U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

High Temperature Electrolysis Manufacturing Workshop

Summary Report

Hydrogen and Fuel Cell Technologies Office

U.S. Department of Energy

March 2022

(This page intentionally left blank)

Preface

Prepared by: U.S. Department of Energy/Office of Energy Efficiency and Renewable Energy/Hydrogen and Fuel Cell Technologies Office, with contributions from workshop moderators and scribes listed below.

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 workshop for their engagement in valuable discussion and for providing informative feedback.

Organizing Team: Ned Stetson, HFTO; David Peterson, HFTO; Anne Marie Esposito, HFTO; McKenzie Hubert, HFTO; Richard Boardman, INL; Olga A. Marina, PNNL; Jamie Holladay, PNNL; Will Gibbons, HFTO; Colin Gore, HFTO; Nikkia M. McDonald, HFTO

Logistics Support: Stacey Young, The Building People; Vanessa Arjona, HFTO

Expert Presenters: Olga A. Marina, PNNL; Brian James, Strategic Analysis; Poul Georg Moses, Topsoe; Venkat Venkataraman, Bloom Energy; Tony Leo, FuelCell Energy; Scott Swartz, Nexceris; Joe Hartvigsen, OxEon Energy; John Pietras, Saint-Gobain; Jens Suffner, Schott; Greg Tao, Chemtronergy; Todd Striker, Cummins

Moderators and Scribes: Harry Abernathy, NETL; Peter Rupnowski, NREL; Jamie Holladay, PNNL; Kerry Meinhardt, PNNL; Dong Ding, INL; Brandon Wood, LLNL; Micah Casteel, INL; Edgar Lara-Curzio, ORNL; Lorraine M. Seymour, PNNL; Long Q. Li, PNNL; Sarah Shulda, NREL; Jeremy Hartvigsen, INL; Christopher Coyle, PNNL; Cameron Priest, INL; Joel Berry, LLNL; Asha-Dee Celestine, HFTO; Fernando Dias, INL; Martha Welander, LBNL; Joshua Tenney, WVU; John T. Zaengle, PNNL; Joshua Gomez, INL; Nathanael T. Royer, PNNL; Lucun Wang, INL; Angela Macedo Andrade, HFTO

List of Acronyms

AST	Accelerated Stress Test
BOP	Balance Of Plant
DFMA	Design for Manufacturing and Assembly
DOE	U.S. Department of Energy
EERE	Energy Efficiency and Renewable Energy
HFTO	Hydrogen and Fuel Cell Technologies Office
HLC	Levelized Cost of Hydrogen
HTE	High Temperature Electrolysis
H2NEW	Hydrogen from Next-generation Electrolyzers of Water
INL	Idaho National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
P-SOEC	Proton-conducting Solid Oxide Electrolysis Cell
QA	Quality Assurance
QC	Quality Control
Q&A	Question and Answer
RD&D	Research, Development, and Demonstration
RFC	Reversible Fuel Cells
R&D	Research and Development
SOEC	Solid Oxide Electrolysis Cell
SOFC	Solid Oxide Fuel Cell
TEA	Technoeconomic Analysis
WVU	West Virginia University

Executive Summary

Hydrogen demonstrates major promise towards reducing CO_2 emissions and increasing energy security. The benefits conferred through hydrogen use range from decarbonizing energy intensive industries, to facilitating a more renewable enriched energy system, to strengthening economies based on the domestic production and market competitiveness of hydrogen. To accelerate the clean energy transition, the U.S. Department of Energy (DOE) launched the Energy Earthshots Initiative. The first Energy Earthshot – Hydrogen Shot – was launched June 7, 2021 and aims to reduce the cost of clean hydrogen production by about 80% to $1 per 1 kilogram in 1 decade (“1 1 1”).[1] Water electrolysis is a promising pathway for producing clean hydrogen when utilizing renewable or nuclear electricity. High temperature electrolysis (HTE) splits steam into hydrogen and oxygen which results in very high electrical efficiencies and, hence, potential for low-cost hydrogen production when the steam is produced by either waste heat or a low-cost thermal energy generator such as a nuclear reactor. This technology is nearing commercialization status and needs improved manufacturing processes that allow for scale-up to high-volumes to realize its low hydrogen cost promise.

On March 8-9, 2022 the DOE Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen and Fuel Cell Technologies Office (HFTO) co-hosted a workshop with the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium on HTE Manufacturing. The goal of this meeting was to bring together leading electrolysis manufacturing experts from industry, national laboratories, and academia to discuss HTE high-volume manufacturing status, barriers and opportunities; electrolysis stack manufacturing costs and technoeconomic analysis; and shared learnings for achieving high volume stack, component, and system manufacturing. To stimulate high-volume HTE stack development efforts to enable achieving $2/kg of hydrogen by 2026 in line with the Hydrogen Shot target of $1/kg of hydrogen by 2031, the workshop emphasized:

- Potential areas of investment for HTE manufacturing
- Identifying challenges, barriers, technological advancements, and prioritizing opportunities for HTE high-volume manufacturing
- Fostering cooperation between diverse stakeholder groups to engineer cost competitive HTE stack manufacturing technologies
- Open dialogue on cell, stack and component development needs related to achieving high volume manufacturing to inform DOE HTE programmatic strategy

---

[1] https://www.energy.gov/eere/fuelcells/hydrogen-shot

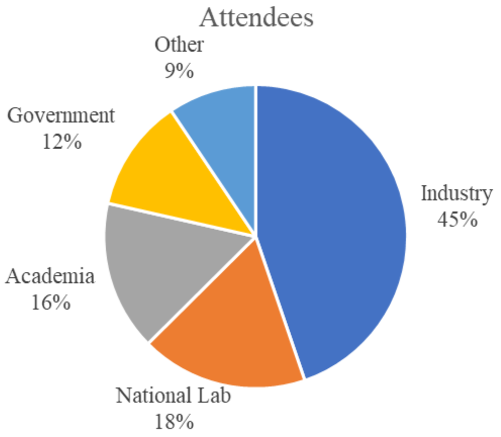

Figure 1. A breakdown of the affiliation of workshop attendees.

Nearly 400 registrants attended the two-day meeting. A breakdown of participants representing diverse sectors is presented in Figure 1. Day one of the workshop featured speakers from industry and national laboratories and industry panels covering current HTE technology and manufacturing status and challenges, future targets, and research and development (R&D) needs. Day two was dedicated to focused breakout discussion sessions on topics ranging from critical HTE manufacturing processes and scaling and throughput to supply chain and quality assurance and quality control. The aim of the focused discussions was to identify existing bottlenecks and prioritize R&D strategies that will help mature and scale HTE technology in support of the Hydrogen Shot initiative.

Workshop attendees highlighted that as HTE technology advances out of the laboratory and is ready for scale-up, driving down material and manufacturing costs is needed to overcome the low-volume HTE manufacturing that exists today. Generally, tape casting, heat treatments, and stack assembly are considered high priority areas for automation. Opportunities to accelerate high-volume production, in excess of 100 MW/year based on modelled cost projections, were identified during this workshop. This includes building multi-industry supply chain connections that can support the material, component and equipment demand that high-volume manufacturing requires. The supply of interconnects was noted as a particular concern. Material availability and quality also remain uncertain and in the transition from R&D to production these challenges must be addressed to enable the expansion. Quality assurance and quality control (QA/QC) must also be explored as establishing standardized procedures to implement QA/QC methods across multiple facets of the manufacturing process will ensure consistency and uniform performance across all HTE systems. The difficulty in these advances is the inherent materials properties and source variability. Better understanding of operational instabilities, device lifetimes, and durability is warranted. Detailed studies of the system and components performance criteria, an assessment of the material property requirements, and insight into the failure mechanisms and working limits of certain materials create the opportunity for use of cheaper materials and/or new materials development for improved cell and stack designs. Strengthening the knowledge base around long-term cell and stack performance degradation mechanisms is critical for realizing HTE based hydrogen production and leveraging this for the development of high-volume HTE manufacturing would prove beneficial.

At high and low manufacturing rates, heat treatments are estimated to comprise ~40% of the total manufacturing costs making this area important for cost reduction.[2] The number of thermal processing steps, the high treatment temperatures (800-1400°C), and the length of time required for each step all contribute to the high cost. Sintering operations require expensive equipment, use significant energy, and is typically the longest process step. Co-firing multiple cell layers at once is a key cost reduction strategy for reducing the number of thermal processing steps. Alternative sintering methods such as microwave heating and spark plasma sintering are another potential opportunity to decrease costs and time associated with thermal processing; however, these techniques are primarily in the R&D phase or have not been applied to HTE components and cells. Also, transitioning from batch to continuous thermal processing becomes an effective way to decrease costs once high enough production volumes are reached.

There are opportunities to incorporate advanced manufacturing processes into the HTE manufacturing process to lower costs, particularly roll-to-roll manufacturing. Roll-to-roll manufacturing can reduce process steps, improve yields, and increase processing speed. Overcoming the multi-step manufacturing process, furnace

---

[2] SOEC Stack Manufacturing Cost Analysis, Strategic Analysis, April 2021

equipment, and the time required to manufacture complete cells and stacks is a potential advantage of additive manufacturing. There could be ways to combine additive manufacturing with traditional processing technologies to result in a low-cost manufacturing process.

Lastly, implementing new and standardized manufacturing techniques and optimized processing approaches would improve yield and aid in cost reduction. It is important to characterize material property changes and tie them to cell performance. These changes are affected when new manufacturing methods are introduced. Manufacturing approaches that reduce the number of cell components in a stack, lower processing temperature, reduce the number of processing steps and shorten the overall processing time will also aid in increasing throughput and scaling production at low cost. Ensuring uniformity in high-volume processes, whether batch or continuous, and adequate equipment to accommodate high throughput manufacturing are key challenges that must also be addressed. Engineering solutions to these challenges can help increase manufacturing capabilities and drive scale-up.

Table of Contents

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, development, and demonstration (RD&D). Among other activities, HFTO organizes and supports meetings that convene stakeholders from the research community, industry, and government to guide research and development (R&D) priorities for hydrogen technologies.

HFTO, in collaboration with the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium, hosted the High-Temperature Electrolysis Manufacturing Workshop on March 8-9, 2022. This meeting was held virtually. The objectives of this meeting were to:

- Learn about the current challenges of domestic high-volume, high temperature electrolyzer (HTE) manufacturing technology
- Prioritize impactful RD&D opportunities to accelerate high-volume manufacturing for high temperature electrolyzers

Feedback from the workshop will be used to help guide research direction, inform potential areas of investment for advancing the commercialization of HTE technology, and establish targets. The meeting included presentations from industrial and national laboratory experts, followed by breakout sessions for more in-depth discussions on specific topics. This effort aims to foster cooperation between diverse stakeholder groups and strengthen synergies between government, academia, and industry to expand hydrogen development and deployment activities. This report highlights outcomes from the workshop that will be used to guide future hydrogen RD&D activities. Speaker biographies, presentations from this workshop, and this report can be found at https://www.energy.gov/eere/fuelcells/us-department-energy-high-temperature-electrolysis-hte-manufacturing-workshop.

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). The Biden-Harris administration has called for the nation to combat the climate crisis and reach energy goals that accelerate the clean energy transition, with the aim of reducing greenhouse gas emissions by 50% by the end of the decade, 100% clean carbon-free electricity by 2035, and reaching a net-zero carbon emissions economy by 2050.[3] Activities in support of the H2@Scale vision will help achieve President Biden's climate pledge. The benefits conferred through hydrogen use include decarbonizing energy intensive industries, facilitating the transition from a fossil-fuel based energy system to a more renewable enriched energy system, and strengthening economies based on the domestic production and market competitiveness of hydrogen. This transition requires RD&D to accelerate development of hydrogen-ready technologies toward national goals. To enable multiple hydrogen end-use applications at large scale, several areas in hydrogen technologies need further RD&D. In support of the Hydrogen Program, the H2@Scale initiative brings together stakeholders to advance affordable hydrogen production, transport, storage, and utilization to enable decarbonization and revenue opportunities across multiple sectors of the economy. The H2@Scale vision established by DOE is a proposed integrated use of hydrogen via new and existing systems and provides a framework for making these RD&D priorities a reality.

---

[3] 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/

A schematic of the H2@Scale vision is shown in Figure 2**Error! Reference source not found.Error! Reference source not found.**.

On June 7th, 2021, DOE Secretary Jennifer Granholm announced the launch of the Hydrogen Shot, the first of DOE's Energy Earthshot Initiatives. The overall goal of the Hydrogen Shot is to reduce the cost of clean hydrogen production to $1 per one kilogram of hydrogen within one decade. For hydrogen to achieve its potential as an energy carrier, its cost must be significantly reduced to be competitive with incumbent and other competing technologies. Hydrogen Shot will focus on developing new technologies in key areas to address this challenge and identify areas of improvement. HTE is a key hydrogen production pathway to implement the H2@Scale vision and achieve the Hydrogen Shot $1/kg clean hydrogen target.

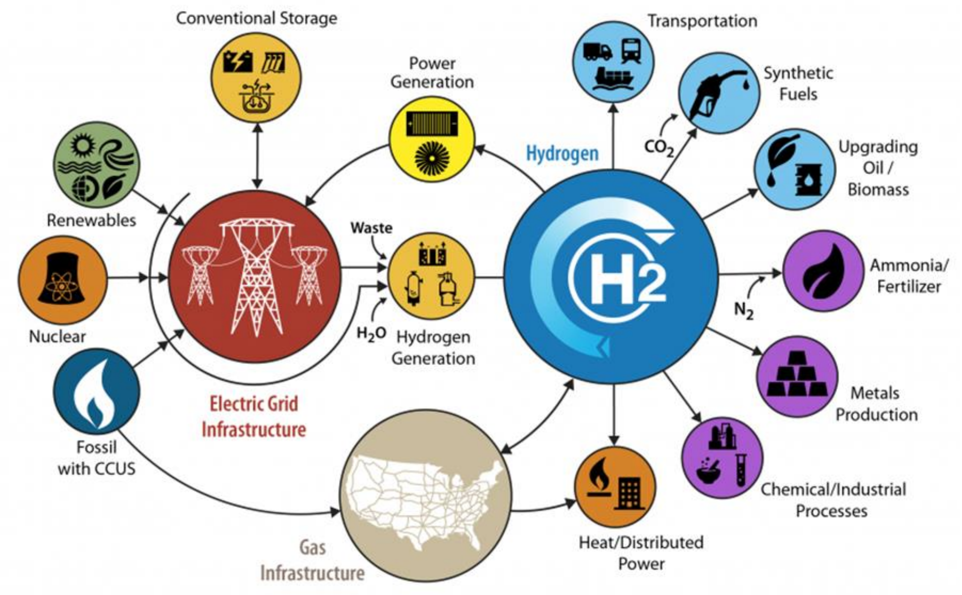

Figure 2. H2@Scale vision to enable decarbonization across multiple sectors of the economy.

1.2 High Temperature Electrolysis

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, nuclear electricity, or fossil fuel that practice carbon capture and storage. These electrolyzers can be coupled to the electric grid or integrated directly with distributed-generation assets to produce hydrogen for various end uses. Water electrolysis offers a pathway toward less expensive hydrogen production as ongoing technology advancements emerge. Currently, only approximately 2% of total global hydrogen production is generated via electrolysis.[4]

Electrolysis cells are comprised of a cathode and an anode separated by an electrolyte. The electrolyzer types are classified by operating temperature, the electrolyte material and its charge conducting species. High temperature electrolysis (HTE) splits steam into hydrogen and oxygen which results in very high electrical efficiencies and, hence, potential for low-cost hydrogen production when the steam is produced by either waste heat or a low-cost thermal energy generator such as a nuclear reactor.

---

[4] https://www.iea.org/reports/the-future-of-hydrogen

Oxide conducting solid oxide electrolyzer cells (SOECs), based on ceramic electrolytes that conduct oxide ions, operate at temperatures of 650-850ºC. SOECs are nearing commercialization status and need improved manufacturing processes to allow for scale-up to necessary volumes. A promising, lower TRL, HTE technology is proton conducting solid oxide electrolysis cells (P-SOECs), which can operate at lower temperatures (400-650°C). This workshop focused on oxide conducting SOEC technology as it will be the first HTE technology to achieve commercialization status. P-SOEC technology should be able to leverage many of the manufacturing advances developed for SOECs.

While there exists encouraging promise for high-temperature electrolysis to play a major role in low-cost hydrogen production, manufacturing methods that enable high-volume production are needed and production costs that make this technology competitive with conventional energy production methods must be reduced before this is realized. During this workshop, experts identified technology gaps, future investment focus and shared their perspective on priority RD&D areas that will provide for effective manufacturing scale-up of HTE technology and ultimately will result in the needed cost reductions to meet the Hydrogen Shot goal.

2 Expert Presentations and Panels

An introduction to the meeting was given by Dr. Ned Stetson, the Hydrogen Production Program Manager from HFTO. Dr. Stetson discussed the priorities of the DOE Hydrogen Program, a coordinated effort across multiple DOE offices, 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. He also discussed near- and long-term goals of the Hydrogen Program. High-temperature electrolysis is included as part of the near-term goals of the Hydrogen Program. Following the introductory remarks **Error! Reference source not found.**were three expert presentations and two industry panels (Table 1). Details are provided in Table 1 and presentation materials can be found on the meeting website. Summaries of the presentations are also provided below.

Table 1. Summary of expert presentations and panels.

Speakers	Affiliation	Presentation/Panel Title
Olga Marina	PNNL	Current Status and Future Focus of HTE Manufacturing
Brian D. James	Strategic Analysis	HTE Stack Manufacturing Cost and Analysis
Poul Georg Moses	Topsoe	Shared Learnings for Achieving High-Volume HTE Manufacturing
Venkat Venkataraman	Bloom Energy	Panel 1: Universal Challenges and Innovative Approaches for High-Temperature Solid Oxide Electrolysis Stack Manufacturing at High Volume
Tony Leo	FuelCell Energy	
Scott Swartz	Nexceris	
Joe Hartvigsen	OxEon Energy	
John Pietras	Saint-Gobain	Panel 2: Stack Assembly, Scale-Up and Component Manufacturing
Jens Suffner	Schott	
Greg Tao	Chemtronergy	
Todd Striker	Cummins	

2.1 Current Status and Future Outlook on HTE Electrolyzer Manufacturing

This presentation was given by Dr. Olga A. Marina, chief scientist in the Energy Processes and Materials division at Pacific Northwest National Laboratory (PNNL). Her talk covered the current status and future focus of SOEC manufacturing. She reviewed the general structure of a SOEC and the state-of-the art materials for each component. Dr. Marina also discussed the general advantages of HTE, including >95% stack electrical efficiency, thermal integration opportunities with process heat sources, low operating voltage, and the ability to pressurize the stack. This talk highlighted the research gaps that need to be addressed to enable a higher manufacturing rate and accelerate the deployment of SOECs.

The H2NEW Consortium is currently investigating the durability and performance lifetimes of HTE cells. There is limited fundamental knowledge on degradation mechanisms and therefore no developed or standardized accelerated stress tests (ASTs). ASTs are critical for examining cell and stack lifetime with targeted cell and stack lifetimes on the order of seven years for existing performance metrics and test designs. The H2NEW Consortium aims to leverage the existing technical capabilities and expertise in ASTs for development of ASTs for HTE electrolyzer technology advancement.

The presentation then covered general cell and stack assembly considerations including, planar cell designs, low-cost manufacturing techniques, stack components, and stack assembly processes. Dr. Marina noted that the key barriers to large-scale manufacturing are the fabrication time and cost, automation of stack assembly and quality assurance/quality control (QA/QC).

Dr. Marina mentioned there are some possible pathways to reach a stack cost target of <$100/kW including, increasing cell size, using advanced fabrication methods, reducing the number of processing steps, QA/QC development, and predictive modeling to aid in manufacturing. The impact of these adjustments can reduce the number of parts and interfaces, minimizing opportunities for degradation and failure. The difficulty in these advances is the inherent materials properties and source variability, particularly for QA/QC development. High-volume production is one of the key drivers to lower costs; predictions indicate an 80% decrease in system costs at a manufacturing rate of ~6000 units/yr. Other factors such as electricity price, thermal integration, performance and lifetime improvements, and the advances discussed above will also enable a low levelized cost of hydrogen (HLC). The research advances discussed here can enable reaching the Hydrogen Shot goal of $1/kg of hydrogen. Overall, this presentation introduced topics that the following presenters and panel speakers discussed in greater detail.

A question was posed during this talk on whether thermal integration with geothermal sources has been considered. The response to this question indicated that geothermal temperatures are generally not nearly hot enough to produce a dry steam that is used by an HTE, but steam from a geothermal site could be used to preheat the boiler feed water which is about 15% of the total energy input needed. There were also a few questions on the current performance lifetime of SOECs, which was indicated to be at least 10,000 h with limited degradation based on tests by INL of third-party stacks. However, private entities likely use their own degradation metrics to determine stack lifetime.

2.2 HTE Stack Manufacturing Cost and Analysis

This presentation was given by Mr. Brian James who leads the Energy Analysis Division of Strategic Analysis Inc. which specializes in the technoeconomic analysis (TEA) of emerging energy systems. His presentation covered the system-level vision for SOECs, the Design for Manufacturing and Assembly cost estimation methodology, cost modeling assumptions, results from a stack cost analysis, and possible pathways to reduce stack cost. He began the presentation discussing industry projections from a Bloom Energy white paper that proposes a path to $1/kg hydrogen production cost.[5] This white paper cites low-cost electricity, waste heat integration, low capital expenditure, and a high manufacturing rate as being the drivers for lower costs. Dr. Marina indicated many of these same drivers in her presentation.

The SOEC system that was modeled by Strategic Analysis involved a 1-GW system comprised of 40 blocks, where each block contains 25, 1-MW stacks. From this analysis, the overall SOEC cost landscape indicates a current system cost estimate of $950/kW and a future system cost of $230/kW, values which are consistent with those published in a Bloom Energy white paper. These preliminary values, along with other assumptions shown in Table 2, have the potential to reach the Hydrogen Shot goal.

The DFMA cost estimation methodology that determined the values in Table 2, involved a bottom-up manufacturing cost analysis which breaks down the system into its components parts and the design and fabrication necessary for each part is determined. This analysis provides insight into the manufacturing processes that have room for cost improvements. The stack cost was estimated for two designs, an electrolyte- and hydrogen electrode-supported cell, at annual production rates from 25-2,000 MW/yr.

---

[5] https://resources.bloomenergy.com/hubfs/BE21_22%20Hydrogen-white-paper_D.pdf?msclkid=d6ebf45cbb4011ecb5b7421d0abf7f94

Table 2. Summary of assumptions to determine HLC from Strategic Analysis

	Preliminary Estimates	
Year	2022[6]	2030
Total System Cost ($/kW)	950	230
BOP Cost ($/kW)	~700	~150
Stack Cost ($/kW)	~250	~50
System Price ($/kW)[7]	1,235	300
Cost of Electricity ($/kWh)	0.02	0.015
Starting Stack Efficiency (kWh/kg H_2)	34.4	34.4
Starting System Efficiency (kWh/kg H_2)	39.8	37.1
Capacity Factor (%)	90	90
HLC ($/kg H_2)	**2.84**	**1.19**

When modeling either an electrolyte- or hydrogen electrode-supported cell the total stack cost begins to level off at a manufacturing rate of 500 MW/yr. The material cost and manufacturing comprise about 80% of the total cost with the remainder of the costs covered by labor, tooling, and contingency costs. At low production rates manufacturing costs make up 50% of the total while at high manufacturing rates materials cover 50% of the total cost. At high and low manufacturing rates, heat treatments comprise ~40% of the total manufacturing costs, which is what makes this area ripe for cost reduction. The number of steps, the high treatment temperatures (800-1400°C), and the length of time for each step all contribute to the high cost. Co-firing multiple cell layers at once is a key cost reductions strategy. One way to reduce firing costs is to tightly pack the furnace with multiple bundles of cells, but QA and the isothermal condition must be considered. Based on price quotes from pusher kiln manufacturers, there is 15-25% price increase for furnaces that can reach 1400°C compared to furnaces that can reach 1250°C. Interconnects, support layer, and the air electrode contribute the most to the total stack materials cost. Using materials that allow for lower temperature sintering could also reduce cost. There are modest cost reductions attributed to materials at high manufacturing rates. The two cell designs yield different cell current densities and different stack cost curves with electrode-supported cells having a lower cost than electrolyte-supported cells.

There are opportunities to incorporate advanced manufacturing processes to lower costs such as additive and roll-to-roll manufacturing. Additive manufacturing for materials coatings could be used to minimize the number of firing steps in manufacturing, but they must be cost competitive and have high performance. Roll-to-roll manufacturing can enable fast line speeds, and individual cell discretization late in the manufacturing process to enable fewer individual steps for individual cells. The cost-effectiveness of this process will be contingent on the thermal treatment steps required to make roll-to-roll manufacturing possible.

---

[6] Assuming 50MW/yr manufacturing rate.
[7] Assuming a 30% markup.

Lastly, Mr. James outlined many cost reduction strategies that could be pursued including the ones discussed in this section. Other notable suggestions were, scaling up cell sizes, leveraging solid oxide fuel cell (SOFC) manufacturing capacity, using lower cost stainless steel, and improved balance of plant (BOP) components.

Questions asked during this session included whether the capacity factors presented here (50-90%) are consistent with integration of wind and solar. The response identified nuclear energy as the planned electricity source which can support higher capacity factors. Nuclear plants have been operating at capacity factors over 90% for several years. Batteries are also coming online to enable load leveling which will allow for higher capacity factors. This area requires more research to match the size of the electrolyzer system and plant with the capacity of the electricity source. A question was posed about whether inflation prices were considered in this analysis. The results presented here was based on pre-2020 price quotes and there have been no efforts to adjust those based on current prices.

2.3 Shared Learnings for Achieving High-Volume HTE Manufacturing

Poul Georg Moses is head of SOEC technology development at Topsoe. The purpose of this presentation was to share learnings from an international company on high-volume manufacturing. Some highlights from the presentation included using pilot manufacturing plants as workforce training grounds to enable greater participation of the workforce as labor hours can dominate costs. To ease widespread workforce training, standardized manufacturing processes are important and pilot plants can help validate these methods.

Dr. Moses also noted research areas that are critical to lowering manufacturing costs. It was emphasized in this presentation that longer lifetimes are a critical need. Other opportunities for improvement included component-level development coupled to manufacturing and linked to lab and pilot-scale demonstrations so improvements can be easily implemented. He noted that development of large and small stacks in parallel would help standardize manufacturing processes. For example, Topsoe uses COMSOL to model gas flow and stack chemistry which allows steady-state operation and validation and further model intermittent operation. COMSOL has been demonstrated to be a critical tool to guide SOEC development.

Questions were raised concerning how the COMSOL modeling results are validated which was explained to be possible through a combination of cell-scale knowledge and scale up stack results. Another question regarding the maximum operating pressure of the stacks to which Dr. Moses replied stacks were previously tested up to 20 bar of pressure and stack pressure optimization is driven by reductions in BOP costs to result in the overall lowest cost system configuration.

2.4 Panel 1: Universal Challenges and Innovative Approaches for High-Temperature Solid Oxide Electrolysis Stack Manufacturing at High Volume

The goal of Panel 1 was to identify opportunities to improve SOEC stack manufacturing at high volume. This information was meant to complement Mr. Brian James' talk and hear from SOEC manufacturer's directly about their needs. Each of the four panelists gave a short presentation followed by questions posed to the panel.

Venkat Venkataraman

The workshop respectfully notes Dr. Venkat Venkataraman unfortunately passed away only a few weeks following the workshop. At the time of his address, he was the CTO and EVP of Engineering at Bloom Energy. He led the development of clean, highly efficient, and low-cost Bloom Energy Servers to generate clean power onsite using natural gas, biogas, and hydrogen as a feedstock. During his 17-year tenure at Bloom, he led the company through many technological breakthroughs bringing SOFC technology from early stages of development to enabling deployment of highly efficient commercial systems deployed across the world, reducing greenhouse gas emissions.

Dr. Venkataraman discussed Bloom Energy's plans for using SOECs and how they will integrate with Bloom Energy's existing SOFC manufacturing capacity. Bloom currently uses the electrolyte supported cell design configuration. He mentioned Bloom's focus on reversible fuel cells (RFCs), due to historic investment in SOFCs and highlighted processes that assist in high-volume manufacturing which include automated processes for cell manufacturing and stack assembly. He mentioned that the manufacturing line for SOFCs could also manufacture SOECs with just some minor modifications. Lastly, he outlined some areas of improvement for stack manufacturing, including material changes to help component manufacturing, continuous sintering and conditioning, and enhanced high-volume electrode printing.

Tony Leo

Mr. Tony Leo joined FuelCell Energy in 1978 and has held key leadership roles in research, development, and commercialization of electrochemical systems during his tenure. Mr. Leo discussed FuelCell Energy's plans to produce low to zero-carbon power using carbon capture, supply clean hydrogen, and store energy from intermittent renewables and covert back to energy on demand. FuelCell Energy's core technology is carbonate fuel cells, which have some overlap with SOECs. FuelCell Energy is currently developing a common stack platform for their solid oxide technologies that supports fuel cell, electrolyzer and energy storage applications. They are planning to use common manufacturing processes for carbonate fuel cells, SOFCs, and SOECs including tape casting, sintering, and automated stacking. They currently have 100 MW/yr manufacturing capacity for carbonate fuel cells at their Connecticut facility with solid oxide electrolyzer technology development and manufacturing operations at their Canada facility.

Scott Swartz

Dr. Scott L. Swartz is the Chief Technical Officer and a co-founder of Nexceris, in Lewis Center, Ohio. Nexceris is a vertically integrated manufacturer of solid oxide materials, cells, coatings, and stacks. Their technology uses a FlexCell to enable a thin electrolyte membrane with a large active area. The FlexStack is designed for a scalable manufacturing process, enabling a large stack module size. Dr. Swartz noted several cost reduction opportunities for cell and stack manufacturing. At the cell level, the cost reduction opportunities include increasing cell area, reducing support and membrane thickness, automating manufacturing processes, maintaining high volume manufacturing, and recycling electrode materials. The cost reduction opportunities for the stack include lower cost seals, high current density operation, reducing the number of components, automating stack assembly, and streamlining the stack conditioning process.

Joe Hartvigsen

Mr. Joseph Hartvigsen is a co-founder and V.P. of Engineering at OxEon Energy, LLC and leads the systems engineering work on SOFC, SOEC, plasma reforming, and synthetic fuels development projects at OxEon. The OxEon manufacturing facility is capable of tape casting and electrode synthesis, cell and stack production, and stack testing. Currently their manufacturing capacity is limited by cell fabrication, at 500 kW/yr. They call on government support to get U.S. manufacturing from its current state to high volume manufacturing, where they can take full advantage of economies of scale. Current U.S. manufacturing base is low in cells, interconnects, glasses, and specialty chemicals. OxEon recognizes the need to avoid single source materials as single points in supply chains creates a weak spot for solid oxide material supply. OxEon is currently developing a 30 kW/10 kW RFC system and is anticipating multiple 150-250 kW demos. They also recognize that customers are looking for larger system sizes (>1 MW) and a stepwise increase in the number of demonstration projects will result in the need for increased manufacturing capabilities and drive scale up throughout the supply chain. OxEon is considering strategies for workforce development, including training opportunities, co-locating to replace coal/oil/gas jobs, and implementing learning from COVID staffing hardships.

During the question and answer (Q&A) session each panelist was asked to respond to questions prepared by the workshop organizers. For a question concerning the primary bottlenecks to scaling up to >100 MW/yr, one panelist was less concerned about the technical challenges to scale-up and noted the challenging part will be the final integration dependent on the end use case. There was agreement that downstream work is necessary, but many bottlenecks and areas of improvement were noted. Sintering operations require expensive equipment and use significant energy, and stack conditioning is a clunky bottleneck. Different approaches to cells and stacks will make standardization and reaching economies of scale difficult. Supply chain issues were also noted by multiple panelists, particularly in the case of interconnect suppliers, which may force use of international suppliers. And with scale up plans, these supply chain bottlenecks will only get worse. One panelist noted that the biggest hurdle for everyone is money, which is necessary to build infrastructure, manufacturing capacity, and demonstrations.

For a question on what are the main QA/QC methods that have been useful for interconnect materials, responses included surface imperfections need to be identified and mitigated, especially where seals are located, was provided as an example. In terms of the coatings themselves, the adhesion and dimensional tolerances are important to ensure before integration into a stack. There was also concern about QA/QC performed at low temperatures as compared to the operating temperature, making the correlation to degradation during operation and QA/QC difficult.

2.5 Panel 2: Stack Assembly, Scale-Up and Component Manufacturing

Panel 2 addressed stack assembly, scale-up, and component manufacturing. This panel focused on the later processing steps for full system assembly, complementary to Panel 1. Each of the four panelists gave a short presentation followed by questions posed to the panelists.

John Pietras

Dr. John Pietras leads the Ceramic Materials and Processing group at Saint-Gobain Research North America. This presentation discussed reducing the number of thermal processing steps, a comment made by many speakers. Dr. Pietras noted that decreasing the number of thermal steps requires materials that are compatible with one another before sintering. Saint-Gobain is currently working on roll-to-roll manufacturing techniques with Oak Ridge National Laboratory (ORNL) to eliminate stacking and lamination steps. Interface characterization is an important research area to determine material compatibility. Saint-Gobain is also considering recyclability of materials in their system designs.

Jens Suffner

Dr. Jens Suffner is currently a sales manager for Glass Powder Applications and responsible for global business development activities for glass powders in the SOFC/SOEC field at Schott, Business Unit Electronic Packaging, Landshut, Germany. Schott is a specialty glass company that manufactures gas and metal sealants with glass production on the scale of tons. They currently develop glass powders for SOFCs and SOECs. SOECs operate at higher steam concentrations as compared to SOFCs therefore, there is greater concern of glass seal volatilization and SOFC glasses may not work for SOEC operation. Schott currently produces 12 products for SOFCs at the production and pilot level. They sell custom products, but working with standard materials is better to achieve high volume manufacturing.

Greg Tao

Dr. Greg Tao is the vice president and co-founder of Chemtronergy. Chemtronergy is a small start-up company engaging in R&D for sustainable energy technologies. They can execute powder processing up to stack assembly and testing. Their company relies on a Design for Excellence approach, focusing on designing for reliability, supply, and manufacturability of SOFC and SOEC products. To design for reliability, a focus on thermal and fluid management is required.

Todd Striker

Mr. Todd Striker is the Manufacturing Leader for SOFCs at Cummins Inc. and has 20 years of experience in the field. His presentation discussed future-looking plans for high-volume manufacturing. Cummins aims to leverage big data to analyze components and materials during manufacturing. This advanced manufacturing technique will help ensure QA/QC throughout the manufacturing process. They also plan to use product tracing to ensure a 100% inspection rate and defect identification. QA/QC at such a high level will enable root cause determination for systems

During the Q&A session, panelists answered a question on how DOE can best support advanced manufacturing. R&D on high-throughput screening and determining the critical level of contamination for system materials was one answer. High-volume manufacturing at this stage requires manufacturers to stand up whole product lines which is costly, and QC can suffer. Support in this area will help ensure the products are reliable even at high scales.

For a question on what advanced manufacturing techniques are good for high volume manufacturing and are there any limitations, panelists did not identify any techniques they would not consider for high volume manufacturing. Roll-to-roll manufacturing could be a key advancement as this process can eliminate process steps and improve yield. Another technique is using additives to decrease temperature and time in thermal processing. However, a key metric for all advanced manufacturing is whether it is simple, robust, and cheap.

One question related to the use of large data sets and machine learning for manufacturing QA/QC and whether there are any non-obvious parameters to record, and if there is any area for DOE to help with this. Overall, the consensus was stack and component manufacturers need to work together on QC for materials. There is a lot of data collected over the course of manufacturing from powders to stack and this data needs to be analyzed to draw conclusions. Trying to leverage familiar materials in system designs can help limit the amount of testing required as new materials require 1000's of hours of testing to correlate performance with new materials which is very time consuming.

During the Q&A any examples of bad experiences with stacks that met QC parameters but failed in the field was requested. One panelist provided a situation where materials shrinkage upon heat treatment was managed by adjusting the sintering temperature; however, the strain at different temperatures was not accounted for. A piece of equipment was changed to accommodate larger volume systems which led to an unexpected decrease in product quality. Overall, there are a lot of factors to consider, not just in manufacturing, but in ultimate operating conditions.

3 Breakout Sessions

On Day 2 of the workshop attendees participated in 2 of 8 breakout sessions. Each round consisted of four breakout sessions running concurrently. A summary of the breakout session topics can be found in Table 3 along with the moderator and scribes for each. Each breakout session allowed participants to share their thoughts through written communication via chat or verbally. Each session was facilitated by a moderator to guide the conversation and assigned two scribes to capture the information discussed. At the conclusion of each breakout session, moderators and scribes collaborated to create a report slide containing the highlights of each discussion and presented the findings to the larger group at the end of the workshop. Moderators and scribes also drafted a follow-up summary report containing more detailed information than what was contained in the report slide for inclusion in this final workshop report.

Table 3. Breakout sessions.

Round 1 - Morning Track				
	Thermal Processing	QA/QC	Advanced Manufacturing Techniques	Component and Stack Manufacturing; System Integration
Moderator	Harry Abernathy, NETL	Dong Ding, INL	Jamie Holladay, PNNL	Kerry Meinhardt, PNNL
Scribes	Lorraine M. Seymour, PNNL; Fernando Dias, INL	Long Q. Le, PNNL; Joshua Gomez, INL	Sarah Shulda, NREL; Joshua Tenney, WVU	Jeremy Hartvigsen, INL; John T. Zaengle, PNNL
Round 2 - Afternoon Track				
	Scaling, throughput, robotics/automation	Interconnect and Protective Coatings	Supply Chain	Sealing and Contacts
Moderator	Peter Rupnowski, NREL	Brandon Wood, LLNL	Micah Casteel, INL	Edgar Lara-Curzio, ORNL
Scribes	Christopher Coyle, PNNL; Joshua Gomez, INL	Cameron Priest, INL; Nathanael T. Royer, PNNL	Joel Berry, LLNL; Lucun Wang, INL	Asha-Dee Celestine, HFTO; Angela Macedo Andrade; HFTO

3.1 Thermal Processing

Thermal processing is a key step in SOEC manufacturing. As noted throughout the panels and presentations, thermal processing contributes a large portion of the cost in stack manufacturing. There are several areas of interest that have the potential to reduce these costs.

Gaps and Key Challenges

There are several gaps and key challenges to be addressed in thermal processing. Reducing the number of thermal processing steps, as has been noted in other discussions, requires compatible materials. More research on using non-reactive materials such as ceria and zirconia would help overcome some reactivity issues. If ceria is to be considered, a denser, thinner layer would help reduce the thermal treatment time. Eliminating this barrier layer would also reduce thermal treatment time, but again connects back to the materials compatibility issue. There is also a lack of research on kiln furniture, a key piece of equipment that must be able to withstand high temperatures and large temperature changes. Researching new materials generally may lead to better performance, but the timetable associated with changes in manufacturing lines is long and possibly expensive. Most thermal treatment infrastructure for SOEC manufacturing is built on batch furnaces as opposed to continuous firing. As discussed in Mr. James' talk, a continuous firing infrastructure could bring energy costs and thermal treatment times down.

RD&D Opportunities

There were several RD&D opportunities identified, which were then prioritized based on the expected timeline to impact. These opportunities were based on the gaps and key challenges identified during this session. Development of new materials to prevent reactions between layers, replace or remove the current barrier layer, and enable co-firing were top priorities. New material development is a top priority due to the time and expense it takes to implement new materials, especially the further along in development a manufacturing plant is. New materials could permit the use of lower temperature kilns. Sintering aids could also help decrease kiln temperature requirements from ~1400°C to ~1200°C, although more research on possible sintering aids and their effect on overall stack performance is needed.

Advanced manufacturing methods were next on the priority list, including roll-to-roll manufacturing and alternative sintering techniques such as microwave/plasma-assisted heating or ultrafast high temperature techniques. It was noted the microwave processes, while possibly automated, produce hot spots, which can lead to cracks or distortions. Low on the priority list included characterization and modeling research on thermal processes, batch and continuous process product design, and TEA for specific thermal processes.

Barriers to High-Volume Production and Manufacturing

There were a few identified barriers to high-volume production. The capital costs in development of improved thermal processing are a concern, despite the long-term cost improvements from fewer, shorter, and less energy intensive steps. A concern was noted on a lack of automation possible with a multi-step process, lowering the chance that automation would be able to decrease costs. Another barrier to high-volume production is the energy cost of kiln heating. And lastly, the material property limitations are a barrier to creating cells that would allow for a one-step firing process.

3.2 Quality Assurance and Quality Control

QA/QC is a key aspect of manufacturing SOECs and will help ensure uniform performance from systems. The objective of this discussion was to identify the gaps in QA/QC for SOECs. There are several manufacturing areas where QA/QC should be implemented, from material sourcing to operation.

Gaps and Key Challenges

This breakout session discussed device testing, characterization methods, and method standardization. Standardized testing procedures should consider what is critical to customers and manufacturers. The testing procedures will be informed by the data required to meet customer and manufacturer needs. Predictive modeling of stack performance would benefit from standardization of data collection so that the information can be translated to multiple stack sizes. Industry participants agreed that standardized data collection to develop predictive modeling is key to QA/QC. They noted that implementing a feedback loop from the collected data to improve manufacturing processes or materials is necessary.

There were no identified properties or characterization methods that should be standardized across industry, but it was noted that industry partners should work with the H2NEW consortium to develop standardized data collection and testing protocols. It was also noted that long-term testing requires significant effort and investment, the benefits of which may not be realized until manufacturing is scaled up.

Barriers to Implementation and RD&D Opportunities

Barriers to implementation of QA/QC include scattered data, ineffective methods, constraints on testing timelines and resources, and high costs. These barriers will be addressed by the RD&D opportunities outlined here. The H2NEW consortium is already working on standardized testing protocols for SOECs, starting with button cells and will eventually move to full stacks. There is potential for artificial intelligence to assist in processing data and determining areas that need improvement. Through data tracking, there is potential to optimize hydrogen yield. Predictive modeling development will require identification of effective accelerated degradation stressors. Determination of accelerated degradation stressors will be completed at the lab-scale and need to be extrapolated and integrated into industrial scale testing.

Learnings from proton exchange membrane and liquid alkaline electrolysis QA/QC implementation in manufacturing can be leveraged. There is also a need to determine the trade-off between costs of QA/QC and benefits gained. Stack testing is often discussed in terms of the number of stacks pulled out of production, but this is not economically feasible. We can improve these costs through standard ASTs performed on a minimum number of stacks and characterizing the stacks as quickly as possible. Some technical focus areas for QA/QC are on material characterization, particularly, the electrolyte coating and sealing materials. The characterization and testing of these materials should be pushed onto the suppliers.

3.3 Advanced Manufacturing

Low-cost advanced manufacturing techniques create opportunities to fabricate a variety of SOEC components and cells of unique material combinations in customizable sizes and geometries that were unattainable before. Other benefits conferred through advanced manufacturing include better performance, more environmentally friendly materials and processing methods, less material waste and reduced solvent use increased cell stack and component reproducibility. Advanced manufacturing can facilitate the mass production of SOECs which is required to move HTE towards the large volume manufacturing needed to realize MW-scale hydrogen production. Advanced manufacturing could also be key to achieving the $1/kg of hydrogen cost target. Considerations related to the use of new manufacturing techniques include potential modification of traditional processes to complement new processes, new performance tests and possible improvements in materials design to support new and changing manufacturing processes. The goals of this breakout session were to identify additive manufacturing and advanced manufacturing techniques, where advanced manufacturing techniques were defined as techniques other than additive manufacturing or those combined with additive manufacturing, and the challenges and opportunities for utilizing these methods for SOEC cell stack and component manufacture.

Gaps and Key Challenges

SOECs, which utilize ceramic based engineering materials, are ideal candidates for advanced manufacturing methodologies. These methods have the potential to lower processing costs, expand the design space and make fabricating unique architectures and complex shapes achievable, currently limited by use of traditional ceramic manufacturing processes. Advanced manufacturing methods, such as 3D printing, can be used to fabricate: unique cell structures with controlled porosity and strength; For example, corrugated component layers within cells can increase active cell area and allow incorporation of gas flow channels within the cell structures to improve fuel transport, both of which can result in higher power densities. Implementing new manufacturing techniques can result in changes in multiple cell, component, or stack characteristics and properties ultimately impacting performance. Thus, it is imperative that developing manufacturing techniques should be carried out concurrently with materials design and any changes must be paired with complete cell and stack testing and characterization to ensure the desired cell performance properties are achieved. The need to employ measures to ensure a high standard of quality control and quality assurance for uniform manufacturing and performance, especially at high-volume production levels, was also highlighted. Concerns regarding the degree of dimensional changes with the use of additive manufacturing was posed and the question of whether this becomes a more significant problem for structures with complex geometries during sintering was raised. The notion that additive manufacturing either creates more opportunity for defects or adds more control over defects was presented though there was consensus that the outcome likely depends on the additive manufacturing technique used and the component fabricated.

Other challenges pertaining to the use of advanced manufacturing include determining which cell components are most suitable for what advanced manufacturing: interconnects, electrodes, seals, electrolytes, contact layers, gas channels, electrolytes. Inkjet printing, 3D printing, sintering (selective laser, photonic, spark plasma, flash, microwave and inductive heating), lithographic techniques and advanced thin layer deposition (plasma spray, flame assisted, e-beam, sputtering, atomic layer deposition, chemical vapor) are potential advanced manufacturing techniques for use. These specific techniques range from academic and national lab-scale development to manufacturing techniques used in other industries, though not yet utilized for HTE manufacturing. There were broad ranges of use for additive manufacturing for creating certain components and entire cell structures suggested. The idea of combining additive manufacturing with traditional techniques was explored with additional questions posed around the tradeoffs, ways to execute and potential performance gains. There were a variety of opinions around whether the proposed additive manufacturing methods can achieve the production rates needed to realize high-volume, giga-watt scale HTE manufacturing in the near term as the timeframe from development to industry maturity and adoption may be longer than ideal. Therefore, it was recommended that specific cell components be targeted where a large number of repeat units are not needed and only where extremely complex geometries or other unique features are required that can only be done with additive manufacturing be considered until the potential benefits and drawbacks are better understood.

RD&D Opportunities

Overcoming multi-step manufacturing processes, expensive furnace equipment and time required to manufacture complete cells and stacks were considered to be the most promising benefits of additive manufacturing. Reducing the number of processing steps, enabling a more continuous layer deposition method, and decreasing the need for multiple sintering steps was discussed. More studies to understand the impact of new materials and new manufacturing techniques on material properties and how this impacts the performance properties for a given application design are needed. While this work may be feasible for large companies, this can be burdensome for small companies and academia. Therefore, a DOE sponsored consortia to accelerate the evaluations would be highly beneficial. The consortia or national laboratory should have the capability to manufacture, test, characterize (pre-test, in-situ and post-test) and model cells and stacks. Worthwhile research on novel, quality material development to ensure the most appropriate material design for the designated advanced manufacturing technology was also mentioned. ASTs correlated to real world performance would also be useful. It was also mentioned that additive manufacturing allows for distributed manufacturing inclusive of both new materials and new techniques. Exploration of the opportunity to combine additive manufacturing with traditional technologies and consideration of the use of roll-to-roll manufacturing for increased processing speed and advanced joining methods such as brazing, localized heating and diffusion bonding for interconnects to densify regions where pore leakage is undesirable, are other areas of interest.. Development of multi-layer films via co-extrusion need to recognize that different layers may require different thermal treatments and/or different thermal treatments may result in different dimensional movements, all of which pose additional challenges. Digitized manufacturing, which incorporates elements of artificial intelligence, machine learning and in-situ sintering techniques, has potential for improved designs and faster design development, increased throughput and better quality control. Examination of opportunities for the use of patterned deposition techniques, as they have the potential to deliver higher electrochemical performance through unique architectures and higher material loading, may also result in greater control over component layer thicknesses.

Barriers to High Volume Manufacturing

The major challenge to high-volume manufacturing was identified as the need for a stronger supply chain of tools and quality materials. The lack of the ability to implement new manufacturing techniques and characterize all the changes related to the performance properties of the cell currently limits mass production of SOECs.

3.4 Stack Manufacturing and System Integration

The goal of this breakout session was to determine industry issues limiting production scale up for both components and stacks and final system integration.

Gaps and Key Challenges

It is difficult to scale up production when the potential errors in stack assembly are unknown. Continuous processing will be used in scale up, but the transition from batch processing is difficult. The learning curve when moving to continuous processing requires significant investment in time and capital. It is key to make decisions on stack and system designs that affect components and BOP equipment decisions before manufacturing scale up.

RD&D Opportunities

There are opportunities to learn from the electronic and automotive industries for manufacturing, particularly in the scale up process. Stack loading, contacts, and conditioning are all bottleneck or issue areas that are a barrier to high volume manufacturing. To properly seal and make electrical contact in the stack, a uniform load must be applied, which is not a trivial manufacturing process. Also, the stack conditioning is a bottleneck due to the long processing time.

System integration requires consideration of stack and BOP needs, and how choices in one affect the other. Stack pressurization is beneficial to the system costs but may affect the stack seals. More research on pressurized operation is desired to determine its feasibility and cost reduction impacts. Attendees requested that DOE provide a steam utilization target because the BOP needs are dictated by steam utilization. Low steam utilization would result in higher stack power but would result in system efficiency losses. The system efficiency would be improved through steam recycling and heat recuperation.

Increasing the cell size is another opportunity to decrease stack material/weight and therefore decrease the supporting infrastructure and capital costs. Increased cell size can result in greater power density with less supporting infrastructure such as insulation. Sealing methods and the stack frame design can be improved to permit larger cell sizes. Interconnects can be integrated with other parts such as current collectors, and/or flow fields to decrease the number of parts and manufacturing steps.

Barriers to High Volume Manufacturing

Sourcing interconnect materials and their coatings is not trivial at large scales. All manufacturers have issues with uniform coatings. As discussed previously, automation will be key to high volume manufacturing, but determining where and when along the production line implementation makes sense is more difficult. Early integration of automation is better as opposed to integration after production is scaled up. Considerations for where automation should be implemented include, areas of repetitious or tedious tasks, specific components that are required at a high volume, and using automation as an avenue to improve QC. Consensus among industry attendees is that the capital for manufacturing scale up will not be available until there is greater demand. Bottlenecks in manufacturing depend on the type of design, electrode or metal supported cells. Electrode supported cells suffer from warping and a slow sintering process. Metal supported cells require longer stack conditioning time, equipment, and active cooling costs.

3.5 Scaling and Throughput

The objective of this discussion was to identify challenges and opportunities to increase scale and throughput. This session focused on specific aspects of SOEC manufacturing that are hard to scale. Batch uniformity, heat treatment, and the necessity to limit manual handling of products were agreed to be the major issues. Additionally, work and research directed towards improving scaling processes was identified as a crucial need.

Gaps and Key Challenges

As discussed previously, sintering processes are one of the key areas for improvement in manufacturing. The scale of the furnace, using continuous firing as opposed to batch processing, optimizing thermal profiles, and optimizing co-firing are all areas that can increase manufacturing throughput and ease manufacturing scale up. The challenge in the addition of new equipment is not in the capital cost of the purchase, but in subsequent analysis to produce a standard, reproducible, product. The plant design is key to implementing new processes and production scale up, including building in redundancy to ensure continuous production. Uniformity is key to producing high volumes, but sintering is a critical area where inconsistencies arise. Batch furnaces in particular have high temperature deviations that lead to non-uniformity.

RD&D Opportunities

There is a large opportunity to focus on furnace optimization, which has been discussed in other sections. This session produced a few additional thermal treatment improvement ideas. Models could be useful in determining at what scale and which parts make sense for a conversion from batch to continuous furnace operation. Novel processes like thermal spraying could also be implemented here to lower cycle time and eliminate some furnace issues. There is also a desire to develop modular systems to make system installation much easier to scale. Implementing these improvements must also consider the QA/QC and how that can best be monitored during each step in the process and continue to be tracked and ensured during scale up.

Automation should be realized in areas that yield the highest cost reductions. The most labor-intensive processes may be key areas for automation and cost reduction; however, the cost of implementing automation may be more difficult than other processes if a lot of human input is required. Generally, casting, heat treatments, and assembly are considered high priority areas for automation.

There is a request for national laboratories to develop manufacturing demonstration facilities for SOECs. The national laboratories can also help develop software tools for optimizing manufacturing processes and assisting in manufacturing plant design. Scale up of manufacturing and the processes performed in electrolyzer manufacturing are not unique to this industry and there is knowledge from other industries such as glass and tile manufacturing that would be helpful here.

Barriers to High Volume Manufacturing

As previously mentioned, capital costs are a significant barrier to production scale up. Industry is looking for an increase in the demand for SOECs to accelerate manufacturing rates. A key to increasing demand is creating more opportunities for direct hydrogen offtake. There is limited existing infrastructure to transport hydrogen, which favors onsite hydrogen production at the offtake site as opposed to isolated hydrogen producers. Scale up to continuous production is a significant upfront and ongoing capital investment. The scale up only pays off if continuous production of electrolyzers does not exceed demand. There was a comment that there are not significant technical barriers, rather economic barriers to scale up. A few technical barriers to high volume manufacturing including fragility of cells, particularly if the cell size increases, and implementation of automation.

3.6 Interconnects and Protective Coatings

The goal of this session was to determine the manufacturing difficulties related to interconnects and coatings. There was discussion on the interconnect technical details, coatings and where they are needed, and overlaps between SOEC and SOFC manufacturing.

RD&D Opportunities

Most of the RD&D opportunities surrounded improvements or suggestions to coating materials and coating deposition. There are several coating types, such as natively formed, deposited, and post treatment formation. It was noted that coatings that require sintering are costly and should be avoided. However, there may be some reasons to using sintering as a coating method and the pros and cons of this processing step need to be better understood. Electrodeposited MnCo spinel is one possible deposited coating option, but the protection from this system is limited. Stamping is another method for depositing a coating layer, however it requires optimization of the pressure, rolling, edge coining, and microstructure engineering. Self-healing coatings were proposed as a method for preventing long-term degradation, but suitable materials for interconnect coating are unknown. The optimal coating composition is still unknown, and more processing research is required. Generally, there is a trade-off between the level of protection and the electrical resistance of the coating. Coatings are not only limited to interconnects, but any part of the system that contains Cr must be coated to prevent Cr vapor formation. Cr poisoning is a known cause of SOFC stack degradation.

The major difference between SOECs and SOFCs when considering interconnects and coatings are the levels of O_2 and steam. High O_2 pressures require high stability for coatings and the protected interconnects. There may be processes to be learned from SOFC manufacturing, but improvements may be needed in the stability and coverage of coatings.

Barriers to High Volume Manufacturing

Interconnect materials generally suffer from reliable availability and high costs. Degradation is still a significant issue, through cracking, pinholes in the coating, and delamination. The key to coatings for interconnect materials is full coverage over a large area. Small defects in the coverage can lead to faster degradation. Overall, cost-effective interconnect and coatings are the key aim. At present, the best coating material and method is unknown and requires more research. Standardization of testing procedures and materials would help develop a robust supply chain for SOEC manufacturing.

3.7 Supply Chain

The goal of the supply chain breakout session was to identify needs for the transition of the SOEC industry from R&D to commercial. The major supply chain issue can be described as the “chicken or the egg” problem. Understanding how to create pulls from electrolyzer manufacturers to material suppliers that will increase material and component production is key to solving this problem. There is also concern about the fragility of the current supply chain, particularly for materials that are sourced internationally.

Transitioning an Industry from R&D to Production

There is a broad spectrum of uncertainty about material quality and availability relevant to SOEC manufacturing. There is a need to build multi-industry supply chain connections. A consortium of SOEC manufacturers should be developed to facilitate communication in the industry and provide leverage when communicating with other industries. This consortium would also help determine standard materials, techniques, and equipment to minimize the number of unique requests required from each individual company.

In the transition to high volume manufacturing, workforce development and identification of current workforces that have transferrable skills is necessary. Aside from mitigating risk in SOEC manufacturing, risk for non-SOEC manufacturers should also be reduced. The hope is that increased demonstrations and commercialization will increase the manufacturing rate of the key materials discussed below.

Current Material and Equipment Concerns

There are currently shortages of specific materials, BOP components, and equipment. Ferritic stainless steel, Y, Sr, and Ni are all suffering from price hikes or limited supply. Another issue is the purity level of either raw or processed materials. It is difficult to set a low purity level threshold due to the varied effect impurities have on different materials at different processing stages. The exact purities that lead to material degradation or poor performance are unknown. Securing these materials could involve expanding the number of suppliers or integrating raw material acquisition into SOEC manufacturing. It was noted that there was a lack of participation from attendees with expert knowledge of the mineral industry. Their perspective would have been helpful here.

A number of BOP components are facing shortages, including power electronics, heat exchangers, and minor electrical components. Heat exchangers in particular are experiencing a more than a one year delay due to labor and Ni-alloy shortages. Other manufacturing equipment such as kilns and presses are also backordered. More information on supply chain issues was addressed in a recent DOE Water Electrolyzers and Fuel Cells Supply Chain report.[8]

3.8 Sealings and Contacts

The objective of this discussion was to identify gaps and key challenges for seals and contacts in SOECs, and how can they be addressed with manufacturing and R&D opportunities.

---

[8] https://www.energy.gov/sites/default/files/2022-02/Fuel%20Cells%20%26%20Electrolyzers%20Supply%20Chain%20Report%20-%20Final.pdf

Gaps and Key Challenges

Sealing and contacts are key to maintaining the lifetime of the electrolyzer and there is knowledge to be gained from SOFC manufacturing. The operating pressure influences the choice of sealant and may rule out some materials. Some other aspects of SOEC operation that must be considered for seals are the addition of steam, the effect of poisoning by stack materials, and the thermal cycling stability. You also need the glass sealant to work at a broader operating temperature than the stack, this could especially be an issue if intermittent operation is considered. To broaden the temperature range, additives to the glass seals might be considered. A tradeoff that could be considered is increasing the compliance of the glass seal which would make it easier to maintain contact, but generally increases the sinterability of the seal.

Contacts are the material used to connect cathodes and interconnects of cells together in a stack. Cell performance decreases when integrated into a stack due to sintering and loss of contact between cells over time. High conductivity and strong adhesion to both the interconnect and the cathode are important characteristics of contact materials. However, the strong adhesion should not affect the cathode or interconnect material properties. Contacts should be optimized to match the thermal expansion coefficient to the surrounding materials to minimize contact area loss. The contact paste should also be porous to allow for gas flow, but not so porous that conductivity is low and sinterability is high.

RD&D Opportunities

More research on seals is needed to identify suitable materials based on the properties discussed above. Tubular SOEC designs use ceramic seals, but other challenges arise for planar stack designs which make ceramic seals unsuitable. There were no identified sealant options; however, there was discussion on combining the sealing choice with the stack design. Making design choices that limit the use of seals or move the sealed areas to lower temperatures could allow for more material options. This decision should also be combined with manufacturing considerations because design choices can have a drastic impact on manufacturability.

Testing of new sealing materials is vital to understand their performance. Testing in real world conditions on short or full stacks is the best way to understand the issues that need to be addressed. Accelerated testing is also important here, 100 hr tests are not sufficient, and 3-5 year tests give the required data, but take far too long. Protocols for ASTs need to be developed to produce accurate degradation issues that are not an artifact of accelerated testing. Modeling could be useful here, though data is needed to validate the modeling approach. Along with AST protocols, standardized evaluation protocols would be useful to validate stack performance. Round robin testing hosted at national laboratories has also been useful in other industries, such as photovoltaics, to validate device performance. Postmortem analysis of stacks would be useful data, but there is no known data for planar cell designs.

R&D for contacts include identification of suitable materials as well as design changes that consider moving the interconnect to areas that do not involve the cathode. There are existing modeling tools that national laboratories have that could be helpful, such as COMSOL and ANSYS.

Manufacturing Needs

Uniformity of seals in manufacturing is a challenge, particularly in the conversion of the glass powder to a glass seal. There are also issues in transferring the glass seal to the stack parts, questions arose about whether tape cast and cutting to size or dispensing as a slurry were better manufacturing processes for seals. Costs were noted not to be a driving factor considering current borosilicate glasses; however, if additives are used, this may change. In terms of certifications and standards, there are not any seal specific standard that would have to be met, this is a consideration for the stack as a whole.

Appendix A. Workshop Agenda

U.S. Department of Energy High-Temperature Electrolysis (HTE) Manufacturing Workshop

Bringing leading experts together to discuss high-temperature electrolysis manufacturing efforts and future opportunities

Organized by HFTO and H2NEW Consortium

March 8-9, 2022

Virtual Meeting

Day 1 - Expert Presentations	
11:00 AM	Welcome
11:15 AM	Plenary Presentations Part I • Introduction • Current Status of HTE Manufacturing • Technoeconomic Analysis • International Perspective on Manufacturing
1:15 PM	Break
2:00 PM	Panelist Presentations Part II • High-volume Stack Manufacturing • Component Manufacturing
4:00 PM	Wrap-up & Adjourn

Day 2 - Parallel Discussions	
11:00 AM	Break-out Discussion Logistics
11:15 AM	Parallel Discussions Round 1 • Thermal Processing • QA/QC (Yield and Reproducibility) • Advanced Manufacturing Methods • Stack Manufacturing and System Integration
12:45 PM	Break
1:15 PM	Parallel Discussions Round 2 • Scaling and Throughput • Protective Coatings • Supply Chain • Sealing and Contacts
2:45 PM	Break
3:15 PM	Report Out
4:15 PM	Final Thoughts and Adjourn

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

Day 1: Overview Presentations from Experts

(Q&A to follow each plenary and final panelist presentation)

11:00 AM	**Welcome, Context, and Overview of Workshop Goals** Speaker: **Dave Peterson and Ned Stetson**, DOE HFTO
11:15 AM	**Plenary 1: Current Status and Future Focus of HTE Manufacturing** **Speaker: Olga Marina**, Pacific Northwest National Laboratory
12:00 PM	**Plenary 2: HTE Stack Manufacturing Cost and Analysis** **Speaker: Brian D. James**, Strategic Analysis
12:45 PM	**Plenary 3: Shared Learnings for Achieving High-Volume HTE Manufacturing** **Speaker: Poul Georg Moses,** Topsoe
1:15 PM	**Break**
2:00 PM	**Panel 1: Universal Challenges and Innovative Approaches for High-Temperature Solid Oxide Electrolysis Stack Manufacturing at High Volume** **Panelist 1: Venkat Venkataraman,** Bloom Energy **Panelist 2: Tony Leo,** FuelCell Energy **Panelist 3: Scott Swartz,** Nexceris **Panelist 4: Joe Hartvigsen**, OxEon
3:00 PM	**Panel 2: Stack Assembly, Scale-Up and Component Manufacturing** **Panelist 1: John Pietras,** Saint-Gobain **Panelist 2: Jens Suffner,** Schott **Panelist 3: Greg Tao,** Chemtronergy **Panelist 4: Todd Striker,** Cummins
4:00 PM	**Wrap-up and Adjourn**

Day 2: Parallel Break-out Discussions

(Combined report out session after Round 2)

Round 1	Thermal Processing	QA/QC	Advanced Manufacturing	Stack Manufacturing System Integration
Round 2	Scaling and Throughput	Interconnects and Protective Coatings	Supply Chain	Sealing and Contacts

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

For more information, visit:
https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office

DOE/EE-2607 ▪ July 2022