. He has been at De Nora for almost 10 years since graduating with a bachelor's in chemical engineering from Case Western Reserve University. Throughout his time at De Nora, he has managed a variety of projects focused on coating and system development for electrochlorination, advanced water treatment, disinfection and sanitization, and alkaline water electrolysis applications. More recently, he has started in a role in De Nora's Energy Transition & Hydrogen business unit, where he serves as a technical liaison between R&D and Business Development for hydrogen related activities.

This presentation focused on the interface and component-specific challenges in LA electrolyzers, specifically of the electrodes, bipolar plates, current collectors, and separators. Similar to Dr. Carmo's presentation, Mr. Revers drew parallels between the development of dimensionally stable anodes (DSAs) for chlor-alkali electrolyzers and the type of development needed and challenges faced by LA electrolyzers. He emphasized that advanced LA electrolyzers will have higher current density, efficiency, and catalyst utilization, and may operate at higher pressures, all of which will require significant material advancements.

Cell design provides significant opportunity for innovation in interface engineering. In particular, the field needs to gain a better understanding of how the separator interacts with the electrodes and how best to design the electrode with the separator in mind. This includes improving understanding of bubble management in the electrolyte and on the electrode surface, the current distribution on the electrode, and interfaces through experimental and modeling research. Monitoring and understanding these properties in existing cell architectures (and at large-scale ($\sim m^2$)) can accelerate the development of next-generation cell designs. One advanced cell design mentioned was the dynamic zero-gap cell. Dynamic zero-gap (as opposed to fixed-gap) cells enable small volume changes which mitigate separator destruction and have reduced ohmic losses across the cell, which improves efficiency. In addition, Mr. Revers echoed Dr. Carmo's call for novel separator materials designed with the electrode-separator interface in mind.

Characteristics of next-generation electrodes include high catalytic activity, high surface area, high conductivity, reduced bubble effect, high permeability and wettability, structural and chemical stability, manufacturability, tolerance to reversal currents, and low cost. Advances in electrode and catalyst design must also consider the need for deposition onto large electrode areas and quality control of the electrode activity across the electrode. The catalyst can be deposited directly onto the current collectors, which are typically Ni-coated bipolar plates of up to 3 m² in geometric area. It has been shown that mitigation of Ni oxidation using advanced coatings can drastically improve efficiency and durability. Though studies have been conducted at the lab-scale, there is a need to characterize degradation mechanisms of large-scale electrolyzer cells. Opportunities to further develop high-quality, robust, and conductive coatings still remain for LA electrolyzers.

Mr. Revers highlighted a few system-level and supply chain considerations for LA electrolyzers. Given the potential use of LA electrolyzers with renewable energy sources, cell design and testing protocols should consider intermittent operation. He also called for the need to develop standardized testing protocols across the field. When asked if Ni would remain a predominant material, he replied that Ni is not a limiting raw material and would most likely continue to play a role in the electrode. He also noted his expectation that non-precious metals will be used as catalysts in future LA electrolyzers, though some advanced catalysts currently under development do contain PGMs.

2.3 System Integration Challenges

Joe Poindexter is the Hydrogen Products Manager at Teledyne Energy Systems, where he is responsible for product development for their alkaline electrolyzers. He has 25 years of experience at Teledyne working on all aspects of the product line, including product design, field service, customer training, sales, and business

development. In his presentation, Joe provided an overview of the challenges of intermittent or variable operation, considerations for managing concentrated KOH, and challenges in manufacturing of systems.

Intermittent operation of LA electrolyzers present several challenges that must be addressed. Rapid changes in power level, and the resulting gas generation, can cause issues with differential pressure control, electrolyte level, and system pressure which could lead to unsafe operation. Also, loss of power to critical control systems and equipment, such as differential pressure control and pumps for thermal management, can impact safety and efficiency. Another challenge to address is shunt currents, or unintended currents that can flow through ports and manifolds. When coupled to renewable energy sources, one must also consider how the electrolyzer system may handle power input that exceeds the maximum rated capacity of the system. In general, intermittent operation can reduce lifetime of the system due to mechanical stress and thermal cycling. There is a need to better understand future operating profiles of electrolyzers when directly coupled to renewable energy sources, and thoughtful system design to most efficiently match those load and operating profiles.

The use of concentrated alkaline electrolyte (~7-8 M) in LA electrolyzer systems at elevated temperature requires using higher cost materials that can withstand those conditions without significant corrosion, such as stainless steel and nickel, for all parts of the system that contact the electrolyte. Though a small amount of corrosion occurs with these materials, this doesn't significantly decrease over lifetime of the system. Maintenance of the electrolyte is not considered a major cost or safety concern. The electrolyte typically is replaced once or twice a year. System operators must be prepared to handle the caustic solution, but this can be managed by simple neutralization of the alkaline solution which can then be disposed of without generating any hazardous material. There are no special permits or regulatory obstacles to managing the alkaline electrolyte.

It was also noted that LA electrolyzers can handle higher impurities in water sources than PEM electrolyzers. Currently, operation can occur on water quality approaching that of tap water, however more research is needed to see how LA electrolyzers could handle water supply with even higher levels of impurities.

2.4 Cell-level Challenges

Steve Kloos is Chief Executive Officer of AquaHydrex and a member of its Board of Directors. Steve led the True North Venture Partners thesis on hydrogen that resulted in the creation of AquaHydrex and has been active with the company through its journey. Prior to AquaHydrex and True North, Steve worked in various R&D leadership roles at General Electric in the US and Asia and also served on their venture capital team. Steve started his career doing water treatment membrane R&D and he holds a Ph.D. in Chemistry from North Dakota State University. In his presentation, Mr. Kloos outlined some of the idealized characteristics of electrolyzer technologies and how novel LA electrolyzer designs could meet those ideals.

Mr. Kloos recognized that LA electrolyzers have a long commercial history, and while there was some research conducted during the early- and mid-1900's, current commercial LA electrolyzers have not advanced much from their historical versions. These LA electrolyzers are characterized by:

- Lower current densities (0.2-0.6 A/cm² compared to 1.5-2.5 A/cm² for PEM)
- Poor performance when turned off or down, such as when coupled to renewable energy sources
 - Cell-level pressure management issues, particularly during large changes in power input, resulting in unsafe gas crossover
 - Parasitic shunt currents which damage catalysts
- Complex balance of plant (BOP) due to flowing caustic electrolyte management

Although lacking in innovation over the last 50 years, Mr. Kloos claimed that some, if not all, of LA electrolyzer challenges are addressable. Areas that will lead to improvement include advanced catalyst development, experimental testing at target operating conditions to assess cell lifetime, and minimizing or mitigating gas crossover. Advanced catalyst development aspects include designing materials for integration into zero-gap cells, understanding how to manage current reversal, and assessing stability at relevant industrial cell conditions. Such catalysts can help push the performance of LA electrolyzers to higher current densities. There is also a need to evaluate material and component performance under relevant conditions, such as higher temperature, pressure, and current density, than is currently done. Under such test conditions, there is a need to better understand degradation mechanisms and how to mitigate them, including at large-scale. With this knowledge, accelerated stress tests can be developed which would enable determining lifetime of experimental materials and components much more rapidly.

During the Q&A, Mr. Kloos responded to a question relating to catalyst activity noting that it would be better to focus on inherent catalyst activity first and work on increasing surface area and stabilizing morphology later. Also during the discussion, a summary priority of innovations for LA electrolyzers was suggested: (1) enable intermittent operation including directly integrating with renewable energy sources, (2) operate at higher pressure (e.g., 30 bar), and (3) achieve higher current density.

2.5 Accelerated Stress Test Development

Rangachary (Mukund) Mukundan is a technical staff member in the Materials Synthesis and Integrated Devices group at Los Alamos National Laboratory. He received his Ph.D. in Materials Science and Engineering from the University of Pennsylvania in 1997. His current research interests include fuel cells, electrolyzers, energy storage devices, and electrochemical gas sensors. He currently serves as a Deputy Director in the Million Mile Fuel Cell Truck consortium and as an LTE Durability liaison in the H2NEW consortium where he is developing ASTs for both fuel cells and electrolyzers. He is the co-inventor on 7 US patents and has authored over 180 peer-reviewed journal and transaction papers, cited over 8500 times. His work has also been recognized through numerous awards.

Dr. Mukundan highlighted known degradation concerns in LA electrolyzer components to motivate the need for developing ASTs. In particular, he showed that the largest losses are found in the anode and separator. The anode suffers from Ni dissolution and formation of Ni oxides, and dissolution is a particularly large challenge for advanced catalyst materials such as NiFeO_x . Commercial separators, on the other hand, have proven stability in caustic environments. However, new membrane designs (thinner, better conductivity) have not. He suggested that using a single cell, lab-scale (5 cm^2), zero-gap testing apparatus could be used for ASTs and bridge the gap between fundamental experiments and large-scale operation. Though he also suggested that degradation mechanisms should be studied in large-scale, commercial cells to ensure the degradation mechanisms at the lab-scale are consistent.

Some key known stressors for LA electrolyzers are temperature, electrolyte flow rates, and cell pressure, of which temperature is likely the greatest accelerator of degradation. Another important stressor to consider when developing ASTs is load profile, such as testing the flexibility and reactivity of electrolyzer systems. ASTs must adequately capture the impacts that may result during dynamic operation, high current, and shutdown. Dr. Mukundan noted AST protocols for LA electrolyzers could leverage the AST development work conducted for PEM electrolyzers. For PEM electrolyzers, for example, it has been identified that different dynamic operation waveforms have different catalyst degradation effects. In addition to these full cell tests, ex situ catalyst dissolution tests and ex situ membrane chemical and mechanical stability tests will help screen materials for full cells and elucidate degradation mechanisms.

2.6 Component & System Technoeconomic Analysis

Brian James leads the Energy Analysis Division of Strategic Analysis Inc. Strategic Analysis specializes in the technoeconomic analysis of emerging energy systems. Brian has led Design for Manufacturing and Assembly

(DFMA) costing efforts, technoeconomic analysis (TEA), and lifecycle analysis efforts in a variety of fuel cell, electrolysis, and hydrogen storage systems as well as batteries and numerous hydrogen production approaches. Mr. James has an MS in Aerospace Engineering, holds six US patents, and is a four-time DOE Hydrogen Program R&D awardee.

Mr. James gave a brief overview of the TEA methodology, and the opportunities for TEA to aid in the advancement of LA electrolyzers. TEA involves creating a system model, balancing the system, evaluating the capital costs, and finally evaluating the cost of H₂ production. The key to making a robust TEA is to have transparent and detailed model assumptions. Key considerations for a TEA of LA electrolyzers include:

- Cell design
- BOP system
- Efficiency targets and projections for future
- Economies of scale
- Economies of manufacturing rate
- Material costs

To conduct the TEA, extensive research was conducted to develop a baseline cell, stack, and system design for current and future LA electrolyzers. The cell designs considered were traditional and zero-gap cells. The two cell designs have different manufacturing costs, but also have tradeoffs in many other parameters such as costs of materials, efficiency, and lifetime. The BOP system is similar to that for PEM electrolyzers, so there is overlap in TEA model assumptions between those systems, though LA electrolyzers require a hydroxide electrolyte circulation loop. Mr. James presented preliminary results of a DFMA analysis, estimating the cost of a 5-MW stack manufactured at a rate of 500 MW/yr, is ~\$300/kW, with the largest stack cost item being the bipolar plates. He anticipates that advanced LA electrolyzer designs could result in stack costs of ~\$70/kW in the future. Preliminary results also showed that the capital cost for 25-MW BOP equipment could be ~\$180/kW, with the electrical subsystem dominating the BOP cost.

There are several levers that can be explored to reach the Hydrogen Shot cost target of \$1/kg H₂. For one, increasing the current density while maintaining high efficiency, and also considering tradeoffs with stack lifetime and material costs, could reduce the effective capital cost. Advanced LA electrolyzers could also utilize simplified cell design to eliminate material cost. Trends in the TEA results also show that large stacks lead to lower costs, though this may be at odds with economies of scale in manufacturing. For example, deploying higher MW systems requires fewer manufactured units. Similarly, the BOP can be sized to accommodate several stacks, though the cost reduction potential of modularizing the BOP can be difficult to reliably quantify. As a result, future analysis could help determine optimal stack and BOP sizes.

The material costs are perhaps the most difficult to estimate given the uncertainty in next-generation electrolyzer designs. Advanced catalyst and separator materials will provide better efficiencies, but perhaps shorter lifetimes and higher costs. Newer materials are also harder to cost model because of the lack of manufacturing information. The costs of the other cell components, as well as the coating method used to deposit the catalyst on the bipolar plates, must also be considered.

Understanding how LA electrolyzers will be operated in the future (e.g., load profiles) could also help to refine the TEA model. For example, if LA electrolyzers are not able to achieve a high turndown ratio for intermittent operation, that could impact the market share, manufacturing rates, and ultimately the cost of LA electrolyzers.

3 Parallel Discussions

On the second day of the experts meeting, attendees participated in 2 of 10 breakout sessions on various topics related to LA electrolysis.

Table 2 shows the breakout session topics as well as each moderator and scribe for that session. Breakout sessions were 1.5 hours long and involved participants using MURAL boards⁸ (digital whiteboards) to consolidate ideas around a central topic. Prior to the session, moderators and scribes prepopulated the boards with more specific questions related to the topic that would be addressed by attendees. The following sections report on the findings from each breakout session.

Table 2. List of breakout session topics and their associated moderators and scribes.

Round 1		
Session Title	Moderator	Scribe
Fundamental Degradation Mechanisms	Rangachary Mukundan, LANL	Elliot Padgett, NREL
Characterization & Diagnostic Needs	Debbie Myers, ANL	Haoran Yu, ORNL
Performance Targets & Status	James Vickers, HFTO	Tobias Schuler, NREL
Manufacturing	Alexey Serov, ORNL	McKenzie Hubert & Colin Gore, HFTO
Cell Integration	Plamen Atanassov, UC Irvine	Julie Fornaciari, LBL

Round 2		
Session Title	Moderator	Scribe
Technoeconomic & System Analysis	Mark Ruth, NREL	Anne Marie Esposito, HFTO
Separator Materials	Marcelo Carmo, Nel Hydrogen, US	Sandipkumar Maurya, LANL
Catalysts & Dimensionally Stable Anodes	Shaun Alia, NREL	Ahmed Farghaly, ANL
Porous Transport Layers	Guido Bender, NREL	Jason Keonhag Lee, LBL
Stack & System	Eric Miller, HFTO	Andrew Tricker, LBL

⁸ <https://www.mural.co/>

3.1 Fundamental Degradation Mechanisms

Traditional LA electrolyzer systems have excellent durability but operate at low current densities. Moreover, the degradation mechanisms operational in these systems are not well understood. Understanding the fundamental degradation mechanisms is key to ensuring the durability of next-generation electrolyzer designs and novel materials with enhanced performance.

3.1.1 Objectives, Attendance, and Structure

The objective of this break-out session was to identify the status of the durability of current state of the art liquid alkaline electrolyzer systems and to determine the research needs for the next generation of advanced liquid alkaline electrolyzers. There were 40 participants in this session with 15 participants identifying with the National Laboratories and Government including DOE, 10 were from Industry, and 5 from Universities. The companies represented included DeNora, AquaHydrex, Electrolytic Technologies System, 3M, Versogen, Kraton Polymers, and Hydrogen Optimized. Amongst the National Laboratories ANL, LBNL, LANL, NREL, ORNL, SLAC and SNL were represented. Academic participants were affiliated with Cornell University, Birmingham University, RPI and University of Oregon.

The breakout session involved discussions around 1) what components degraded, 2) how to quantify degradation rates, 3) how to accelerate the degradation mechanism to develop accelerated stress tests, 4) relevant mitigation strategies, 5) operating conditions that influence degradation rates and 6) R&D needs to be addressed related to degradation.

3.1.2 Current Understanding of Component Degradation

Traditional liquid alkaline systems have negligible durability issues but do not have high performance or significant load following capability. There is a pressing need to significantly enhance performance without compromising durability to approach the Hydrogen Shot cost targets. Fundamental understanding of degradation mechanisms of catalysts and separators is lacking. Correlation of durability with composition and morphology is also lacking for both separators and electrodes. Operational and design limitations of current materials are also not widely known. Finally, the durability of advanced electrolyzer materials, components, and designs is unknown. Several specific durability challenges were identified with respect to separators, catalysts/electrodes, balance of plant, and stack.

3.1.3 R&D Opportunities

In general, it was understood that durability targets must be met simultaneously with cost targets. Thus, advances in performance and materials costs must be done without compromising durability.

- Define requirements for intermittent operation: How much can traditional designs address this?
Develop advanced designs to follow renewable power sources
 - Develop stress tests reflective of intermittent operation and accelerate degradation modes to facilitate materials evaluation and discovery
- Improve fundamental understanding of degradation mechanisms (both chemical and mechanical) of catalysts, separator materials, and supporting electrolyte
 - Develop ex-situ chemical compatibility (screening) tests for materials
 - Define limits of materials stability in terms of temperature and chemical compatibility and have a database of materials meeting this viability (for separators, electrode materials, and BOP components)
 - Understand durability implications of advanced cell designs

- Understand impact of material stability on the electrolyte (e.g., impurities, corrosion productions), performance, and lifetime
- Understand degradation mechanisms of traditional designs (especially catalysts and separators)
 - Understanding the effect of stressors (dynamic operation, temperature, pressure) on materials durability
 - Develop characterization and modeling techniques to better understand durability and its relation to cost and performance

3.2 Characterization & Diagnostic Needs

Characterization and diagnostic tools are key to understanding the fundamental degradation mechanisms in LA electrolyzers. As multiple materials and interfaces between components exist in the electrolyzer cells, tools with the spatial and time resolution required to understand nanoscale to mesoscale phenomena occurring during cell operation need to be identified, developed, and implemented.

3.2.1 Objectives, Attendance, and Structure

The objective of this discussion was to identify challenges with LA electrolyzers and to determine the R&D opportunities for developing characterization and diagnostic tools that will provide the cell and material-level information to enable reaching the \$1/kg H₂ target. There were 14 participants with a range of backgrounds and experiences: 7 from national labs, 3 from academia, 2 from industry, and 2 from government. The companies represented in this breakout session were De Nora and Hydrogen Optimized. Discussion was structured by key components of LA electrolyzer cell and aspects of performance. Current status and knowledge gaps were identified for each component. This was followed by discussions on how characterization and diagnostic techniques are to be developed, augmented, and implemented, and what DOE can do to assist. Participants were asked to comment on the status of existing characterization and diagnostic tools, challenges with LA electrolyzers, and R&D opportunities for addressing challenges including the development of innovative characterization and diagnostic tools.

3.2.2 Current Diagnostic Methods

At the LA electrolyzer cell level, polarization curves are commonly used for determining the cell performance. Electrochemical impedance spectroscopy (EIS), which are usually used for PEM fuel cells, has not been extensively used for LA electrolyzers. For materials and components development, rotating disk electrode (RDE) testing is used for catalyst development and traditional ex-situ characterizations techniques such as scanning electron microscopy (SEM) and nitrogen physical adsorption are used for catalysts and other components to understand morphology and surface area. For characterization of interfaces between components, ex-situ conductivity measurements have been performed for separator/electrolyte interfaces. Catalyst/substrate interfaces have been characterized using four-point conductivity measurement or EIS. Furthermore, properties of the electrolyte, such as temperature, viscosity and surface tension, are being monitored.

Discussion also covered existing techniques utilized for other electrochemical systems (e.g., PEM fuel cells and water electrolyzers). At the cell and component level, these techniques include polarization curves and EIS using reference electrodes, segmented cells, small active area differential cells, effluent analysis, and spectroscopy. Material characterization techniques include: RDE, SEM, transmission electron microscopy (TEM), X-ray photoelectron spectroscopy, X-ray absorption spectroscopy, X-ray diffraction, X-ray scattering, mercury intrusion porosimetry, cryo-TEM, and identical-location TEM. Additional ex-situ techniques include measuring the electronic conductivity and ionic conductivity of materials and layers using four-point probe and EIS methods.

3.2.3 Challenges & Diagnostic Needs to Improve Understanding

There are several challenges limiting LA electrolyzer system efficiency and operation, and subsequently affect system complexity and cost, that could be addressed if additional characterization and diagnostic tools were identified. These challenges are associated with rapid transitions between low and high current densities (e.g., as occurs during intermittent operation) causing degradation of interfaces between components (i.e., catalyst/substrate, catalyst/electrolyte, and separator/electrolyte); blockage of active sites by oxygen and hydrogen bubbles; and hydrogen and oxygen crossover through the separator. Characterization and diagnostic techniques should be developed to understand, at the nano- and micro-scales, the factors influencing bubble formation and the impact of bubble formation in the catalyst layer and in the PTL, the impact of transitions between high and low current and intermittent operation on the durability of materials and interfaces, and the rates, mechanisms, and impact of product crossover.

3.2.4 R&D Opportunities

- Reference electrodes for diagnosing sources of efficiency losses in single cells (i.e., component-level voltage breakdown).
- Segmented or sub-scale cells to understand spatial distribution of current, overpotentials, pressure gradients, and bubble formation.
- Methods such as liquid cell electron microscopy and optical microscopy with high-speed cameras to visualize bubble formation.
- Techniques to characterize interfaces, either ex-situ or, ideally, operando. If ex-situ, methods for characterization and sample preparation that will not damage or alter the interfaces.
- On-line analysis of degradation products of catalysts and other cell components in the cell effluent using time-resolved techniques, such as NDIR and ICP-MS.
- Techniques for operando material, component, and interface characterization from atomic scale to millimeter scale during intermittent operation and during fast transitions between high and low currents (including imaging of porosity evolution).

3.3 Performance Targets & Status

3.3.1 Objectives, Attendance, and Structure

The scope of this session focused on obtaining feedback on performance and target status of liquid alkaline electrolysis stacks and systems. There were a total of 21 participants with a wide spectrum of experiences including 6 from 3 different national labs, 12 from 7 different companies and 1 from academia. Companies represented include Dioxide Materials, Teledyne, AquaHydrex, De Nora, Hydrogen Optimized, Giner Inc., and Fortescue Future Industries.

The objective of discussion was to review and propose technical stack and system 2022 status and 2026 and ultimate targets with experts and industrial contributors. The draft technical targets table (

Table 3) was presented for comment and served to direct discussion. All characteristics and metrics in the table were covered as well as feedback on other characteristics to include. Other concerns or items missing were also recorded.

Table 3. Draft stack and system technical targets for LA electrolyzers.

Stack				
Characteristic	Units	2022 Status	2026 Targets	Ultimate Targets
Performance		0.5 A/cm ² @ 1.9 V/cell	1.0 A/cm ² @ 1.8 V/cell	2.0 A/cm ² at 1.7 V/cell
Energy Efficiency	kWh/kg H ₂ (% LHV)	50 (66)	48 (70)	45 (74)
Lifetime	Operation hr	60,000	80,000	100,000
Average Degradation Rate	mV/khr (%/1000 hr)	3.2 (0.167)	2.25 (0.125)	1.6 (0.1)
Capital Cost	\$/kW	250	100	50
Operating Pressure	bara	1	30	30

System				
Characteristic	Units	2022 Status	2026 Targets	Ultimate Targets
Energy Efficiency	kWh/kg H ₂ (% LHV)	55 (61)	52 (64)	48 (70)
Lifetime	Operation hr	60,000	80,000	100,000
Uninstalled Capital Cost	\$/kW	500	250	100
H ₂ Production Cost	\$/kg H ₂	5.00	2.00	1.00
Turndown Ratio	%	85	90	95

3.3.2 Feedback of Proposed Targets

Overall, the characteristics and metrics in the draft technical targets table were deemed to be well defined and in line with what participants believe need to be targeted. Feedback on several of the characteristics was provided which ultimately could lead to modifications to the above table. For example, an intermediate (2026) target on the order of 10 bar for operating pressure was suggested as being more realistic. Also, the system efficiency metrics were thought to be potentially over aggressive. Defining efficiency on an HHV basis instead of LHV was discussed, though this approach would result in inconsistency with definitions in other parts of HFTO's portfolio (e.g., fuel cell efficiency is based on LHV). Defining efficiency on a kWh/kg H₂ basis is less ambiguous. Also, the participants suggested that the stack and system lifetimes should be different; the system lifetime should be related to an installation's lifetime (e.g., 20 year) and the stack lifetime should be based on the number of stack replacements required.

It is also important to include a characteristic related to the ability of next-generation alkaline systems to operate on intermittent renewables. Turndown ratio was thought to be not the correct characteristic or would need to be used in conjunction with another characteristic to better define dynamic operation needs. The participants suggested that a parameter along the lines of 'time to go from 100% to 10% in x sec' would be better.

3.3.3 Challenges of Setting Technical Targets

Several challenges related to setting technical targets were identified. The idea that these targets are just one of many sets of parameters that can get to \$2/kg and \$1/kg H₂ was brought up repeatedly and that this should be made clear with future technical target tables. Also, a deeper understanding of cell, stack, and system-level cost drivers and interactions would provide further insight for target setting. Setting cell and component level targets (e.g., separator area specific resistance) would be useful for the research community as well. As a

starting point it was suggested that cell-level performance targets should be very similar to the stack-level targets.

3.3.4 R&D Opportunities

- A primary purpose of these targets is to help guide R&D efforts. However, this needs to be balanced by realizing that multiple sets of parameters can result in meeting the hydrogen production cost targets.
- When comparing current technology status with the targets for next-generation technology, performance and, hence, efficiency need to be significantly improved and cost will need to be further reduced even with improved performance.
- The impact of improving performance (e.g., higher current density) and reducing cost on lifetime is unknown and is an important consideration.
- It is important to include characteristic(s) relevant to dynamic operation to drive development of stacks and systems that can operate on intermittent renewable energy sources.

3.4 Manufacturing

Low-cost and high-throughput manufacturing of LA electrolyzer components, especially for advanced systems, is key to achieve a target of \$1/kg of H₂. Scaling-up manufacturing of newly developed advanced materials will require either adjustment of currently used technological processes or the design and implementation of new processes. While optimizing performance is a key design parameter for advanced materials, other considerations such as manufacturing scalability, end-of-life recovery, and use of environmentally friendly processing methods are also critical in achieving cost-effective and clean electrolysis.

3.4.1 Objectives, Attendance, and Structure

The main objective of this breakout session was to identify manufacturing challenges and R&D opportunities for new, advanced LA electrolyzer components: catalysts, separators, porous transport layers, and electrodes. This session consisted of 16 participants with a broad range of backgrounds, including in catalyst development, membrane/separator development, electrode fabrication, and electrolyzer stack and system production. The participants represented a range of institutions, including national labs (4), component and electrolyzer OEMs (7), and government (3). Representatives from De Nora, Versogen, Strategic Analysis, and DOE were participants in the discussion.

To begin the session, each participant was encouraged to briefly introduce themselves to the group. Then the moderator facilitated the discussion based on individual components: catalysts, separators, porous transport layers, and electrodes. There was also discussion of topics related to designing materials for performance and manufacturability. For each discussion topic, participants were asked to comment on the status, challenges, and R&D opportunities either verbally or with written comments on the MURAL board.

3.4.2 Status of Manufacturing LA Electrolyzer Components and Systems

There was consensus among participants that a majority of the R&D and manufacturing of LA electrolyzer components is concentrated abroad and there is neither much manufacturing nor R&D activity in the US. Notable exceptions are catalyst and alkaline exchange membrane production and R&D. Components are not standard across electrolyzer designs from different OEMs, resulting in custom-made products to meet requirements of individual electrolyzer OEMs. Electrolyzer OEMs indicated that electrode manufacturing is a bottleneck in their stack development process, and requires significant R&D. Additionally, OEMs suggested that there is some consideration for re-use and recycling during the design of materials and manufacturing processes, though it was unknown how deployed electrolyzer systems are managed at end-of-life.

3.4.3 Challenges

Novel components with enhanced performance for LA electrolyzers can be challenging to manufacture with a high degree of quality control and quality assurance. Some examples mentioned include the difficulty of controlling the homogeneity of a catalyst layer coated onto a substrate and/or controlling the thickness of thin separator materials. In addition, manufacturing different size components (e.g., cm vs. m length scales) can require different manufacturing processes, which subsequently introduce variability into product performance.

Adapting existing manufacturing facilities to accommodate novel material developments may also be a challenge. For example, it was noted that significant R&D is needed to develop thinner and more robust separators for improved performance even under high-pressure operation. As such new materials are developed at the lab-scale, a challenge is the time delay between development and their adoption at the commercial-scale with high-throughput and large-scale manufacturing processes. While modeling can aid in the design of materials for manufacturability, companies have limited computational resources. It was noted that for some processes, such as electrode production, changing out components, such as one catalyst for another, does not present large process changes, but does require process optimization.

A large challenge in achieving GW-scale manufacturing is the large capital investment required to establish new production facilities. In addition, upgrading existing facilities to accommodate novel materials, components, and designs may require costly modifications to existing equipment and processes. Deeper conversations with component and electrolyzer OEMs would be needed to identify pathways to a domestic supply chain in the US, and to better understand individual company's manufacturing needs.

3.4.4 R&D Opportunities

- Reduce the number of manufacturing steps in electrode production: Reducing the number of cell components and manufacturing steps can reduce overall capital costs.
- Explore the application of manufacturing techniques from other technologies: High-throughput manufacturing processes, such as roll-to-roll coating are widely used in the production of technologies such as fuel cells. Exploring the application of these techniques to LA electrolyzers could result in higher-throughput and reduced capital costs.
- Develop materials for performance and manufacturability: While most R&D efforts in the US have focused on catalyst development in the past, more R&D is needed to develop other components, such as separators and substrates.
- Understand structure/function relationships and the impact of manufacturing processes: Because manufacturing processes are modified during the scale-up of novel materials in size or throughput, a better understanding of how manufacturing processes impact the material structure and how that structure impacts the performance of the material is needed to maintain high efficiency of the novel material.
- Establish a materials pipeline from lab- to commercial-scale: A pipeline from lab-scale research to high-throughput and large-scale manufacturing processes is needed, for example, to scale-up existing novel catalyst compositions and structures.
- Increase modeling efforts: Modeling the separator structure, metal substrates, and their configuration in the cell using computational fluid dynamics could accelerate improvements in both performance and manufacturability.

3.5 Cell Integration

Cell integration for LA electrolyzers is a key component in scale-up and durability of these systems. Understanding how different components of LA electrolyzers can contribute to overpotential losses is key to

increasing the lifetime of the stack. Electrodes, architectures, separators, and other components can be studied to better understand their influence on cell performance.

3.5.1 Objectives, Attendance, and Structure

Within the breakout session discussion, the aim was to understand the status of LA electrolyzers, the important challenges to the current technology, and R&D opportunities that the DOE could capitalize on. Specifically, the R&D opportunities show there is more to be studied and understood within these systems. Within this breakout room, there were 16 participants with a range of backgrounds: national labs (4), academia (6), industry (6), and government (1). De Nora provided a lot of experience-based context on the current status of LA electrolyzers, and Versogen and Giner Inc. gave insights as to the critical challenges, barriers, and pitfalls of the current technology and research efforts directed to overcome those. All participants were asked to comment on the status of these devices, the challenges, and the R&D opportunities. In general, participation from industry was most prevalent in this session.

3.5.2 Current Status & Challenges

The current status of LA electrolyzers and specifically the cell integration included a discussion on the typical architectures of the systems, which include both 2D- and 3D-electrode designs. The most widely commercialized cell to date is the 2D-electrode design that uses a mesh for the electrode and a porous separator. It was noted that this cell type is exemplified by De Nora products and has been implemented in several of the company's products. One challenge within this design includes catalyst integration into the structurally supporting mesh in a way that maintains high surface area and porosity of the catalyst layer and minimal catalyst loss during operation. Most of the catalyst layer characteristics were described to be strongly affected by the processing/sintering techniques used when integrating the catalyst with the mesh. Additionally, the laboratory scale is not always representative of the scaled-up system due to the fabrication processes employed and the sizes of the materials used. The geometric size of the cells assembled with 2D-electrode designs is close to or above 1 m² and is entirely based on stainless-steel or corrosion-protected steel frame. As a result, the issues of integration are mostly related to welding and corrosion protection of the metal frame. There are less issues related to pressure handling and these 2D-electrode cells are operated as “gap cells” with minimal pressure drop or gravitational outgassing of the gaseous products.

The 3D-electrode design is considered to be more advanced and less-mature than the 2D-electrode design, and has more interfaces to take into consideration. Usually the 3D-electrode design uses an integrated electrode with a “zero-gap” between the electrode and the separator. The quality of the microporous separator was discussed as part of cell integration concerns. Also, the integration strategies for the separator will be different when the system is at scale. Catalyst integration, however, is the main challenge here as well. In the case of 3D-electrode architectures, the critical issue is finding an appropriate binder for the catalyst layer or forming the catalyst layer as an integrated component of the PTL. It is critical that catalyst integration and binding not lead to catalyst loss or change the catalyst or electrode structure during operation. The challenges with cell integration for the electrodes are different for the 2D- and 3D-electrode designs. From the discussion, there is yet to be a clear predominant technology and both should be explored.

Additional challenges include how components change under cell operation, how the components are altered under compression, and how bubble formation occurs and impacts performance with different materials. As discussed by participants from academia and industry, component properties can change from ex-situ analysis to in-situ testing. Integration has a large influence on component properties, and compression could be one parameter that is currently underexplored. It was clear from the discussion that there is a need for a variety of diagnostic tools to better understand the discrepancies observed with cell components before and after integration. Development of operando techniques for cell diagnostics appeared to be desired by all participants in the discussion. In summary, there are many unanswered questions related to how cell integration impacts performance, and there are plenty of research opportunities to explore.

3.5.3 R&D Opportunities

- Need of advanced diagnostics to determine the main causes for overpotentials at laboratory, at pilot, and at full-size deployment scales;
 - EIS, CV, special cycling protocols (to be developed);
 - In situ x-ray techniques, or acoustic techniques;
 - Operando X-ray computed tomography or neutron imaging techniques.
- Introduce in situ, operando tests to better identify where the failures of LA electrolyzers take place
- Introduce standardized test cells for the two predominant product definitions: 2D-electrode and 3D-electrode designs of appropriate size (at least 100 cm²)
- Determine how different configurations and components can lead to failure and understand the different failure modes
- Develop in-depth multi-physics models to better understand transient processes and specifically the new phase (bubble) formation, development of mechanical stresses, etc.
- Develop segmented cells to study spatially distributed effects at sizes and scales that are relevant (at least 100 cm² and desirably larger with segments addressing zoning issues).
- Need to systematically determine the impact of separators on overpotential of the cell.

3.6 Technoeconomic and System Analysis

Technoeconomic analysis is important to understand potential cost reductions, prioritize R&D opportunities, and identify market readiness for technologies. Specifically, it can be used to identify and quantify drivers of hydrogen levelized cost.

3.6.1 Objectives, Attendance, and Structure

The overall goal of this session was to identify TEA priorities for near-term (1-5 yr) and long-term (6-10 yr) time frames. Participants initially identified TEA needs and then voted to prioritize them.

Participants focused on 4 key questions:

- What are the most impactful drivers to achieve \$1/kg H₂? What analysis capabilities do we need to achieve these drivers?
- What are the key analysis and modeling uncertainties we should address?
- Which economies of scale will or will not be available through development of multiple technologies?
- What design advancements should be considered in technoeconomic analysis?

From the above questions, the group distilled the answers into analysis priorities for the short and long term (1-5 years and 6-10 years). Participating in this session were 6 people from industry, 5 people from government, and 3 people from national labs. NREL, LANL, HFTO, AquaHydrex, GTA, Teledyne Energy Systems, and Hydrogen Optimized were represented.

3.6.2 Status of TEA Models

The Component & System Technoeconomic Analysis presentation from Brian James (Strategic Analysis, Inc.) adequately described the status of TEA and DFMA studies for LA electrolysis (see Section 2.6). With that

briefing, along with individual prior knowledge, the participants were equipped to dive into discussions of challenges and research opportunities. Further details on current status were not solicited from the participants.

3.6.3 Summary of TEA Needs and Recommendations

The main role of TEA in context of this workshop was to identify and model the cost drivers for hydrogen production. This breakout session group identified several uncertainties in parameters that result in uncertainty in LA electrolyzer and hydrogen cost estimates, as well as recommended important parameters for further investigation that could provide a pathway for cost reduction.

The first recommendation was to improve analysis of electricity prices. Low electricity costs ($<2\text{¢/kWh}$) are necessary to get to $\$1/\text{kg H}_2$. Future analysis should consider the impact of increased electrolyzer deployment on electricity prices. Looking to the future, the cost trends of renewable electricity will be important and is likely to change the marginal cost of electricity. Thus, electricity market structures may change and the potential for dynamic operations is likely to be affected.

The second recommendation was to improve capital cost (CAPEX) estimates considering the differences between future and current electrolyzer designs. Advanced designs may improve stack current density, reduce the electrolyzer footprint, or remove components. The advanced designs will likely determine membrane selection (and be limited by membrane technology). Membranes are an expensive component of LA electrolyzers and the costs are not well known. More advanced designs may lead to decreases in electrolyzer lifetime, which also needs to be considered. The stack size will also affect the CAPEX, considering both the cost of the stack itself as well as the footprint of those stacks at the desired deployment size. Recyclability of components will also decrease CAPEX costs over time.

Economies of scale will almost certainly decrease the costs of electrolyzer deployment and therefore hydrogen production. Identification of the BOP technologies that overlap with other electrolyzer technologies may accelerate the pace at which economies of scale are achieved for those components. Stack size is also an important consideration; larger stack sizes will require fewer units and thus economies of scale gained by larger units may be offset by reduced manufacturing economies of scale.

Operating costs are likely to be impacted by operating temperature and pressure which will result in tradeoffs between stack size, efficiency, BOP costs, and lifetime. Decreased lifetime relates to decreased durability and more frequent replacement. Dynamic operation will also likely have an effect on durability and lifetime. Tradeoffs between cost, performance and durability need further exploration and are further complicated by considerations involving different system designs and operating strategies.

Determining the cost of electrolyzers will involve selecting the right size for the application. Considerations include everything discussed above as well as any limitations on size due to power electronics as well as the footprint of the proposed system. Policies are another large unknown that will drive electrolyzer costs, electricity costs, and the market size.

3.6.4 Prioritized R&D Opportunities

Participants developed near-term (1-5 yr) and long-term (6-10 yr) priorities by voting. The priorities for each timeframe follow; ranked by number of votes:

Near-term (1-5 yr):

1. Incorporate electrolysis within electricity grid models (planning & operations)
2. Conduct supply chain analyses (materials, processed materials, recyclability)
3. Develop a LA electrolyzer system performance model

4. Quantify deployment tradeoffs (direct connection to variable renewable electricity generation vs grid connection – system sizing tradeoffs)
5. Continue refining DFMA analysis

Long-term (6-10 yr):

1. Model integrated hydrogen and electricity markets
2. Assess feasibility of coupling with offshore wind

3.7 Separator Materials

Separator materials based on inorganic oxides (such as ZrO_2) supported by a polymer/metal matrix have been used in traditional alkaline electrolyzers since the middle of the last century. These materials are robust and present very high durability in hot caustic KOH electrolytes but are responsible for high ohmic resistances inside LA electrolyzers. Employing some of the latest R&D from materials science with a focus on nanostructures and polymer chemistry shall open the door for the more efficient separators for LA electrolyzers.

3.7.1 Objectives, Attendance, and Structure

One objective for the breakout session was to identify separators which are commercially available and that could be defined as reference materials. The purpose was to discuss the limitations of these commercially available separators by listing their important properties in order to understand what could be defined as an optimal separator. Other objectives were to list possible fabrication limitations, and to discuss how recent developments in alkaline exchange membrane electrolyzers may be transferrable to LA electrolyzer technology. Additionally, an objective was to determine which activities could be defined so that the typical ohmic resistances of separators could be reduced, and positively impact the cost of the produced hydrogen.

There were 20 participants with a range of backgrounds and experiences, including 10 from national labs, 4 from academia, and 5 from industry. Companies represented in the session included Nel Hydrogen, Hydrogen Optimized, Giner Inc., Fortescue Future Industries, and 3M. The discussion was structured into 8 main topics, and ~10-20 minutes time was dedicated to each. The topics were defined based on objectives previously specified, and information was organized using the MURAL board. Participants were asked to comment on the status, challenges, and R&D opportunities, and add their comments directly to the MURAL board.

3.7.2 Status

Zirconium oxide supported in a polysulfone matrix is the baseline separator, which is also commercially available. There was no clear understanding on how many companies today can fabricate and sell these separators, but particular attention was given to the company AGFA. Other materials that could serve as reference were listed. The other polymer materials such as Ryton®, Porous Celgard®, polysulfone, and expanded porous PTFE were also listed as possible references, since these are porous, with substantial liquid KOH uptake, and should be stable in hot high concentrated KOH. Advanced ion solvating membranes were also mentioned, such as polybenzimidazole (PBI), PiperION®, Ionomr®, Sustainion®, etc. However, there was clear consensus in the group that these membranes are not stable in hot high concentrated KOH and should only be seen as possible R&D opportunities but not as reference materials for commercial LA electrolyzers.

3.7.3 Challenges

Chemical and mechanical stability, as well as gas permeation, were listed as the main challenges. There is a gap in fundamental understanding how inorganic and organic components and materials used to fabricate separators degrade in LA electrolyzers. It is unclear how any difference in KOH concentration, dissolved H_2 and O_2 gases, and separator swelling impact the durability of both polymer matrix and inorganic materials, but

is needed so that less pin hole formation in separators can be achieved. The challenge of creating thinner separators with lower resistances, while at the same time not compromising long-term durability and low gas crossover, was also discussed.

The group discussed the gap in the understanding of the porous structure inside the separator and how it should behave to provide high hydroxide ion (OH^-) transport and low gas crossover. Other points related to mechanical stability were also listed as important challenges, such as creep under pressure, electrode/PTL compression over the separator, dynamic pressure behavior (anode vs. cathode), and the lack of mechanical degradation test protocols. Related to the challenge of gas permeation, points such as how zero-gap configuration can influence the gas crossover, zero-gap vs. finite gap comparison, gas permeation as a function of KOH concentration and concentration gradients, permeability vs. permeation rate, and permeation as a function of operation conditions (dynamic power input) were also discussed.

3.7.4 Prioritized R&D Opportunities

Near-term (1-5 yr)

1. Fundamental understanding of the role and durability of separator components
2. Better understanding of wettability, porosity, and ion/gas transport in catalyst layers and the catalyst layer-separator interface
3. Interfacial understanding of resistances and corrosion mechanisms
4. Molecular modeling to understand and inform design of materials and interactions
5. Multiscale, multiphysics modeling for examining tradeoffs and operating and material space and determining property targets
6. Mechanical properties and their dynamic evolution
7. Impact of operating parameters on membrane properties

Long-term (6-10 yr)

1. Hierarchical design of chemical and/or physical spaces within separators, and the control of interfaces
2. Creation of internal and external composite (inorganic/polymer) structures
3. Deep understanding of durability mechanisms and tradeoffs with other components (electrodes)
4. Judicious use of fixed charges in the separator chemical structure to increase OH^- transport (functionalization)
5. Development of advanced backbone/mesh support to allow thinner separators, or its complete elimination by using robust and durable ion solvating membranes.

3.8 Catalysts & DSAs

Understanding state-of-the-art catalysts and their limitations is critical to developing new materials that address the performance and durability limitations of LA electrolyzers. Developing novel material classes can provide opportunities for improved performance and durability in alkaline electrolysis, and enable cost reductions that reach the \$1/kg target.

3.8.1 Objectives, Attendance, and Structure

The objective of this discussion was to identify current state-of-the-art catalysts in the hydrogen and oxygen evolution reactions, and their limitations. There were 28 total participants (25 active on the MURAL board) with a range of backgrounds and experiences: 3 were from DOE, 6 were from industry (Synata Bio, Hydrogen Optimized, NEL, AquaHydrex, De Nora, Evonik), 5 were from academia (Colorado School of Mines, Binghamton, Oregon, Cornell, UC Irvine), and 11 were from national labs (NREL, LANL, ANL, ORNL, SLAC).

Participants were asked to comment on current state-of-the-art catalysts, their limitations, novel material classes, lab-scale targets, and concerns specific to the scaling of nickel. Participants were further asked how DOE can help address catalysts and dimensionally stable electrode issues.

3.8.2 Status and Challenges

Discussions on current state-of-the-art materials were separated into those for the oxygen and hydrogen evolution reactions. Oxygen evolution catalysts include nickel and nickel-iron-based materials (ruthenium and iridium oxides as platinum group metal (PGM) options). Limitations to these non-precious metal catalysts include: their eventual dissolution and migration; their susceptibility to redox transitions, passivation, and the loss of electronic conductivity; the instability of multiphase elements; and performance losses with limited understanding of degradation mechanisms. Hydrogen evolution catalysts include nickel-based materials (platinum as the PGM option). Limitations to these catalysts include poisoning for electrolyte impurities, and interfacial, adhesion, and delamination issues.

3.8.3 Promising New Material Classes

In oxygen evolution catalysts, nanoporous/nanostructured materials, nitrides, and multi-metal oxides were discussed, including perovskites, metal organic frameworks, and specific elements (nickel-, iron-, cobalt-derived materials). In hydrogen evolution catalysts, sulfides and multi-metal materials were discussed (nickel-, iron-, cobalt-derived materials).

3.8.4 R&D Opportunities

- Lab-scale targets and protocol development was discussed as the highest priority
 - Test protocols (half- and single-cell, performance/durability/surface area quantification) and standardized operating conditions
 - Performance/durability metrics and targets for pure water operation and concentrated KOH
- Catalyst development that focuses on activity, utilization, and durability
- Long-term durability of gap/zero-gap cells with intermittent and steady state operation to evaluate the impact of renewable inputs and to develop accelerated stress tests
- Assessments of catalyst durability under higher temperature and pressure, including quantification of dissolution rates and mechanistic understanding of dissolution or other degradation mechanisms

3.9 Porous Transport Layers

The PTL is a key component in LA electrolyzers that has the potential to improve efficiency by reducing contact and mass transport in the system. The expression PTL is used for a range of component variations. It spans from a metallic structure that conducts current and supports or interfaces with the catalyst to an engineered complex 3D structure that facilitates mass transport and electron transport.

3.9.1 Objectives, Attendance, and Structure

The objectives of this session were to:

- Identify the role and current state-of-the-art PTL and discuss if the term “porous transport layer” is valid for LA electrolyzers.
- Discuss pathways to increase state-of-the-art current densities to 1 A/cm².
- Determine the research needs to advance PTL materials

There were 3 participants from industry (De Nora and Dioxide Materials), 5 participants from national labs and 1 participant from academia. Industry participants had experience directly related to LA electrolyzers, while the background and experience of all other participants was more focused on electrochemical cells that utilized solid polymer electrolyte membrane materials.

At the beginning of the session all participants were asked to introduce themselves and state their name and affiliation. Subsequently a series of questions previously posted on a MURAL board were discussed. The questions were divided in three categories: (i) “What we know (Current status),” (ii) “What are the goals, technical targets, and metrics?” and (iii) “What we don’t know and what we need to know (R&D priorities in 1-5 years and 6-10 years)”. The questions were color-coded and the group was encouraged to place comments and notes in any of the respective sections during the discussion. Additional areas on the MURAL board such as “Missing Questions” and “How can DOE help?” gave opportunities for any other thoughts or comments.

3.9.2 Status

The functionality of the current PTL for LA electrolyzers can vary significantly and depends on the architecture of the cell. The most common functionality is the conduction of current from the power source to the reaction sites. Additional functionalities may be the support of the catalyst material, the catalysis of the reaction, and/or the electrical contact to a self-standing electrode. The PTL is one essential component in creating a zero-gap configuration that significantly reduces ohmic cell overpotentials. For a conventional LA electrolyzer, the PTL is used as a substrate that is similar to a porous transport electrode in PEM electrolyzers. For a zero-gap configuration, the PTL is used as a backing layer that interplays gas transport, liquid transport, electron transport, and mechanical support. One current metric of the PTL is to support current state-of-the-art performances of 1 A/cm² at 1.8-1.9 V.

3.9.3 Challenges & R&D Opportunities

One future demand on the PTLs is to support ≥ 2 A/cm² at voltage ranges of 1.8 – 1.9 V, i.e. double the current density that is currently state-of-the-art in industry. Various pathways to move towards this target were discussed. The approaches are dependent on the cell architecture, but may include increased PTL surface area to increase catalytic activity, novel catalyst support and zero-gap strategies, as well as novel concepts that allow forced convection or other solutions for effective bubble detachment and removal. Such new components would need to be manufactured without cost increases, which was of big concern, while maintaining some critical properties such as, for example, weldability. The concept of combining PTLs with catalyst layers in zero-gap configurations is relatively new in the field, and therefore requires pioneering designs and research on different configurations. The durability of the PTLs and their various PTL/catalyst coatings/catalyst layer combinations was a big unknown and needs to be studied under the expected operating scenarios, which include dynamic operation and start/stop processes. LA electrolyzers typically do not employ flow fields. The resulting lack of forced convection may cause performance penalties due to mass transport limitations. The PTL design may be key to facilitate gas removal and reactant intake and basic research in this area seems necessary to advance the technology.

Targets and R&D opportunities for PTLs are listed below by their potential impact on performance, durability, bubble management, and cost.

- Performance
 - Increase current density to at least 2 A/cm² without cell voltage penalty (1.8-1.9 V)

- Improve current PTL designs
- Develop advanced high current design with novel cell architecture that deviates from the current cell designs.
- Investigation on fabrication methods to vary structure of the PTL
- Analyze different cell architectures: conventional design vs catalyst coated diaphragm + PTL
- Durability
 - Quantify durability of PTL, PTL coatings and/or PTL/catalyst interface on variable operational stresses
 - Development of coatings to improve performance and durability
- Gas evolution & bubbles
 - Understand bubble detachment and removal from catalyst layer and PTL
 - Investigation of gas evolution under extreme conditions such as high pressure and high temperature
- Economic & Cost
 - Cost economic analysis to set operating conditions
 - Develop cost and performance targets for individual components in LA water electrolyzers.
 - Low cost processing to increase surface area

3.10 Stacks & Systems

At research scales, electrolyzers are typically studied at the cell-level with just a single anode, cathode, and separator. Stacks consist of a certain number of cells stacked in series or parallel, a necessity to produce hydrogen at industrial scales. Systems include the stack and the peripheral processes necessary to manage the potassium hydroxide electrolyte and hydrogen generation and storage.

3.10.1 Objectives, Attendance, and Structure

The objectives of this breakout session were to:

- Identify the current industrial standards for stack and system operation and gaps in improving the economics for LA electrolyzers
- Discuss potential ways to overcome these gaps, with an emphasis on collaboration between industry and national labs.

There were 7 participants from industry (AquaHydrex, Electrolytic Technologies Systems, Power to Hydrogen, FFI, Teledyne) and 6 participants from national labs (including NREL, ANL, & LBNL), with additional participation from Federal government employees and contractors. Several industrial participants had direct experience with current alkaline electrolysis systems.

The MURAL board was laid out in a 3-by-7 grid with one column for each of the six discussion points: KOH management; BOP concerns in system design; dynamic operation/turndown capabilities/drive cycles; pressurized/high temperature operation; general operating parameters; and novel system designs. A seventh column was included for additional discussion points the participants wanted to bring up. The rows were

divided into “Status”, “Gaps”, and “Priorities”. Initially, the participants posted their thoughts and comments on the status and gaps in the different subject areas. Next, each of the topics was discussed as a group to determine the priorities.

3.10.2 Status

LA electrolyzers have been used relatively widely at industrial scale. Current systems operate at 48 – 55 kWh/kg with high KOH concentrations (~30%), moderately elevated temperatures (80-85 °C), and with the potential for elevated pressures up to 30 bar. The costs of manufacturing, assembly, and waste treatment dictate larger capacity systems at rated capacities of 10 MW or larger.

3.10.3 Challenges & R&D Opportunities

With the goal of improving the economics, the participants focused on standardization as a key challenge and priority for future development of stacks and systems. The development of standardized parts for the stack was identified as a high priority. Standardization would lower the costs of the individual stack components, improve supply chains to lower component costs, and decrease assembly costs for the stacks. Additional operational and control challenges were prioritized in areas such as shunt currents, separators and gas crossover, and dynamic response and load following. A key mode of collaboration between industry and the national labs was identified as the development of standardized testing and reporting for R&D of stacks. Here, national labs would build out drop-in testing capabilities for stacks between 100 kW and 1 MW and develop standard operating procedures, allowing industrial partners to test new materials/configurations/etc. and accurately compare results across different stacks. Such collaborative capacities would greatly facilitate research in developing new stack materials and components suitable for higher temperature and pressure operation (targeted for higher conversion efficiency), understanding stack durability under dynamic load, and optimizing stack architecture. A list of specific R&D opportunities is below.

- National Lab Capabilities
 - 100 kW up to 1 MW stack testing infrastructure for LA electrolyzers that is adaptable to stack configuration and cell size such that it has drop-in testing capabilities
 - Development of standardized testing procedures and reporting protocols
- Performance
 - Increased operational temperature range to 120-140 °C, which will require new materials and coating for separators, seals, pipes, and stack components in general
 - Innovation in power and control system architecture versus stack-level design to accommodate optimal current/voltage operations at lowest cost
 - Innovation in separator development that maintains performance and durability at reduced materials cost
- Durability
 - Understanding impacts of dynamic loads (intermittence of renewable energy) on stack performance and durability
 - Novel mitigation schemes to remove contaminants and impurities (e.g. KOH scrubbing, sacrificial electrodes and other approaches) that most adversely impact stack lifetime
 - Better fundamental understanding of degradation mechanisms in general to facilitate development of the most cost-effective mitigation schemes

- Physical and operational solutions to avoid deleterious effects of shunt currents
- Economic & Cost
 - Automated manufacturing at the component and cell-levels, and automated assembly at the stack- and system-levels
 - Standardized sub-components for stack and balance of system to address supply chain issues
 - Material innovations providing cost-effective solutions to mitigating leaks and stack contamination
 - Novel approaches (such as membrane-less systems) with potential for cost reductions in next-generation systems

Appendix A. Workshop Agenda

A U.S. DOE Hydrogen Energy Earthshot Experts Meeting on...

Advanced Liquid Alkaline Water Electrolysis

*Bringing leading experts and the research community together
to discuss future R&D and manufacturing efforts*

**Sponsored by the DOE Hydrogen & Fuel Cell Technologies Office
and the National Renewable Energy Lab**

January 26-27, 2022

Virtual Meeting

Jan. 26 - Expert Presentations		Jan. 27 - Parallel Discussions	
11:00 AM	Welcome	11:00 AM	Break-out Discussion Logistics
11:30 AM	Presentations, Part I <ul style="list-style-type: none"> • Introduction • Interface & Corrosion Challenges • System & Integration Challenges 	11:15 AM	Parallel Discussions, Round 1 <ul style="list-style-type: none"> • Fundamental Degradation Mechanisms • Characterization & Diagnostic Needs • Performance Targets & Status • Manufacturing • Cell Integration
1:30 PM	Break	12:45 PM	Break
2:00 PM	Presentations, Part II <ul style="list-style-type: none"> • Cell-level Challenges • Accelerated Stress Tests • Technoeconomic Analysis 	1:15 PM	Report Out & Discussion
4:15 PM	Wrap-up & Adjourn	2:00PM	Parallel Discussions, Round 2 <ul style="list-style-type: none"> • Technoeconomic & System Analysis • Separator Materials • Catalysts & Dimensionally Stable Anodes • Porous Transport Layers • Stack & System
		3:30 PM	Break
		4:00 PM	Report Out & Discussion
		4:50 PM	Final Thoughts, Q&A, Adjourn

All times in Eastern Standard Time (EST) and subject to change

Jan. 26: Overview Presentations from Experts*(Q&A to follow each individual presentation)*

Welcome, Context, & Overview of Workshop Goals	
11:00 AM	Speakers: TBA, <i>DOE Hydrogen & Fuel Cell Technologies Office</i> Bryan Pivovar, <i>National Renewable Energy Laboratory</i>
11:30 AM	Introduction to Liquid Alkaline Electrolysis Speaker: Marcelo Carmo, <i>Nel Hydrogen US</i>
12:15 PM	Cell & Stack Components (Interfaces & Corrosion Challenges) Speaker: Ed Revers, <i>De Nora</i>
1:00 PM	System & Integration Challenges Speaker: Joe Poindexter, <i>Teledyne</i>
1:30 PM	Break
2:00 PM	Cell-level Challenges Speaker: Steven Kloos, <i>AquaHydrex</i>
2:45 PM	Accelerated Stress Test (AST) Development Speaker: Rangachary “Mukund” Mukundan, <i>Los Alamos National Laboratory</i>
3:30 PM	Component & System Technoeconomic Analysis Speaker: Brian James, <i>Strategic Analysis</i>
4:15 PM	Wrap-up and Adjourn

All times in Eastern Standard Time (EST) and subject to change

Jan. 27: Parallel Break-out Discussions*(Report out sessions after each round)***Round 1**

Session Title	<i>Moderator</i>	<i>Scribe</i>
Fundamental Degradation Mechanisms	<i>Rangachary Mukundan</i>	<i>Elliot Padgett</i>
Characterization & Diagnostic Needs	<i>Debbie Myers</i>	<i>Haoran Yu</i>
Performance Targets & Status	<i>James Vickers</i>	<i>Tobias Schuler</i>
Manufacturing	<i>Alexey Serov</i>	<i>Colin Gore, McKenzie Hubert</i>
Cell Integration	<i>Plamen Atanassov</i>	<i>Julie Fornaciari</i>

Round 2

Session Title	<i>Moderator</i>	<i>Scribe</i>
Technoeconomic & System Analysis	<i>Mark Ruth</i>	<i>Anne Marie Esposito</i>
Separator Materials	<i>Marcelo Carmo</i>	<i>Sandipkumar Maurya</i>
Catalysts & Dimensionally Stable Anodes	<i>Shaun Alia</i>	<i>Ahmed Farghaly</i>
Porous Transport Layers	<i>Guido Bender</i>	<i>Jason Keonhag Lee</i>
Stack & System	<i>Eric Miller</i>	<i>Andrew Tricker</i>

Appendix B. List of Participant Affiliations

3M	DOE Advanced Manufacturing Office	Pennsylvania State University
Advent Technologies		pH Matter
Argonne National Laboratory	DOE Hydrogen and Fuel Cell Technologies Office	Phillips 66
AquaHydrex	Hgen	Plug Power
Bekaert	Hydrogen Optimized	Power H2
Carnegie Mellon University	Idaho National Laboratory	Rensselaer Polytechnic Institute
Celadyne	Ionomr	San Diego State University
Colorado School of Mines	Kraton	Sandia National Laboratory
Columbia University	Los Alamos National Laboratory	Stanford University
Cornell University		State University of New York at Binghamton
Cummins	Lawrence Berkeley National Laboratory	
De Nora	Lubrizol Corporation	Strategic Analysis
Dioxide Materials	Michigan State University	Synata Bio
Electrolytic Technologies	Nel Hydrogen, US	Teledyne
Evok Innovations	New Mexico Institute of Mining and Technology	University of California, Irvine
EvolOH		University of Delaware
Evonik	New Mexico State University	University of Oregon
FFI Ionix	Next Hydrogen	University of Pennsylvania
FFI Ionix	Northwestern University	University of Southern California
Fortescue Future Industries	NREL	
Giner, Inc	ORNL	University of South Carolina
GTA, Inc	Pajarito Powder	Versogen

