Hydrogen Production Technologies – 2023

Hydrogen Production Technologies Subprogram Overview

Introduction

The Hydrogen Production Technologies subprogram funds research, development, and demonstration (RD&D) to reduce the cost and improve the efficiency and reliability of technologies used to produce hydrogen from diverse renewable domestic feedstocks and energy resources. Activities of this subprogram support the Hydrogen Energy Earthshot (Hydrogen Shot) goal of $1 for one kilogram of clean hydrogen in one decade and align with the *U.S. National Clean Hydrogen Strategy and Roadmap*. The subprogram also incentivizes the development of innovative off-roadmap technologies with potential to meet the Hydrogen Shot goal through the American-Made H-Prize: Hydrogen Shot Incubator, also known as the Hydrogen Shot Incubator Prize.

One RD&D focus of the Hydrogen Production Technologies subprogram is water splitting through low- and high-temperature electrolysis using renewable energy resources. The Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law [BIL]) includes a provision for clean, low-carbon hydrogen production from water electrolysis. Since the enactment of the BIL, all electrolysis activities have been funded through procurements authorized under the BIL, including both the Sect. 816 Clean Hydrogen Electrolysis Program and Sect. 815 Clean Hydrogen Manufacturing and Recycling Program. Electrolysis RD&D has been coordinated primarily through activities with the Hydrogen from Next-generation Electrolyzers of Water (H2NEW), HydroGEN Advanced Water Splitting Materials (HydroGEN), and Electrocatalysis (ElectroCat) consortia.

In support of the H2@Scale initiative, the Hydrogen Production Technologies subprogram also continues to fund non-electrolysis technologies at lower technology readiness levels (TRLs) through the subprogram's annual appropriations. These advanced hydrogen production pathways include direct solar water-splitting processes, such as photoelectrochemical (PEC) and solar thermochemical (STCH), as well as biological processes that can convert biomass or waste streams into hydrogen.

Goals

The Hydrogen Production Technologies subprogram aims to develop clean, low-carbon hydrogen production technologies. Specific subprogram objectives include the following:

- Develop and validate low-cost, sustainable, and low-carbon hydrogen production technologies with the potential to meet an intermediate hydrogen production cost target of \$2/kg H_2 by 2026 and the Hydrogen Shot target of \$1/kg H_2 by 2031.
- Develop new, low-cost materials and components to improve performance and durability of hydrogen production technologies, including high- and low- temperature electrolysis and lower-TRL approaches such as PEC and STCH hydrogen production.

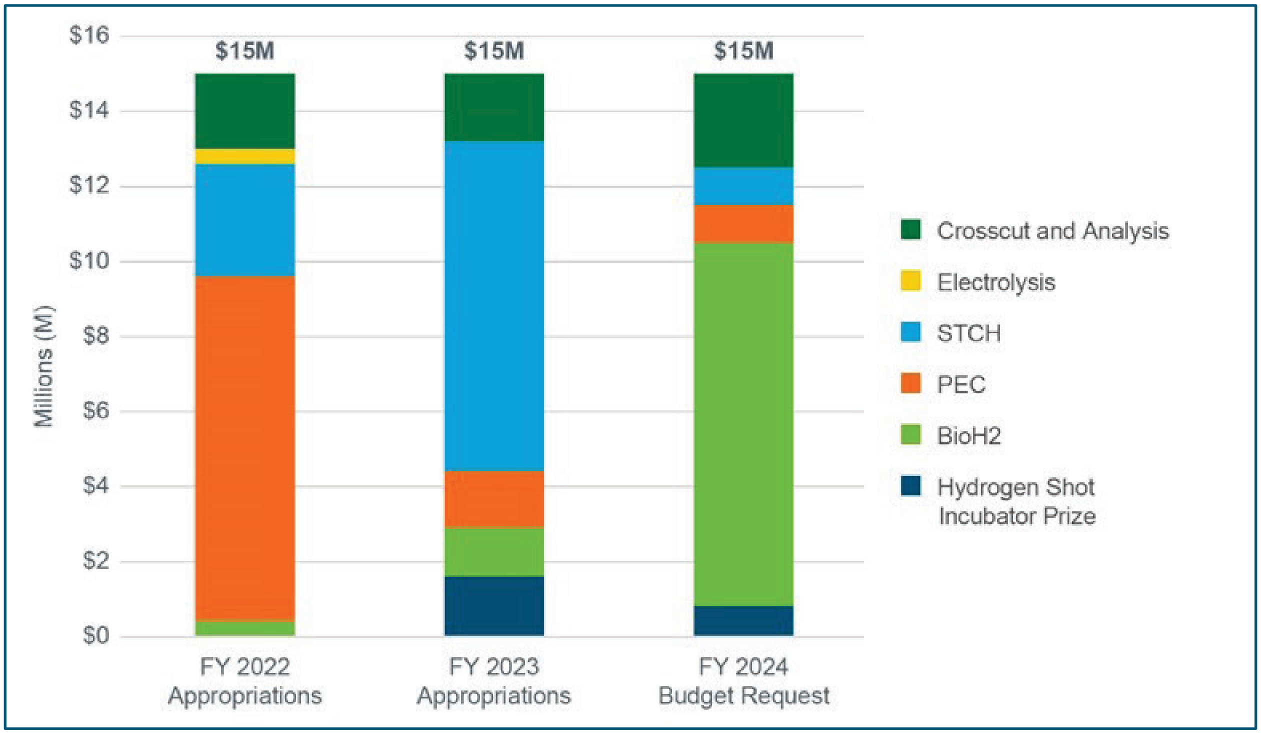
Key Milestones

The Hydrogen Production Technologies subprogram has established the following key milestones:

- Develop clean hydrogen production technologies able to meet cost targets of \$2/kg H_2 by 2026 and \$1/kg H_2 by 2031.
- Develop proton exchange membrane electrolyzer technologies able to meet stack targets of \$100/kW at 3 A/cm^2 and 1.8 V with an 80,000-hour lifetime by 2026.
- Develop high-temperature electrolyzer technologies able to meet stack targets of \$125/kW at 1.2 A/cm^2 and 1.28 V with a 40,000-hour lifetime by 2026.

Budget

The Fiscal Year (FY) 2023 appropriation for the Hydrogen Production Technologies subprogram was $15 million, which covers all non-electrolysis work, with an emphasis on advanced pathways. All electrolysis work is supported under the BIL Sect. 816 Clean Hydrogen Electrolysis Program and Sect. 815 Clean Hydrogen Manufacturing and Recycling Program, which, in total, provide more than $200 million/year.



The $15 million received for each FY 2022 and FY 2023 supported direct solar water-splitting research, including work toward advancing PEC and STCH durability and efficiency; biological hydrogen production using microbial processes (BioH2); and hydrogen production cost analysis. Funding also supported the Hydrogen Shot Incubator Prize to incentivize development of innovative off-roadmap technologies with the potential to produce clean hydrogen at $1/kg in one decade. The FY 2024 request is $15 million to continue research and development (R&D) in advanced pathways for hydrogen production.

In FY 2024, the BIL (Sect. 816, in particular, and provisions in Sect. 815) will fund a range of electrolysis activities to improve efficiency, increase durability, and reduce the cost of producing clean hydrogen using electrolyzers to less than $2/kg by 2026. Emphasis will be on efforts to improve and develop new materials and components, as well as to advance manufacturing technologies to get to economies of scale for electrolyzer manufacturing. BIL Sect. 816 funding will continue to support national-lab-led consortia (H2NEW, HydroGEN, and ElectroCat) focused on electrolysis R&D, as well as efforts to develop megawatt-scale electrolyzer test and validation facilities. BIL Sect. 815 funding will support—for both electrolyzers and fuel cells—establishing a recovery and recycling consortium and a national-lab-led consortium focused on roll-to-roll manufacturing.

Annual Merit Review Results

During the 2023 Annual Merit Review, 43 projects funded by the Hydrogen Production Technologies subprogram were presented, and 17 were reviewed, including 4 HydroGEN Seedling projects (a breakdown by budget category is shown on the right). The 4 HydroGEN Seedling projects received scores ranging from 2.9 to 3.2, with an average score of 3.0. The other 13 reviewed projects received scores ranging from 3.0 to 3.7, with an average score of 3.2. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

Number of Projects Reviewed by Budget Category	
BioH2	4
PEC	3
STCH	1
Electrolysis	5
Crosscut and Analysis	4

Following are reports for the 17 reviewed projects. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Project #P-148: HydroGEN Overview: A Consortium on Advanced Water-Splitting Materials

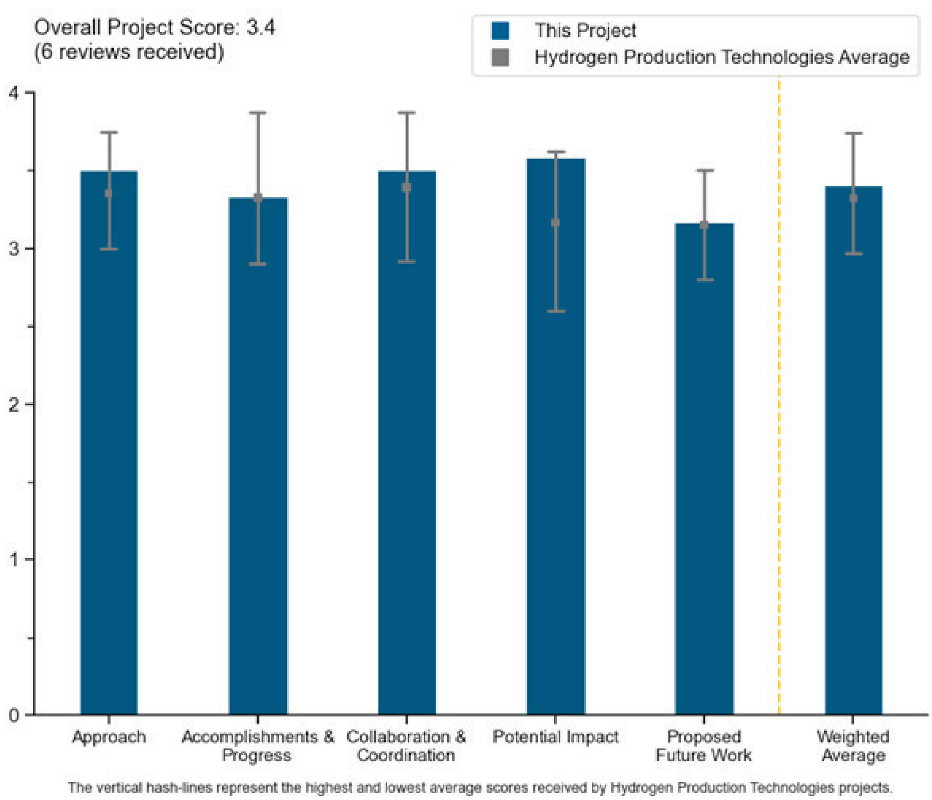
Huyen Dinh, National Renewable Energy Laboratory

DOE Contract #	WBS 2.7.0.518 (HydroGEN 2.0) and 2.7.0.513 (Node Support)
Start and End Dates	6/1/2016
Partners/Collaborators	Lawrence Berkeley National Laboratory, Sandia National Laboratories, Idaho National Laboratory, Lawrence Livermore National Laboratory
Barriers Addressed	• Cost • Efficiency • Durability

Project Goal and Brief Summary

The HydroGEN Consortium's objective is to facilitate collaborations between federal laboratories, academia, and industry to evaluate and accelerate the research and development (R&D) of innovative, advanced materials that are critical and necessary to advanced water-splitting technologies for clean, sustainable, and low-cost hydrogen production. Water-splitting technology pathways supported by HydroGEN include photoelectrochemical (PEC), solar thermochemical (STCH), low-temperature electrolysis (LTE), and high-temperature electrolysis (HTE). In addition to collaborating with industry and academia, HydroGEN uses a synergetic, multi-laboratory approach, utilizing and integrating the labs' world-class capabilities to address the critical research gaps identified by the lab teams and HydroGEN Benchmarking and Protocol workshops in each of the advanced water-splitting technologies.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The idea to have a foundational “home” for national laboratories to work on water-splitting technologies is excellent, with constancy of purpose and breadth of scope. This nurtures capabilities and relationships and provides stability for data-sharing (Data Hub). The focus on standards development and benchmarking is fantastic to see, and the team is encouraged to consider how to do more of this.
- The project has very good collaboration and inclusion of both national laboratories and industry shown in its approach. The approach shows clear separation of problems to address for each of the hydrogen technology areas.
- The overall design and approach to consortium operation is excellent, promoting information exchange, collaborative efforts with national laboratories and industry, and development and dissemination of best practices/protocols that help to elevate the entire R&D community.
- As a portfolio rather than a specific project, it is a little more difficult to assign specific performance metrics. Also, because of the maturity of the technologies (which by definition are low technology readiness levels [TRLs]), there is clearly a long way to go to achieve the $1/kg cost target. However, given that this is an aspirational target requiring unrealistically cheap electricity (~1.2 c/kWh) for the reference electrolysis pathway, there should be reluctance to require individual projects to show a path to $1/kg. However, it would make sense to determine what is realistically possible without the current pressure to meet an unrealistic target with what are likely unachievable cost estimates (e.g., $25/m^2 for PEC cells when the glass alone is probably this cost). Overarching barriers are well identified (cost, efficiency, and durability), but—without killing off potentially useful research avenues—some higher-level metrics could help focus on the barriers. The techno-economic analysis (TEA) seems to be used a little inconsistently in the seedlings (though only the PEC seedlings were reviewed). Slide 12 pulls together the challenges nicely—without, however, specifying actual performance metrics.
- The project combines four hydrogen production technologies—low-temperature water electrolysis (LTWE), high-temperature water electrolysis (HTWE), STCH, and PEC—that are very expensive. The Data Hub is beneficial for the green hydrogen production community. Roadmaps and deliverables for each technology need to be clearly defined. Some work, such as the Chemours project and HTWE, overlaps with the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) scope of work.
- It is unclear how the new STCH materials investigated perform compared to the state-of-the-art materials and what critical factors determined the hydrogen production rate. Proton-conducting solid oxide electrolysis cell (P-SOEC) Faraday efficiency should increase with current density (slide 29). Metal-supported SOEC should address Cr poisoning under high steam conditions, and the operating temperature of 700°C seems too high for metal support.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The consortium, including a couple of complementary programs and endeavors spanning many stakeholders and projects, has been successfully rolled out. The presentation highlighted key technical progress results from various projects across the four different low-TRL hydrogen production technologies directly supported through the consortium. Highlights of note include the following:
    - Regarding STCH, the project established high-throughput computational-driven discovery of the materials framework; this was used to synthesize >10 identified compounds of interest and validate two of these, setting the stage.
    - Regarding HTE, impressive performance and progress is reported for the H+ conducting intermediate-temperature electrolyzers.
    - Regarding PEC, the project has made significant progress in terms of demonstrating high solar-to-hydrogen (>17%), durability, as well as prototyping that represents a notable step forward in terms of TRL for this class of technology.
- Overall, most projects have made good progress. LTWE and HTWE projects have progressed very well. Idaho National Laboratory (INL) shows performance of 1.51 V at 6 A/cm^2 at 600°C (published in Nature), which is very impressive. Chemours thin proton exchange membranes (PEMs) with low hydrogen crossover is encouraging. The anion exchange membrane water electrolyzer (AEMWE) project achieved less than 2.0 V at 3 A/cm^2. STCH projects have made good progress on the new materials selection.

Durability for most projects was not sufficient. There was only about 200-hour durability for INL's project. For the AEMWE project, the durability data varied from 15 hours to 10 days. For STCH technology, a device assembly and testing data are recommended.

- A tremendous amount of technical progress has been made by the many projects. It is hard to absorb it all in a presentation this broad and dense, frankly. As for the HydroGEN effort itself, at the next Annual Merit Review (AMR), perhaps the team could break out metrics for the HydroGEN Consortium by year (for example, how many publications, workshops, non-disclosure agreements, etc. there were in the past year).
- The decent number of high-impact publications indicates some good science is being done. Not all projects have a clear path to DOE goals, but given the low TRL, it could be argued that if appropriate performance metrics supported by TEA are in place, then HydroGEN represents a valuable chance to build up human capacity through students and perhaps make an important or serendipitous discovery. That said, supported projects probably need to have a least some chance of making it to implementation, which is a struggle for PEC.
- Progress toward the \$1/kg target for hydrogen has been demonstrated in all technology areas. The different technologies to produce hydrogen were presented in a way as to show the maturity of each. It might be useful to add a TRL number to each to track against future progress made.
- All subprograms are making good progress.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- Benchmarking efforts, including establishing standard protocols accepted by the community, are invaluable across the various lower-TRL hydrogen-producing technologies. HydroGEN provides an effective framework for connecting university and industry researchers (at least those with funded projects) with national laboratory experts and resources. It appears that all or most projects involve close collaboration within the HydroGEN Energy Materials Network (EMN) framework, leveraging expertise and capabilities of national laboratory partners, as intended. It is great to see the demonstration of reproducible stability measurements for PEC devices across different laboratories.
- Most projects seem to be effectively leveraging the broad materials capabilities across the EMN network, which is a real strength of HydroGEN.
- It appears only one company (Chemours) is currently collaborating with HydroGEN. More industry engagement on the "HydroGEN 1.0" (i.e., EMN) side is encouraged. The project should be proactive and may need to show the industry how it can benefit. The Data Hub is a good vehicle for collaboration. It is nice that HydroGEN extended it to cover H2NEW. There is collaboration with similar European efforts, which is good.
- National laboratory and industry collaboration were presented as effective. The high volume of publications, workshops, and outreach for science, technology, engineering, and mathematics (STEM) were clearly shown as evidence of successful collaboration.
- There are strong collaborations between national laboratories and research institutions. More collaborations with industries are needed.
- Strong collaboration within laboratories and academia was observed.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- With the current potentially existential threat of per- and polyfluoroalkyl substance (PFAS) bans on current PEM technologies, there is a real need for alternatives. For STCH, it is becoming clear that finding stable yet active materials is very challenging, but there is still some life in perovskites, and the machine learning model developed is potentially significant for STCH and maybe other areas. For HTE, it is also useful to explore alternatives to current oxygen-conducting membranes to improve operating conditions and durability, given a lack of operational experience accumulated with SOECs. The LTE seedlings appear well directed. What is perhaps missing is fluorine-free ionomers. The PEC branch is the most challenging in terms of seeing a potential impact, as a realistic chance of success is hard to see.

- Critical work is being performed to address current technology limitations. The project has demonstrated progress made against these barriers and has evidence of progress made toward DOE hydrogen targets. The involvement of national laboratories and industry ensures areas of focus are valid and will serve to support broader penetration of these technologies into the commercial sector.
- Supporting knowledge-sharing, capability-building, and standards and protocols within the hydrogen production community across all low-TRL technologies can be expected to have a huge impact on accelerating the rate of development of these technologies. The Data Hub also has high potential for impact for the broader community, although it is unclear how big the impact is and can be. It is recommended that the project improve the ability to track data download and (if possible) information about who is downloading the data (industry vs. academic, U.S. vs. international, etc.) to better assess the success of this information-sharing vehicle.
- The national laboratories do great work on any problem they set their minds to, but the early-TRL nature of the projects in this portfolio creates the potential for misalignment with DOE objectives of accelerating deployment of low-cost, low-carbon hydrogen. Much project management is required, which seems to be there, but it is hard to know for sure. STEM workforce development is listed as an impact area; more needs to be said about this at the next AMR.
- The consortium fosters a strong collaboration to tackle the critical issues facing electrolysis for hydrogen technologies.
- The impact can be more significant if some breakthroughs can be made, which may lead to next-generation green hydrogen technology. Given that the consortium has existed since 2016, more progress is expected. There have been incremental improvements of the performance, but durability has not made a major breakthrough.

Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- Future work is structured to resolve open issues and continue progress toward technology challenges and barriers. Proposed future work aligns with technology needs for improvement.
- Each technology area outlined plans that seem reasonable, but the areas are too much and too detailed for the reviewer to provide a strong opinion.
- The proposed future work was not really articulated at the program level. Although individual areas talked about high-level goals (slides 22, 35, 45, 55), there was a distinct lack of numerical targets (admittedly, this is perhaps challenging across multiple seedling projects). A discussion of the overall strategy and what the coming research priorities look like would be preferred (more of a top-down view that considers whether the current project portfolio is adequate for what is really a rapidly developing industry).
- The future work is weak. It does not include clear technology development information. For example, the project should clarify the major technology focus and major technology barriers that need to be addressed.
- A focused research on degradation mechanisms is suggested.

Project strengths:

- The consortium successfully engages many stakeholders involved with advancing hydrogen production technologies across low- to medium-TRL scale. The consortium enhances interactions between national laboratory subject matter experts and university/industry researchers. The consortium has promoted best practices in benchmarking and testing protocols that greatly benefit the broader R&D community.
- This is a very strong team with expert experience in different hydrogen production technologies. The consortium is dedicated to developing next-generation hydrogen production technology. There has been good progress on HTWE and LTWE technologies. The Data Hub approach is beneficial to the researchers in this community.
- The project is a vehicle to unleash the tremendous capabilities of the national laboratories to significantly advance water-splitting science.

- A nice range of technologies is covered, with what appears to be effective collaboration, a feature of many projects. It is good to see that there is a decent allocation of funding to this strategic, forward-looking research.
- The project has a strong team and collaboration. Information and data collected are shared with the community to provide the current state of the technology available for other researchers.
- A consortium collaboration mechanism is a strength for the project.

Project weaknesses:

- It is hard to really get a feel for how HydroGEN, as a project, functions at the overall coordination level, as much of the discussion (with the exception of the cross-cutting work) was about the seedlings. It would be good to understand how TEA is informing the choice of performance metrics so that there is a clearer focus on the critical ones. The impression is that there is a certain inflexibility, or at least inertia, in the work program; so it would be interesting to better understand how agility could be brought to the portfolio and whether there should be an element of tactical, as opposed to strategic, work. The PFAS bans will need to be addressed, for instance, and the consortium could look for ways to support industry and/or use operational data to inform the work program.
- Some projects may be venturing into Basic Science land, which does not mean great work, but it probably should not be funded out of the Office of Energy Efficiency and Renewable Energy. Connecting projects to technical targets required for commercialization, or a technology roadmap, would dampen this impression. Otherwise, some discussion of how to think about science versus technology in this space would be useful.
- For the Data Hub, it is recommended that the project improve the ability to track data download and (if possible) information about who is downloading the data (industry versus academic, U.S. versus international, etc.) to better assess the success of this information-sharing vehicle.
- Most durability data was short, which limits the significance of project progress. The collaboration with the industries is not strong. There are no clear roadmaps and targets for each technology. Technology transfer needs to be well documented.
- Synergy across different subprograms such as HTE and STCH, which both involve high-temperature oxygen nonstoichiometric materials, may need encouragement.
- It was not clear how the data quality was being evaluated, prior to being uploaded to the Data Hub.

Recommendations for additions/deletions to project scope:

- Presumably, there was a TEA supporting the decisions made by HydroGEN around which technical areas to target and which projects to fund, but if not, there should be. The same can be said for technical targets. At the next AMR, it would be good to see more discussion of the “strategic planning” for HydroGEN and how it interacts with H2NEW. (The 2.0 seedling projects can present their own work.)
- The project should give greater emphasis on TEA/performance metrics, specifically avoiding the need to hit $1/kg, as this is a little unrealistic. A higher-level project portfolio analysis and awareness of looming issues or challenges are needed.
- It is recommended that the consortium strengthen its collaboration with industry to test the technologies under an industrial environment. Having a clear technology roadmap and targets in certain years is also recommended.
- In the future, the consortium can provide a year-to-year progress (since 2016) that would provide an overall outlook of the accomplishments. Focus should be given to long-durability testing.
- Degradation mechanisms studies should be planned.
- The project scope is appropriate.

Project #P-170: Benchmarking Advanced Water-Splitting Technologies: Best Practices in Materials Characterization

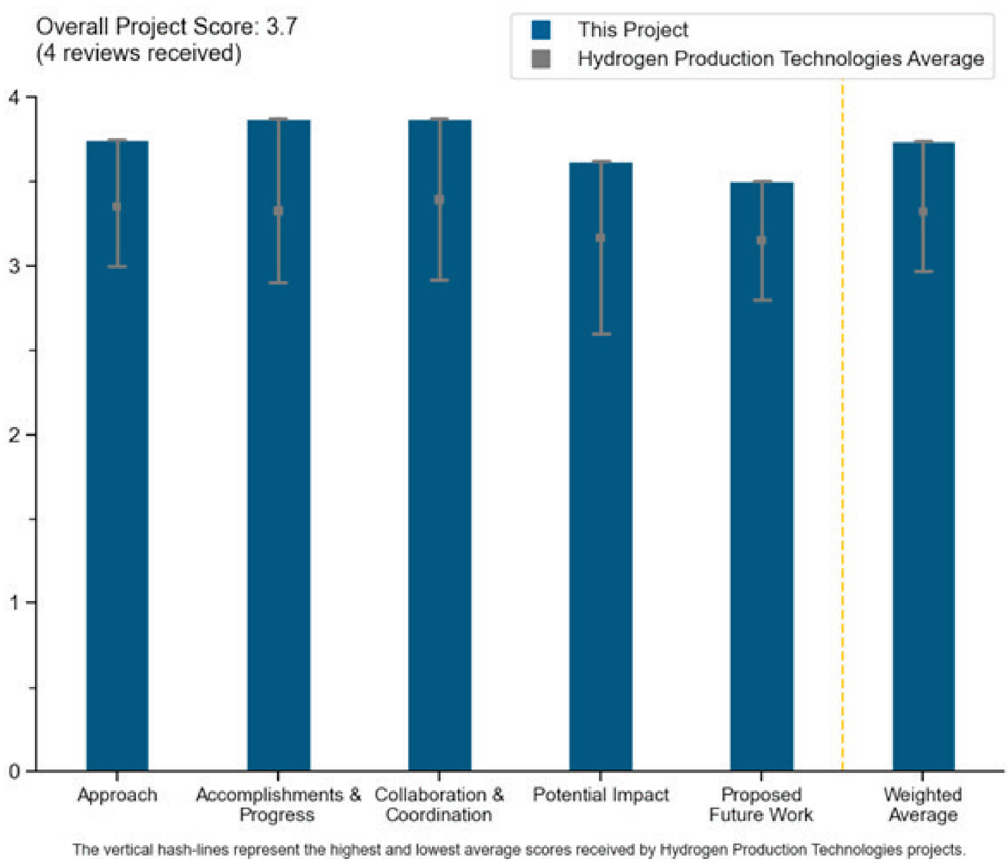
Olga Marina, Pacific Northwest National Laboratory

DOE Contract #	WBS 2.3.0.708
Start and End Dates	10/20/2021
Partners/Collaborators	Nel Hydrogen, Arizona State University, California Institute of Technology, H2 Technology Consulting LLC
Barriers Addressed	• Hydrogen generation by different technologies • Improve energy resilience and sustainability • Establish a universal system for benchmarking • Provide access to benchmarking results to community

Project Goal and Brief Summary

Making significant advances in advanced water-splitting technologies (AWST) requires the effective use of AWST research, development, and demonstration resources. To that end, this project will help establish a universal system for benchmarking. Researchers will develop and verify protocols for AWST validation testing and improvement within the categories of low-temperature electrolysis, high-temperature electrolysis, photoelectrochemical, and solar thermochemical hydrogen (STCH). This project will contribute to the strategic coordination of benchmarking in the water-splitting community and the advancement of test protocols.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach to project objectives of developing benchmarks, developing protocols, and providing guidance to the various water-splitting communities has been exceptional. The workshops and other channels to engage the research community, DOE, and industry have been outstanding in their success in acquiring input from experts and practitioners. The general approach of developing well-defined benchmarks and protocols and how to deliver those to the community has been highly successful.
- The approach used to engage technical staff in developing standards is well-rounded. The project has scientists and engineers from several national laboratories and multiple universities and a few industrial participants.
- This is definitely a needed exercise to conduct. The approach of including multiple stakeholders is good.
- The project has an excellent approach to benchmarking. Slides 6, 7, and 8 give an excellent outline of the project approach and deliverables.

Question 2: Accomplishments and progress

This project was rated **3.9** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments and progress toward achieving the project goals have been outstanding. The team has made significant progress against all of the project milestones in a timely manner and contributed directly to achieving DOE goals to standardize the benchmarks and protocols for evaluating AWSTs. The development of so many protocols over so many different processes and water-splitting technologies is particularly impressive. The one area that seems to be slower than hoped, possibly because of specific challenges with defining good protocols and benchmarks, is the STCH AWST.
- Technical progress is represented by 55 Annual Merit Review (AMR) posters, 4 prior workshops, and 20 published protocols. There is strong engagement by the technical communities that receive funding from this project.
- Excellent progress has been made with this project. The project has completed 55 test protocols, with 35 identified for validation, and has published most of them in an open access journal.
- Progress is very good.

Question 3: Collaboration and coordination

This project was rated **3.9** for its engagement with and coordination of project partners and interaction with other entities.

- The collaboration and coordination with other institutions, including international partners, has been outstanding. The team is broad and distributed over several institutions, which enables it to engage with a wide range of AWST stakeholders. The workshops bring together a large number of people from the AWST communities, which promotes collaboration, and also require close coordination and collaboration to organize them and make them successful. The published articles demonstrate significant collaboration across many institutions and researchers, including international partners. The establishment of protocols and benchmarks will also positively impact the ability of the AWST community to communicate and understand the accomplishments and challenges of each AWST research/development effort.
- Many academic and national laboratories have participated in the first four years, with some international participation with speakers from the German Democratic Republic, Switzerland, France, and Norway.
- The project has excellent coordination with DOE, national laboratories, academia, and industry. International coordination is unclear but appears to be happening also.
- The four partners have really identified an excellent list of collaborators to write the protocols on slide 14.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The potential impact of accomplishing the goals of this project is critical to the progress and development of AWSTs. Previous efforts have been hindered because of challenges with understanding the performance of different conditions, systems, materials, etc., but the results of this project have the ability to greatly reduce those barriers and improve progress in each AWST area.
- Once it concludes, the project will have huge implications in standardizing test protocols, especially as the industry is growing and welcoming newcomers. This will also allow existing participants in this field to have a fair way to compare performance and lifetime achievements.
- The project advances benchmarking and protocols, which is an important step in supporting the Hydrogen Program's goals and objectives.
- The project's technical impact aligns with DOE goals.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The proposed future work is detailed and thoughtful and would add significantly to the success of this work. The one suggestion would be that the team should discuss how to increase the level of engagement with the community beyond what has previously been done or identify advanced testing protocols. For example, although the workshops have brought together various members of the AWST community, it could be expanded even further, for example, by creating sessions as relevant national meetings in which the community could provide results from their efforts framed by the protocols and benchmarks.
- The project has goals for future work similar to previous ones and is missing a vision for how this consortium will engage industry and government.
- The Fiscal Year 2023 Quarter 1 task is still listed as future work. It would be good to identify the sites to validate the protocols.
- Completion of the work with input from various organizations is planned.

Project strengths:

- The project is well organized, making excellent progress with outstanding results, and has exceptional collaboration/engagement with a high potential impact.
- The project's technical expertise is outstanding and well balanced across the major disciplines. AMR reporting and the annual workshops serve the role of external reporting.
- Prioritization and verification of protocols are the biggest strengths.
- The project has an excellent, dedicated team and is making very good progress.

Project weaknesses:

- This is more of a challenge than a weakness: there is a current lack of well-defined approaches to continually update protocols and benchmarks. The project mentions updating, but how updates will be made is not yet well defined.
- The project could clarify the frequency and mechanism for internal engagement among the consortium members (i.e., weekly, monthly, etc.). Perhaps the National Renewable Energy Laboratory Advanced Water Splitting Materials SharePoint is effective at this. It is cited in the AMR as the only other mechanism.
- While it is early, including new and emerging solid oxide electrolyzer technologies must be considered. The protocol should allow flexibility to expand the range of conditions to test that still give comparable data. This may emerge as the protocols are developed and validated for the current state-of-the-art technology.

- It will be hard to harmonize protocols across the world since each region will have its own sponsors and goals. Considering international input or validation would provide opportunities for harmonizing protocols.

Recommendations for additions/deletions to project scope

- It is unclear whether there is a mechanism for leadership turnover at the top level. This is essential to ensure technical innovation, engagement of external stakeholders (those not funded by this program), and fresh ideas from other informed stakeholders within DOE and academe. Engagement of industrial stakeholders is low or missing. It is unclear what outreach has taken place to bring in those stakeholders. It would be helpful to know whether there has been engagement from state governments, other than Colorado, and whether they see themselves as potential hosts for hydrogen technologies.
- More detail could be added about how to maintain a process for future protocol/benchmark updates. The team could describe how to continue to have community engage with the protocol and benchmark process, even after award end date, especially if this program no longer funds the workshops. This may already be implied in the proposed future work.
- Publications of protocols co-authored by international participants may make them stronger and acceptable worldwide.
- Progress is excellent. The team is encouraged to continue the good work.

Project #P-179: BioHydrogen (BioH2) Consortium to Advance Fermentative Hydrogen Production

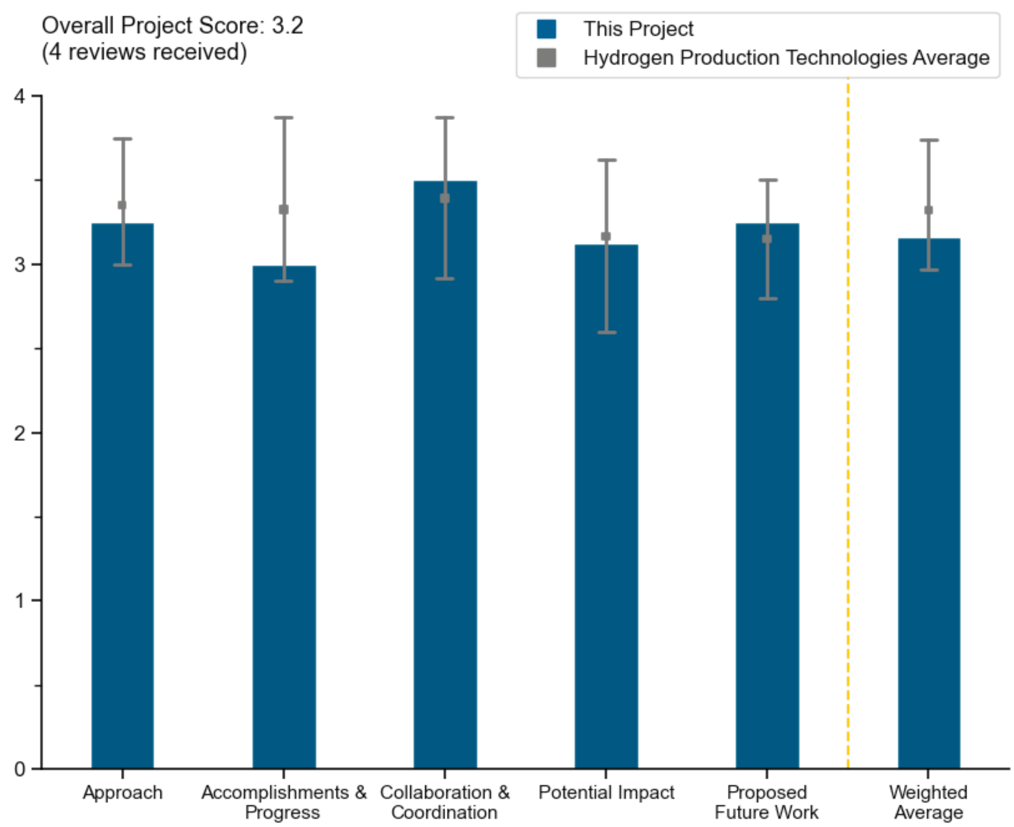
Katherine Chou, National Renewable Energy Laboratory

DOE Contract #	WBS 2.4.0.516
Start and End Dates	10/1/2018
Partners/Collaborators	Lawrence Berkeley National Laboratory, Argonne National Laboratory, Pacific Northwest National Laboratory
Barriers Addressed	• Capital cost • Feedstock cost • H_2 molar yield • System engineering

Project Goal and Brief Summary

The goal of the BioHydrogen Consortium is to develop a carbon-neutral microbial dark fermentation technology integrated with a microbial electrolysis cell (MEC) to convert waste lignocellulosic biomass into low-cost hydrogen. This collaborative team of national laboratory scientists aims (1) to improve the rates and molar yields of hydrogen production (moles of hydrogen/moles of sugar) via metabolic engineering of the cellulose degrader, *Clostridium thermocellum*, (2) to optimize the bioreactor for high solids loading to reduce reactor cost, (3) to develop an integrated MEC system to improve hydrogen molar yield and reduce fermentation waste product, and (4) to conduct a technoeconomic analysis (TEA) and lifecycle analysis with data generated by team partners to identify major cost drivers and guide integration efforts.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project has nice collaboration between multiple national laboratories in well-formulated tasks that cover the major technology areas for MEC-based conversion of lignocellulosic feeds (biology, reactor design, and electrochemistry). The sustained effort to address fundamental questions, with a track record of progress, is appreciated.
- The project comprises three parallel tasks for developing technologies for hydrogen production from waste lignocellulosic biomass and for conducting TEA for these technologies. The project stimulates collaboration between four national laboratories and groups developing different, but synergetic, technologies for hydrogen production. Task 1 improves biomass utilization to hydrogen production by employing enhanced pre-treatment and developing modified bacterial strains. Task 2 develops a bioreactor for a high yield of hydrogen under high-solids conditions. Task 3 develops an MEC for hydrogen production. The project needs to explain more clearly how the three technologies may be integrated or how each one is optimized for integration with the others, beyond just programmatic support. The issue of technology integration needs to be more clearly addressed in the next phases of the project.
- National Renewable Energy Laboratory (NREL) has developed a consortium with an effective approach to overcome the barriers of hydrogen production via a microbial pathway. The feedstock has been identified as costly. Perhaps more work can be completed to address feedstock, specifically approaches that eliminate the need to buffer feedstock.
- This is an interesting effort, with some significant progress toward scientific knowledge. Critical barriers have been identified and are addressed, but the progress toward the goal of hydrogen at a reasonable cost appears to have slowed. Based on the information presented, it is difficult to envision that the target of hydrogen cost on slide 14 by fermentation/MEC can be achieved, given the current status. This reviewer hopes to be proven wrong.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- Each task demonstrates significant accomplishments in the last year, showing significant improvement on the specific metric for each technology approach. TEA identified pathways for cost-reduction opportunities in the bio-hydrogen production route. Yet estimated cost of hydrogen production by these technologies remains significantly higher than even the older target of $2/kg, even after accounting for the projected improvements in the technology developments and for the hydrogen production tax credits. The project needs to analyze whether there are additional cost benefits, such as water removal, and particularly beneficial locations where the technology can be deployed that can help mitigate the higher cost of produced hydrogen.
- The NREL consortium is making good progress toward achieving the main objective of $2/kg. NREL could suggest the techno-economic framework for evaluating the levelized cost of hydrogen via the microbial process, as the levelized cost of hydrogen being calculated may not be consistent throughout all consortium members.
- The presentation, on slide 25, includes a table with quantitative metrics from 2021 Quarter 2 , not 2022, which is a problem. Some targets for 2022 and 2023 are mentioned throughout the presentation, but there is no summary table. From the material presented, additional progress has been achieved in 2022 (MEC current density and MEC total hydrogen production), but at least the former (40 A/m^2) is far from the numbers that are used in the TEA on slides 14 and 26. The TEA presented on slide 14 seems to show the current density and the electrode/material cost as the most significant components of the cost, while the impact of the work done in Tasks 1 and 2 is unclear. As a result, the fermentation process of milled corn stover (CS) versus unmilled CS versus deacetylated/mechanically refined (DMR) CS would affect the cost, or affect the productivity gains from the advanced engineered strains, and cannot be judged easily. Given the significant contribution of the MEC materials to the cost, more effort, such as another task, would be expected.
- The project continues to make advances in all four task areas.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The project provides for continuous ongoing close collaboration between teams in four national laboratories.
- NREL has great collaboration with all consortium members.
- Task leadership and required coordination among the tasks have been identified. However, the TEA work does not seem well connected with actual experimental information (see current activity assumed on slide 14). The TEA should reflect the current status based on the progress in the tasks and also guide the decisions on the path forward for the other tasks.
- The project has excellent collaboration at the national laboratory level, with what appears to be good leadership, but the project is limited by only national laboratory involvement.

Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The developing technologies can provide a commercially viable pathway for production of low-cost hydrogen in decentralized, small-scale facilities in remote locations and in developing economies thorough monetizing non-food biomass and organic waste streams. These possible benefits need to be quantified in the TEA to help mitigate higher projected cost of hydrogen production.
- This project/consortium executes an interesting effort to utilize some biomass toward useful forms of energy, in this instance, by hydrogen obtained through the fermentation/MEC approach. The project could comment on how this pathway compares with alternative pathways that utilize biomass, such as gasification, pyrolysis, and even fermentation to ethanol. The TEA team has this information and could help provide the relative value of a successful project versus alternatives.
- Inherently, MEC will be a niche hydrogen production pathway, but this is the type of project DOE should fund if DOE wants to build the credibility and applicability of MEC routes to hydrogen.
- The NREL consortium has excellent alignment with the Hydrogen Program and DOE research, development, and demonstration (RD&D) objectives and has the potential to advance progress toward DOE RD&D goals and objectives.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The project team is aware of the challenges for each of the three experimental tasks on slide 17. The actions on slide 18 toward overcoming the barriers, though, are not always clear or consistent. For example, one can envision how the Task 1 team is planning to use strain engineering to maximize yield using identification of key remaining chemical bonds in biomass to break. In Task 2, though, it is not clear how the decline of conversion at higher solids will be addressed. The questions the project could answer involve the current solids/conversion, the target, the impact of the improvement on the cost, and how “optimization” of the reactor, other than impeller geometry, would help. Also, since nitrogen blanketing has been identified as an issue, the project could clarify how this will be addressed. Furthermore, mixing/solids loading will be affected by scale as it is known in processes with solids in liquids. The specific path/plan to study the impact is unclear. Similarly, clarification is needed on the ideas to be tested for Task 3 to improve conversion efficiencies and hydrogen molar yield on milled biomass effluent. What seems clearer is the need for characterization and testing of different biofilms, which could potentially lead to better MEC design and operation. The additional gaps that should be addressed in the path forward are how scale will affect the operations (both at fermentation through mixing and at the MEC step) and the lifetimes of the membranes and electrodes. From the TEA slide, it is clear that the cost of hydrogen is quite significant, so lifetime/frequency of replacement should be important. The TEA does not indicate the replacement rate assumed, and the future plan does not specify if/when/how this parameter will be evaluated.

- The project's proposed future work will continue the ongoing development and has presented a good continuation plan.
- The NREL consortium is planned in a logical manner. Some uniformity in approaches to TEA should be identified. The TEA will help compare funded projects as technologies mature.
- The project should be open to exploring developments being made in other MEC projects, such as new electrodes.

Project strengths:

- The project develops technologies that would provide pathways for utilization of low-cost lignocellulosic biomass or negative-cost organic wastes for hydrogen production. Development and commercialization of these technologies will allow decentralized hydrogen production through waste biomass utilization.
- The project conducts a comprehensive investigation, looking at the pathway in its totality. It appears that progress has been achieved in the three investigative tasks.
- The project has a strong focus on fundamentals with strong collaboration among national laboratories.
- The national laboratory leadership lends to the project's strength.

Project weaknesses:

- The project's future path is unclear, given the achieved stage. The presented TEA does not seem to be representing actual progress; it would be helpful for the TEA to include actual process/experimental parameters and inputs as factors in the analysis to clearly guide the experimental work toward the most impactful steps.
- It is not clear how synergetic the technologies are. Overall integration strategies should be considered early in the project to promote optimization of each individual technology's performance in a way that benefits the other components.
- The project does not engage potential commercialization parties and could look at including an advisory board.
- The TEA is a project weakness.

Recommendations for additions/deletions to project scope:

- Steps/actions in the TEA have been recommended, specifically comparing alternative pathways for feed and potential impact of successful completion of the overall target's next steps. The study of scale effects and lifetime of electrodes/membranes should be included in the path forward. It does not seem that the planned optimization of the lab fermentation reactor is needed at this stage, based on the information provided, and scale and strain developments may deem this work irrelevant; it could be a candidate for deferment unless TEA shows otherwise. The tornado in the TEA indicates that improving above 175 g/L loading has a relatively small effect on the hydrogen cost. If the target has been achieved, clarification is needed on why work is continuing on solids loading. The TEA uses a base case of 66 A/m^2 (current case), while the experiments indicate that only 40 A/m^2 has been achieved. If so, the current case should adjust for the lower current density. The project should clarify how realistic it is to project a higher (300-500 A/m^2) future state if only 40 A/m^2 has been achieved. Clarification is needed on the cost at the current demonstrated density. The project could clarify the impact of using unmilled biomass versus milled versus DMR biomass in the overall cost. Additionally, the project could clarify the issues related to using less treated biomass.
- Regarding the TEA, the project could be clearer about where and how CO_2 will be captured for the carbon capture and sequestration cases and how this project will lower feedstock costs. The project could also increase coordination between Task 1 and Task 2 since the reactor design may benefit from changes in microbe performance. Lastly, the project could consider including feedstock pretreatment options, such as are being championed by Idaho National Laboratory.
- The project could look at approaches that eliminate the need to buffer feedstock. The project could also outline an offtake pathway so it can be modeled and costed by all consortium members.

Project #P-184: Scalable and Highly Efficient Microbial Electrochemical Reactor for Hydrogen Generation from Lignocellulosic Biomass and Waste

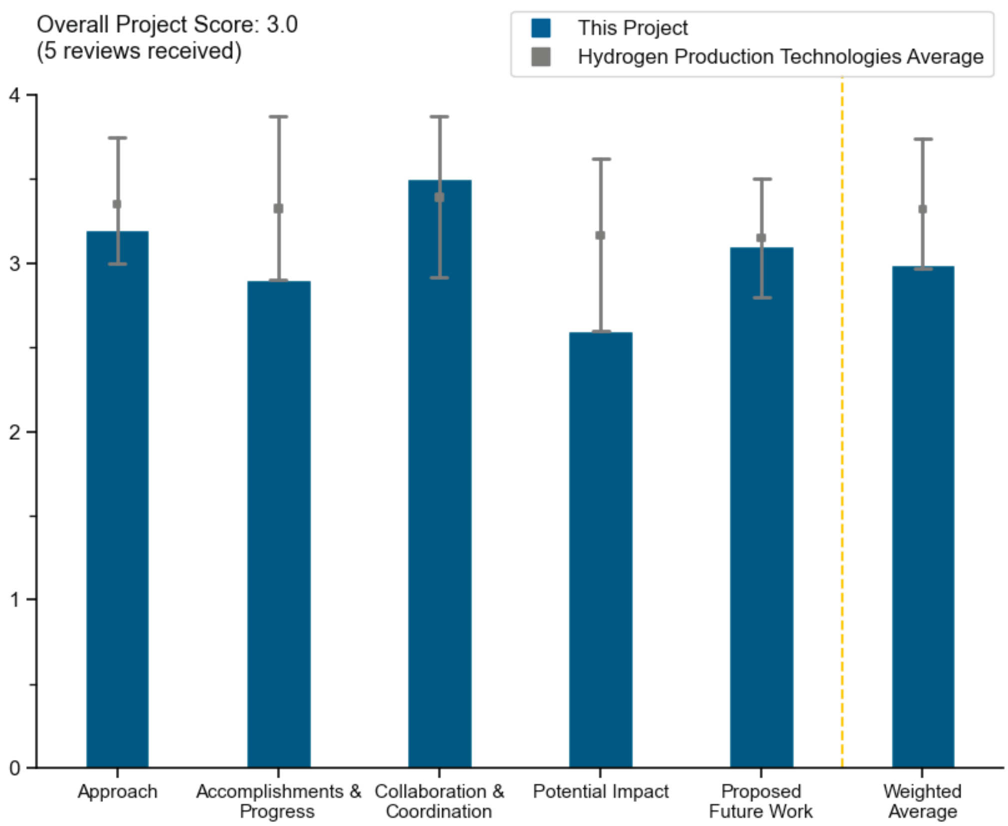
Hong Liu, Oregon State University

DOE Contract #	DE-EE0008844
Start and End Dates	10/1/2019–3/31/2024
Partners/Collaborators	Texas A&M University, Pacific Northwest National Laboratory
Barriers Addressed	• High electrode cost • Low hydrogen production rate

Project Goal and Brief Summary

This project is developing a scalable hybrid microbial electrochemical reactor to produce hydrogen from waste streams. The reactor design combines fermentation and microbial electrolysis cells (MECs) and includes low-cost electrodes and catalysts. Robust microbial communities will be used to optimize operating conditions, reducing the operating cost. This project will provide a method of producing hydrogen from waste streams at a cost of close to or less than \$2/kg H_2 (the DOE target).

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Based on the data presented, the project team has made great progress on the topics of identifying, building, and testing less expensive electrodes in a microbial reactor. The project team has presented solid technical information in demonstrating the project's solution in the right scale.
- The project addresses MEC performance through better anodes and cathodes. The project does a good job of exploring some new ideas. Real waste streams were investigated, which exposed limitations and is commended. The team seemed open to investigating surprising results that lead to a novel additive-free approach to reducing the impact of hydrogen scavengers.
- The low current density in MECs represents the most critical barrier toward commercialization, and the current project aims at addressing these barriers by developing high-performance and inexpensive electrode materials and by focusing on the reactor scale-up. The project is well-defined and -designed.
- The project objectives are to develop MEC components that provide significant cost reduction to the anode and cathode of the cell and to increase operation current density, which together would reduce the capital cost of the MEC system. Building a demonstration of a system having multiple cells at 10 L reactor size is ongoing. These are reasonable objectives to the MEC development. The project needs to better assess the cost and conduct life cycle analysis of carbon nanotube production to determine whether this technology can be scaled up to higher production levels.
- The critical barriers to $2/kg H_2 via microbial electrochemical reactor development have been clearly identified by Oregon State University (OSU). This project is in its final stage, with many of the milestones having been successfully completed. A few tasks will be tackled within the next year, but the project might be underspent. A more detailed review of funding might be appropriate at the next technical review.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and DOE goals.

- Progress has been made in developing a lower-cost anode and cathode. Replacing carbon cloth material with Ni mesh on the cathode appears to reduce the cost and increase the current density. High current density in the cell was demonstrated in fresh wastewater but rapidly decreases with time. The project indicates that pre-fermentation of the wastewater would be required to sustain high-current-density operation. The cost of this additional pre-treatment step needs to be estimated.
- The project is proceeding well toward the planned milestones. However, the decrease in current density with real fermentation effluents can be problematic. The need to add buffer capacity to the solution (either by adding salts or basifying the solution to self-generate a bicarbonate buffer) can limit commercial-scale application with real wastewaters. The low performance with large volatile fatty acid (VFA) variability represents another obstacle.
- OSU has about a year to complete the project. It is not clear whether the project will meet the cost target of $2/kg H_2. OSU has made good progress in developing a reactor, as well as testing microbes to make hydrogen. As outlined in previous reviews and answered by the principal investigator, OSU has made progress on updating the techno-economic analysis (TEA), as well as in reactor durability.
- The progress toward the project objectives is obvious.
- It appears solid work has been done, but the project has not yet pulled together to demonstrate overall improvement in cost or productivity. This should be a focus for the next Annual Merit Review.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The collaboration between OSU, Texas A&M University (TAMU), Pacific Northwest National Laboratory (PNNL), and Mazama Brewing seems to have been fruitful. OSU shows good interactions between its partners. Mazama Brewing should allow for a good demonstration of the proposed reactor. The project could have identified an off-take customer. The project could identify a local off-take customer for follow-on of this work.

- The project has close working collaboration between OSU, TAMU and PNNL. The industrial brewery partner has been identified to supply the wastewater for 10 L reactor testing and for further technology commercialization.
- The project has collaborations on new materials, electrode performance, and waste feedstock. The project may want to add a collaborator if waste stream pre-treatment is an axis that needs to be explored.
- The project has good synergy between the different entities.
- The project appears to have reasonable collaboration, although this is difficult to judge from a single presentation.

Question 4: Potential impact

This project was rated **2.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Inherently, MECs will be a niche H_2 production pathway. The main objective of this project is to develop improved electrodes, but it is unclear how much of an impact this will have. The project's TEA suggests that most revenue for the system operation arrives from the credit for reduction of biochemical oxygen demand (BOD) of the brewery wastewater discharged into public wastewater treatment facilities. It was also suggested that the MEC technology cannot fully clean the wastewater, and further discharge to the public facility would still be required. Yet full credit for the wastewater cleanup was taken in the TEA.
- The project indicated that this MEC technology would be applicable to medium-size breweries with capability to produce about 1,000 kg H_2/day. While this may be a significant amount for local application, the number of facilities where this technology would be applicable is fairly low, so this will remain a niche market. Further purification of H_2 was not accounted for either.
- Impact may be reduced by the limits of the system due to the need to increase buffer capacity. The fact that the current drastically decreases with real effluents can limit impact. The final goal for H_2 cost relies heavily on credits.
- OSU has proposed a careful program to address the DOE goals for hydrogen production through biological methods. Without an off-take approach, it is difficult to rank how well this effort aligns with the Hydrogen Program and DOE research, development, and demonstration goals and objectives.
- The data and analysis presented in the package have not demonstrated how relevant the delta is in the cost of the hydrogen from the lower electrode cost, which, based on some information in the presentation, can be estimated as quite small. So, although lower cost is always good, it is not convincing that the low-cost electrodes pursued will be crucial toward the pathway of lowering the hydrogen cost. This reviewer is looking forward to information to be convinced otherwise.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- OSU has effectively planned the project to address the DOE goals for hydrogen production through biological methods. The program has been executed well against its project plan. The technical achievements may not be met within the next year. Although addressed by the principal investigator, the TEA may still need revision to achieve the fidelity found on other projects. When completed, this project will serve as a baseline for other efforts to generate hydrogen through biological pathways.
- The proposed future work is well planned and can further advance the project. However, the variability of the wastewater compositions has been overlooked. Only one effluent has been used and tested, which is not representative of the variability in effluent chemistry and compositions.
- The plan appears to be set to bring all the elements together.
- The proposed future work is reasonable for continuing technology development.
- The next phase should demonstrate the stability/lifetime of the system at a relevant scale. The plans indicate that, but they are rather economical on the specificity. In any case, the economics assume a "3 years for anode and 5 years for cathode" lifetime, so this should be a target. The plan for the next phases

indicates (Milestone 5.1) a 72-hour test, which does not appear long enough. The project should clarify how the long-term stability will be established in realistic feeds.

Project strengths:

- The project addresses the critical barrier of increasing MEC current density and performance. The project is aiming to develop novel, inexpensive material, which is critical to reaching the goals set for MECs. The team is working synergistically toward the completion of the specified goals.
- The project has an innovative approach to electrode materials and is receptive to new opportunities to improve MEC performance. Dropping the lignocellulosic biomass fermentation aspect was a good thing, as it allowed the project to focus on materials and challenges for less controllable waste streams.
- The project made good progress in lowering the cost of MEC electrodes and in increasing the current density.
- The project strengths are highlighted by the leadership provided by OSU. Identifying an industry sector and brewers to partner with could lead to the distribution of this technology.
- The project has good technical information and good documentation.

Project weaknesses:

- Most of the initial work was focused on synthetic media, overlooking the complex composition of real media. Only one wastewater type and composition appears to have been tested to date. The impact of the wastewater composition (low buffer capacity that needs to be increased by adding salts or generating bicarbonate in solution, VFAs) on performance can limit impact of the proposed work.
- The project weakness can be identified by not having clearly defined an off-take for the produced hydrogen. Off-take would ultimately define the price of hydrogen and thus help with determining whether the cost target of \$2/kg H_2 is adequate.
- It is not apparent how the several workstreams will come together to produce an improved MEC device. The project needs to clarify which electrode approach is better and how robust these developments will prove to be when put into a working device.
- The project is still in a very low technology readiness level, and it is not clear how much commercial interest there would be for technology application.
- The project has weak economics (based on the incomplete information this reviewer has).

Recommendations for additions/deletions to project scope:

- The project scope should make sure that the technology is evaluated with actual feeds to establish the long-term stability, especially compared to the more expensive alternative. A cheap electrode that does not last that long will not be the economic solution. The economics on slide 4 are somewhat confusing. The effect of the electrode material and production cost per kilogram of hydrogen is not clear. The project should clarify how significant the reduced-cost electrodes are per the \$/kg H_2. (The table suggests a capital cost contribution of \$1.2/kg, but it is likely not only electrode cost.) The project needs to clarify the electricity use per kilogram of hydrogen. (It shows cost, but there is no kWh/kg information or \$/kWh cost assumed.) Although the principal investigators have addressed another reviewer's question on the credits, this reviewer does not consider the credit applicable. Likely, BOD reduction can be achieved by fermentation alone in a waste treatment plant, so the electrolytic approach cannot use this credit that exists simply in the base case. Electrolysis allows the additional production of hydrogen, at the expense of power and electrodes. It is not clear if the cost applies to the electrolytic (additional) hydrogen or to the total (including the fermentation one). This needs explanation. According to the stoichiometry on slide 4, theoretically, only two-thirds of the hydrogen is due to the electrolysis (the rest is simple fermentation). Further from the data, slide 13 says, "Cathodic hydrogen recovery indicated that over 97% hydrogen was produced via the fermentation process, rather than the MEC process." One would then question what the benefit of electrolysis really is. It is not clear what the effect is of electrode lifetime per kilogram of hydrogen. This information is likely crucial, so an indication is needed. In addition, it appears that "[b]utyrate and propionate are found to decrease the maximum attainable current density and could not be utilized in MECs," and as a result, treatment is necessary. The project should clarify how the cost of hydrogen produced here (including hydrogen separation/purification cost, sludge treatment, pre-treatment, etc.) compares to electrolytic hydrogen from water derived from the same wastewater (after necessary pretreatment).

- The project should engage PNNL (or other national laboratories) to do a detailed TEA, including all known non-energy operating and manufacturing costs (e.g., nutrients and buffers). An outcome of that analysis would be how sensitive the hydrogen production cost is to the cost of electrodes. Also, as presented, one might conclude that the main utility of MECs is a waste stream (partial) treatment technology, with hydrogen as a side hustle; the project should address this.
- The main suggestion is to implement tests with different wastewater types/sources. If brewery wastewater is the main target, effluents from different companies need to be tested in the MECs.
- No change of scope is recommended.
- The reviewer has no additions or deletion to the current project scope.

Project #P-196: H2NEW Consortium: Hydrogen from Next-Generation Electrolyzers of Water

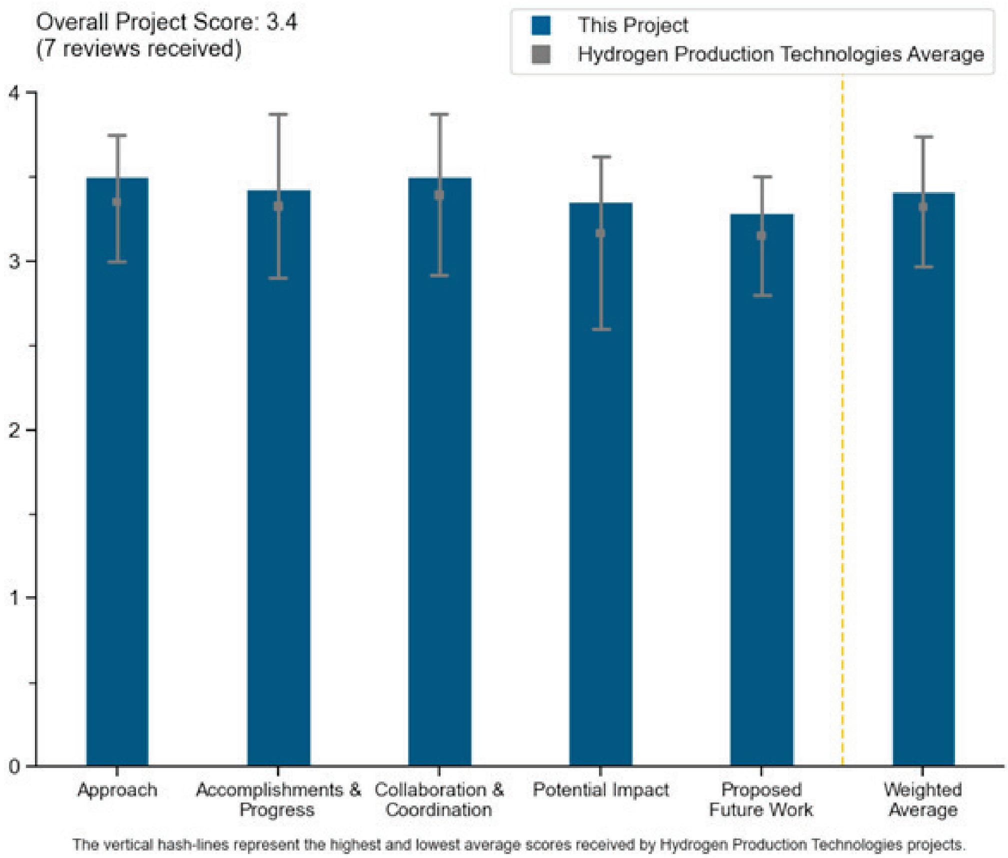
Bryan Pivovar, National Renewable Energy Laboratory, and Richard Boardman, Idaho National Laboratory

DOE Contract #	multiple
Start and End Dates	1/1/2020
Partners/Collaborators	Argonne National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, National Energy Technology Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, National Institute of Standards and Technology, SLAC National Accelerator Laboratory, University of California, Irvine, Carnegie Mellon University, Colorado School of Mines
Barriers Addressed	• Durability • Cost • Efficiency

Project Goal and Brief Summary

The H2NEW (Hydrogen from Next-generation Electrolyzers of Water) consortium is a comprehensive, concerted effort focused on overcoming technical barriers to enable affordable, reliable, and efficient electrolyzers that can achieve <$2/kg H_2 by 2026. H2NEW is studying both low-temperature electrolysis (LTE), based on proton exchange membrane (PEM) and liquid alkaline technologies, and high-temperature electrolysis (HTE), based on oxide-ion-conducting solid electrolyte. The core H2NEW national laboratory team is addressing components, materials integration, and manufacturing research and development. The team is working to improve scientific understanding of the performance, cost, and durability tradeoffs in electrolysis systems, including under predicted future dynamic operating modes, by using a combination of experimental, analytical, and modeling tools.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is needed work to meet the hydrogen production cost target: a consortium that includes multiple national laboratories to bring in experts to address technology barriers, with input from industry stakeholders. The H2NEW consortium, led by Drs. Boardman and Pivovar, is a great example of massive collaboration between large cross-functional teams across national laboratories. It was a pleasure seeing such a large effort and progress; this is well done. Developing cells, stacks, and testing stands for larger systems is going to be beneficial for the industry—and mostly for start-up companies, academia, and national laboratories. The project could consider incorporating a top-to-bottom approach across the H2NEW consortium regarding understanding what customers need, who will be buying hydrogen, and what operators/owners who will be running hydrogen plants will need to meet customer demands. Major effort is spent on the technology but not enough on who would be buying, incorporating, or financing such technology. Developing such relationships or hiring industry consultants who can provide some guidance would be beneficial. Variable operation is an important consideration covered in the presentation. Perhaps the team could consider variable operation from the perspective of boundary conditions of the entire hydrogen production plant, not just the electrolyzer system. The team could reconsider levelized cost of hydrogen (LCOH) cost calculations, especially capital and operating expenditures, depending on the type of hydrogen off-take agreement (whether the customer will accept any interruption/variability in hydrogen supply and how such interruptions are accounted for in the LCOH). The project team could consider a side-by-side analysis of how development of alkaline technology in the United States compares to mature alkaline technology and technology deployment in the rest of the world.

- The National Renewable Energy Laboratory (NREL) has developed the H2NEW consortium to overcome the barriers of hydrogen production via electrochemical pathways. The critical barriers for each technology have been identified and are being addressed. The project is well defined and seeks to compare electrochemical hydrogen production technologies on the basis of LCOH. H2NEW has a steering committee, which comprises the top industry leaders in electrochemical hydrogen machinery. The committee enables H2NEW to address any challenges uncovered during the mass manufacturing of electrochemical hydrogen machinery.
- The lead for the HTE solid oxide electrolyzer cell (SOEC) part of H2NEW has been able to piece together an excellent team and appears supportive to team members. However, the SOEC should benchmark the PEM work, primarily at NREL, which has an excellent organization and structure. Key issues have been methodically isolated and effective strategies developed there. Approach focus in HTE must be on quickly lowering cost, lowering area-specific resistance (ASR), increasing the current (hydrogen production rate), improving longevity and heat addition into the SOEC, and disseminating the results to real energy system integrators. Given the state of progress, the approach for LTE should be in performance, manufacturing, durability, and dissemination of results to energy system integrators.
- The project has clear evidence of a fully developed approach that shows a pathway from bench-testing to scale-up verification.
- This is a very comprehensive and complex project that needs tremendous leadership and coordination from the principal investigators. The low-temperature water electrolysis (LTWE) part covers important components such as catalysts, membranes, and porous transport layers (PTLs). However, new catalyst (TiO_2 supported catalyst) and thinner membrane (e.g., Gore 80 micro membrane) are not included. The ink stability and coating study is meaningful for the scale-up and manufacturing (slide 28). Alkaline water electrolysis is a new plus. However, the principal investigators need to consider the challenges of the integration between the intermittent renewables and the electrolyzer. Advanced diagnostics tools, such as x-ray absorption spectroscopy (XAS) and neutron imaging, have been implemented to pinpoint mechanisms. LTWE and high-temperature water electrolysis (HTWE) are quite different in terms of materials, approaches, and technology readiness levels (TRLs). Therefore, it is not logically reasonable to combine them into one presentation. They can be split into two different projects or presentations.
- The team has done excellent work. A wide range of accomplishments were reported. However, it is unclear how the approach has been selected for each task.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- Great accomplishments have been made in the past year, including benchmarking baseline proton exchange membrane water electrolysis (PEMWE) performance across different laboratories, mechanisms for Ir oxidation and dissolution, PTL interface, and membrane thinning. Liquid alkaline water electrolysis (LAWE) has been added to the scope of work. Baseline performance has been established rapidly. LAWE performance using stainless steel is higher than using Ni, but it is hard to interpret the data. The benchmark PEMWE performance decay rate (4,000 hours) 28 µV/h is still high. The decay rate should be 10 times lower (3 µV/h). Oxygen crossover and contamination are two different subjects and should be on different slides. For the HTWE part, the work of identifying stressors is meaningful to analyzing degradation mechanisms. For HTWE on slide 56, nano-computed tomography (nano-CT) shows high-quality pictures of interface densification. It is really a great job. The project could consider how LAWE can be integrated with the renewable impermanency. Reverse current during shutdown can lead to fast decay of the electrodes. In addition, shunt current is a great challenge. The project needs to report Faradaic efficiency.
- The H2NEW consortium has achieved several significant milestones in the development of low-temperature electrolyzers, including basic science approaches to durability and approaches to calculating the LCOH. The work on understanding utility pricing of electricity is also prized, as it is used by industry when considering hydrogen plant locations. Each of these accomplishments is a step that enables DOE to meet the $1/kg H_2 goal.
- Accomplishments have shown significant progress toward understanding most aspects of cell and subcomponent design, related to cost and durability. Testing has been done to simulate real-world

environments to project how LTE devices will respond under the cycling conditions expected in applications tied to renewables.

- Significant progress has been made. However, because of the large amount of information and many details given in the presentation, it is difficult to assess the effect of the accomplishments/progress toward the project and DOE goals.
- The project has made very good progress. However, the frequency of meetings to seek stakeholder input is unclear.
- Excellent progress was made in LTE and HTE.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The H2NEW consortium hosts technical reviews and steering committee meetings to interact with each of the consortium members. These meetings often comprise breakout sessions to best collect input to refine H2NEW programs.
- The project has clear demonstration of successfully collaborating and leveraging the different lab, academic, and industrial partners.
- The project appears to be well coordinated to bring in expertise from a variety of laboratories and industrial partners.
- The project has excellent collaboration among national laboratories and universities.
- The collaboration for this project is really strong between national laboratories. However, the participation from the universities and industries is weak, although some industrial members sit on the advisory committee.
- The presenter did not provide examples or describe the approaches/procedures to ensure full participation of every member of the consortium and have appropriate coordination/strategy of the activities between many members of the consortium working on different tasks and different technologies.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has clear evidence of the potential impact. The project has a cost analysis included in technical progress to show areas of focus needed to drive $/kg down to the targets needed for broad electrolysis deployment. Technical work has shown significant progress toward development of materials and understanding that work toward DOE cost targets for hydrogen.
- The H2NEW consortium is critical to the Hydrogen Program and has potential to significantly advance progress toward DOE research, development, and demonstration (RD&D) goals and objectives. This is specifically found in the efforts to rank emerging technologies against LCOH metrics. This ranking can help DOE better plan future funding opportunity announcements to ensure the Department's RD&D goals and objective can be effectively met.
- Addressing key technical and cost barriers would be critical in transitioning the energy sector toward renewables.
- The project aligns very well with the Hydrogen Program and DOE RD&D objectives.
- This project is very impactful because of its substantial investment from DOE, the scope of work, and some insightful results. However, the project can become more significant if it can come up with solid strategies for performance improvement and degradation mitigation. Given the substantial DOE investment, it is very much to be hoped that the project can produce transformative results rather than incremental improvements. Technology transfer efforts and outcomes are not strong.
- The Idaho National Laboratory presenter mentioned the proton-conducting solid oxide electrolysis cell (P-SOEC) and alkaline technology development. The protonic P-SOEC technology, whatever advantages it may eventually have, once validated, has a low TRL and Faraday efficiency and no industrial partner in the

forefront of development. It is uncertain whether the project should continue to be pursued, other than as an academic curiosity. DOE has driven three or four fuel cell technologies to demonstration. The cost of developing a fuel cell technology to the demonstration stage has historically taken at least a $1 billion and decade(s) per technology. Developing to demonstration or market such a low-TRL (incredibly small millimeter scale) and unvalidated technology such as P-SOEC will take a billions of dollars and decade(s). There are eight years left to 2030 and only limited funding to reach the Hydrogen Program goals. There will be insufficient time for such protonic technology to impact 2030 or perhaps even 2050 goals. HTE proton-conducting technology should clearly be beyond the scope of HydroGen and H2NEW. The alkaline appears to have already been commercialized to some outside the United States.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The H2NEW consortium is planned in a logical manner. The consortium has the appropriate decision points to update its focus if an emerging technology shows promise.
- Proposed future work clearly identifies remaining challenges and high-level goals for future work.
- The project appears to be on track to accomplish the stated objectives.
- Proposed future work at SLAC and other locations to focus on in operando degradation work is exploratory in nature, may not ever be relevant, and may detract (in a funding-constrained program) from the real purpose. The focus of all the research in the Hydrogen and Fuel Cell Technologies Office (HFTO) is to drive to the 2026 goals of low ASR, high current, and rapid acceleration to deployment to meet 2030 and 2050 goals.
- The proposed future work is just a list of project tasks. It does not highlight most imminent challenges or provide priorities of the future work.

Project strengths:

- This project has many strengths. In HTE, Pacific Northwest National Laboratory (PNNL) is providing solid contributions toward material characterization, standardization, and testing. Industry, per se, is not likely to share its own information and may shut out others, reducing the speed of their own commercialization and the meeting of HFTO goals. A basic shared understanding and information transfer (Data Hub) and distribution across all Hydrogen Program areas will help achieve HFTO goals and objectives. PNNL is correctly focusing on standard technologies and materials sets. Some researchers think it would be great to do endless investigation into promising alternative materials. However, continuously jumping around and changing materials sets (with low or no repeatability) leads to new and more developmental challenges each time and to ever-longer development cycles and not to meeting HFTO goals.
- The project has a strong and capable leadership team and is addressing the most important elements of LTWE and HTWE. Great accomplishments have been made in the past year, including benchmarking baseline PEMWE performance across different laboratories, mechanisms for Ir oxidation and dissolution, PTL interface, and membrane thinning. LAWE work has been added to the statement of work.
- The H2NEW consortium strengths are found in the industry-based steering committee. The focus on the LCOH as a metric also aligns the consortium to enable DOE to meet its goals.
- The project has strong collaborations and well-planned technical work, which is supported throughout with a techno-economic analysis to identify areas of focus.
- The project has a broad range of activities addressing various aspects of different hydrogen technologies. The project involves many experts in different areas from national laboratories.
- The project team make-up is the biggest strength.

Project weaknesses:

- No major weaknesses are identified in the H2NEW consortium. A consortium weakness could develop as the number of projects it oversees continues to grow.

- At this stage, the project appears to be fixed on a certain cell design and materials. Incorporation of new and emerging materials is valuable and expected to happen soon.
- The collaboration with the industry is weak at this time, with national laboratories playing a dominant role. Technology transfer outcome is weak, and the results are incremental, not transformative.
- The use of accelerated testing may have limited usefulness. Focus must be on lowering cost, lowering ASR, increasing current (hydrogen production rate), and improving longevity and heat addition into the SOEC.
- The priority for the different project activities is not well defined. It appears that activities/focus areas have been selected based on expertise at national laboratories. There is a need for broader participation.

Recommendations for additions/deletions to project scope:

- The H2NEW consortium showed leadership in developing a reference design for a liquid electrolysis system, which was required, as liquid electrolysis is showing promise of maintaining dominance as electrochemical machinery for hydrogen production. It is proposed that the H2NEW consortium develop a reference design for a gigawatt to help guide industry in this development. Also, establishing pathways to hydrogen off-take can also aid industry.
- Highly integrated synchrotron x-ray diffraction (XRD), with questionable relevance to well-developed commercial materials sets and to the real cell operational conditions, may be beyond the scope of this effort, with such limited funding being available. The goal is to quickly lower ASR, increase the current density, and improve heat addition into the SOEC to meet 2026 HFTO goals. The project is still performed solely by national laboratories, so industry participation is largely missing. Industry participation is a key aspect of HFTO; all work needs to be integrated with industry.
- Regarding the collaborations with universities and industry, some tasks can be undertaken by universities at lower cost and by industry at larger scale. Technology transfer needs to be strengthened. The results need to be adopted by industry. In the future, the project can be divided into two projects, LTWE and HTWE, which can be presented separately. Fundamental investigations are good, but the project's insights on performance improvement and degradation reduction need to be specified.
- More focus, defined priorities, and broader participation are recommended for this project.
- Near-term, highly focused efforts are needed.

Project #P-197: Advanced Manufacturing Processes for Gigawatt-Scale Proton Exchange Membrane Water Electrolyzers

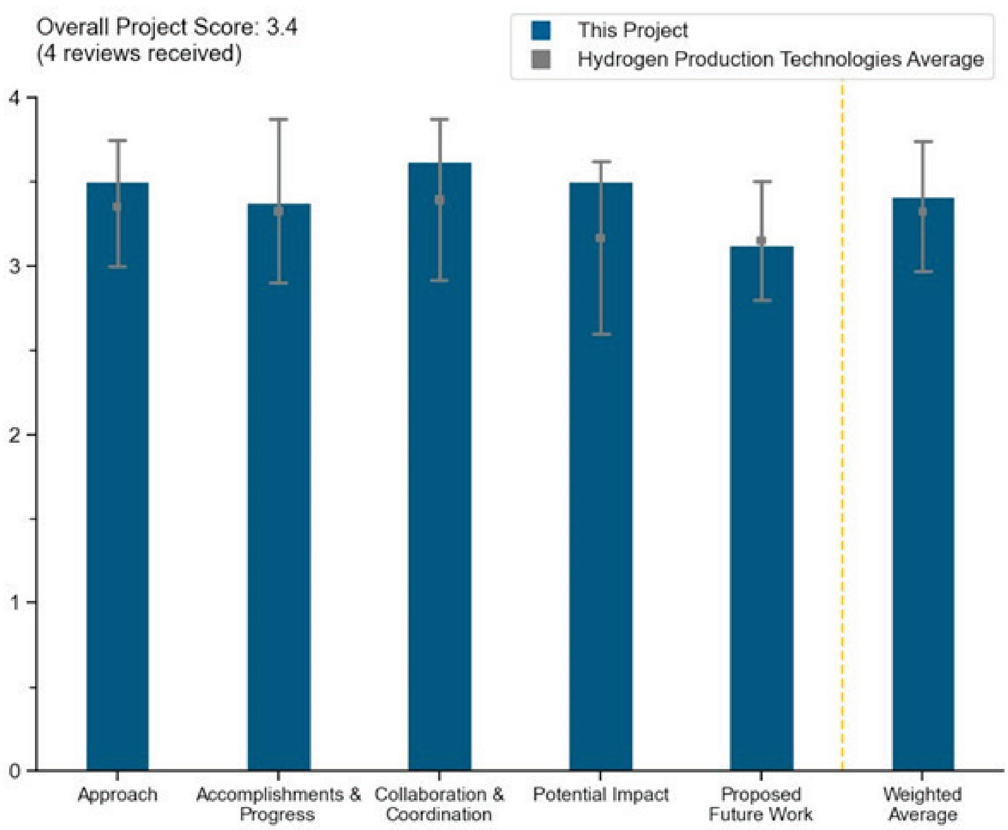
Andrew Steinbach, 3M Company

DOE Contract #	DE-EE0009237
Start and End Dates	1/1/2021–9/30/2024
Partners/Collaborators	Giner, Inc., Plug Power Inc., National Renewable Energy Laboratory, Oak Ridge National Laboratory
Barriers Addressed	• Capital cost • Manufacturing

Project Goal and Brief Summary

This project aims to develop manufacturing processes for reproducible and uniform proton exchange membrane water electrolysis (PEMWE) components at commercial scale, specifically for an oxygen evolution reaction (OER) catalyst, electrode, and thrifted catalyst-coated membranes. Once developed, these processes will be scaled up to gigawatts per year, and component production will begin. The produced components will then be assessed and validated for efficiency, durability, power density, and low iridium content in megawatt-capable stacks relevant for gigawatts-per-year deployment scale. If successful, this project's results will help satisfy industry needs for high-volume capacity PEMWE and reduced manufacturing costs for the necessary components.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project is timely and directly addresses the current needs for manufacturing gigawatt-scale catalysts and electrodes. The approach to developing low-iridium-loaded catalyst-coated membrane manufacturing, while also demonstrating the performance and durability in high-pressure differential operation, is addressing the barriers and is on the right track.
- The team is taking a strong technical approach based on addressing the most important needs for improved water electrolysis, including reducing Ir loading, increasing performance at high current, and improving durability.
- The Ir/nanostructured thin film (NSTF) has proved to be very promising as the OER catalyst for PEMWE. The NSTF has demonstrated great performance and durability simultaneously. The scalability of the Ir/NSTF powders, electrodes, and membrane electrode assemblies (MEAs) has been investigated. The catalyst cost has not been studied. 3M has been using its own membranes. For a comparison, 3M may need to test its catalysts with the Nafion™ membrane.
- The approach slide did not have much detail. The milestones were only in the back-up slides, and even those lacked details. It would also be good to compare the cost of this process to that of conventional catalysts.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- The team is making excellent progress in the efforts to develop improved NSTF-based electrolyzers, and the work is highly beneficial to the larger Hydrogen and Fuel Cells Technologies Office (HFTO) program. The 2,000-hour, steady-state durability test and the variable renewable energy test showed promising results, as did the highly accelerated stress testing on the modified catalyst. Overall, the NSTF powder approach seems to be achieving promising results.
- The project has made significant advancement in meeting the milestones. The project has also taken steps to address the drawbacks presented in the previous year. The project has met milestones regarding performance, durability, and loading targets and is on track to meet the manufacturing rate milestone.
- The 1,000-hour testing (5 A/cm^2, 300 psi) at Giner progressed very well. The MEA is very stable. However, the sudden H_2 crossover after 1,000 h increase is under question. A repeat needs to be done as soon as possible. The Ir/NSTF catalyst can achieve performance of <2.3 V at 10 A/cm^2 with low Ir loading (0.5 mg/cm^2) and with low decay rate of 1 µV/h. This low decay rate at high current density is particularly meaningful. The short stack data has not been demonstrated. The cost analysis of the catalyst and MEA has not been conducted.
- Excellent progress was shown on various aspects of the project. Excellent performance and durability data were shown. Two critical manufacturing steps still need to show progress toward project goals.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- The project involves good interactions between the lead (3M) and several subs, including characterization at Oak Ridge National Laboratory (ORNL) and National Renewable Energy Laboratory (NREL), durability testing at NREL, and testing/validation at Giner and Plug Power.
- The project demonstrated excellent collaboration with national labs and industry, leveraging their capabilities for diagnostics and further development of the MEA.
- There is excellent collaboration with Giner, Plug Power, and the National Renewable Energy Laboratory (NREL). The presentation does not show the contribution from Plug Power.

- There is good partnership with Giner, Plug Power, and NREL to cover all aspects of the project. If 3M is exiting polyfluoroalkyl substance (PFAS) manufacturing, then other partners need to be identified to provide PFSA membranes and ionomers.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project is very impactful because of its distinctive approaches, and encouraging results were demonstrated. The Ir/NSTF can become a new commercial catalyst if its cost can be reduced.
- Excellent durability and performance were demonstrated. If the project can show cost and manufacturing feasibility, it will have a very high impact.
- The project is highly relevant to HFTO efforts in development of gigawatt-scale manufacturing of electrolyzer catalysts and electrodes.
- If all continues to go well in this project, it could have a substantial impact by enabling higher-performing and more durable electrolyzers with reduced Ir content. Overall, the impact of the project could be quite positive. On the other hand, since the NSTF approach is highly specific to 3M, there is some question about how impactful the work will be to the broader community and some risk that the work could go to waste if 3M ultimately does not pursue commercialization.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The proposed work on addressing the manufacturing barriers related to rate and catalyst layer uniformity will help overcome the barriers in meeting the milestones.
- There is excellent proposed work with demonstrations in Giner and Plug Power stacks.
- A small, short stack (Giner) and large stack (Plug Power) are included in the future work. Economic analysis should be included in the project. 3M can work with Strategic Analysis to expedite this process.
- The future work makes sense and represents a logical path to addressing the project challenges, but the project would be more valuable if it included future work with a more science-focused effort that would be broadly beneficial to the electrolyzer community outside 3M.

Project strengths:

- The Ir/NSTF approach to make OER catalysts for PEMWE is very innovative. Remarkable PEMWE performance and durability have been demonstrated. The project has assembled a strong team that includes 3M, Giner, Plug Power, NREL, and ORNL.
- The work builds on a long history of NSTF development at 3M and excellent capabilities for manufacturing NSTF-based materials. The principal investigator is highly experienced and has an excellent focus on meeting project goals and pushing the technology forward.
- Excellent durability and performance were shown at low loadings. Thorough work was shown with durability testing under various conditions, including on/off and constant current over >1,000 hours.
- The main strength of the project is the development of capabilities to manufacture high-performance and durable electrolyzer MEAs. The team is capable of delivering on the targets.

Project weaknesses:

- The sharp focus on NSTF means that the project does not have much impact on approaches outside of NSTF, thus limiting the value and impact of the project in the wider community.
- The project needs to address the additional cost of NSTF manufacturing and demonstrate that the additional cost can be tolerated with improved performance or durability.

- The team needs to address the higher Ir dissolution rate with the low-loaded Ir MEAs. The benefit of Ir/NSTF over Ir/IrO_x nanoparticles is unclear.
- Economics analysis is needed to understand the cost of NSTF materials.

Recommendations for additions/deletions to project scope:

- Economic analysis should be included in the project. 3M can work with Strategic Analysis to expedite this process. Further Ir loading reduction to 0.25 mg/cm^2 and 0.1 mg/cm^2 is recommended. At low Ir loading, the effect of some contaminants needs to be investigated.
- The project would benefit from utilizing the capabilities of the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium to understand the Ir catalyst durability, for example, Ir dissolution of the NSTF catalyst using techniques such as online inductively coupled plasma mass spectrometry (ICP-MS).
- The project should add cost projections for NSTF and compare them to those of conventional MEAs.

Project #P-198: Enabling Low-Cost Proton Exchange Membrane Electrolysis at Scale Through Optimization of Transport Components and Electrode Interfaces

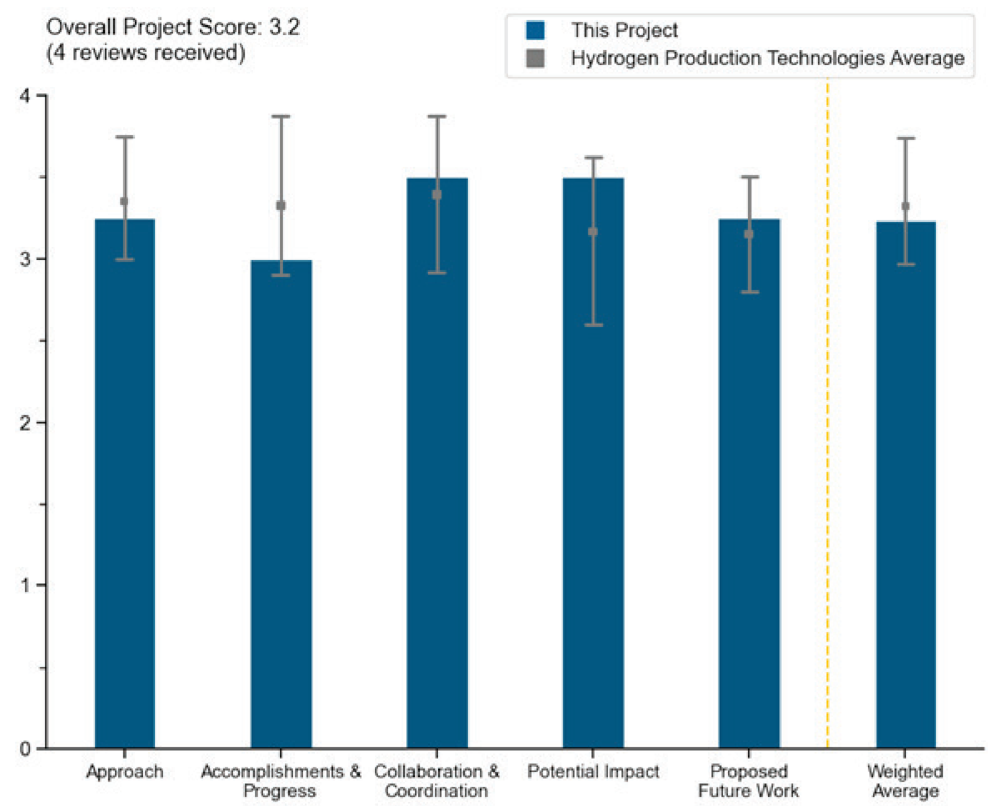
Chris Capuano, Nel Hydrogen

DOE Contract #	DE-EE0009238
Start and End Dates	10/1/2020–4/30/2024
Partners/Collaborators	National Renewable Energy Laboratory, Oak Ridge National Laboratory, De Nora Tech, LLC, University of California, Irvine
Barriers Addressed	• Capital cost • System efficiency and electricity cost

Project Goal and Brief Summary

This project aims to develop an optimized porous transport layer (PTL) designed for an electrolyzer system and upscaled to manufacturing level. The PTL serves many purposes: the distribution of water flow across the cell, the removal of gaseous oxygen from the anode, the establishment of contact between the anode and current collector, and the provision of mechanical support for the membrane. At present, available PTL materials are adapted from other industries' materials and not optimized for electrolysis. The addition of a microporous layer (MPL) to the existing design will provide a more closely packed pore structure immediately adjacent to the catalyst layer, balancing porosity with contact area. Porosity will also be balanced against mechanical strength to support hydrogen pressure. These improvements will enable good fluid management while providing a uniform interface to the catalyst and membrane. The PTL will enable integration of advanced membrane electrode assemblies (MEAs) in service of advancing electrolyzers toward the DOE cost goal of $2/kg.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project approach focuses on developing improved PTLs for proton exchange membrane water electrolyzers (PEMWEs), including MPL approaches that could provide improved catalyst utilization and higher durability. This project is addressing some of the most important barriers to clean hydrogen production. While the listed tasks are focused on PTL development, the presentation included several slides on seemingly unrelated work on catalyst characterization, ink properties, and testing of a large number of MEAs with different catalysts and loadings; the relevance of this work to the project seems limited.
- The project goal is to develop a PTL with an MPL. The project utilizes computational modeling and x-ray characterization in optimizing the PTL substrate and MPL morphological properties. The project is also developing coating methods to thrift platinum group metal coatings.
- This project works on the PTL and its interface with electrodes, which is a critical area for PEMWEs. The x-ray computed tomography (CT) is a powerful tool to investigate PTLs. DN catalysts do not have information. It is unclear what their differences are. This is a PTL project. It is not clear why IrO_2/NbO_x and IrO_2/oxidic support catalysts were investigated.
- There is a good, detailed approach with quantifiable milestones.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- The project is on track to the accomplish the milestones. Development of PTLs with MPLs is necessary for low-loaded anode catalyst layers needed to achieve Hydrogen and Fuel Cells Technologies Office (HFTO) targets regarding low-cost clean hydrogen. The project has demonstrated improved durability with low Ir loading.
- Significant progress has been made toward developing improved PTLs. Most importantly, the team has succeeded in demonstrating improvements in durability and reductions in Ir loading through the development and integration of improved PTLs. The characterization work at the University of California, Irvine (UCI) is providing valuable insight into the effect of pore size and porosity on oxygen removal. The work at De Nora Tech, LLC (De Nora) has yielded several promising PTLs, and the Nel Hydrogen work on developing coatings with reduced Pt content appears valuable, though a lack of any technical information about how the materials are made makes the progress of limited value to those outside the project team.
- Reasonable progress has been demonstrated, given the supply chain issues. The work at Oak Ridge National Laboratory (ORNL) (slides 12 and 13) and National Renewable Energy Laboratory (NREL) (slide 14) seems to be on catalysts and inks, while the main project is focused on MPL and PTL development. This needs to be integrated better. Longer-term durability tests are critical, and 100-hour testing might not reveal the true durability of these materials in the long term. Excellent short-term durability was demonstrated.
- The PTL has lower Ir loading. The MPL with Ir 0.1 mg/cm2 loading can achieve comparable performance to the baseline MPL with Ir loading 1 mg/cm^2. One major task is optimization of the MPL thickness, particle size, and porosity. No good data or progress has been shown. Not all the PEMWE performance is great. For example, the voltage is clearly 2.0 V at 1.8 A/cm^2. A partial reason could be the low operating temperature of 50°C. It is unclear why a higher temperature was not used. The presentation did not show advanced PTL manufacturing. Perhaps this is a partial scope of work of this project.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The project has a well-coordinated team to achieve the project targets.
- The project features excellent interactions between the lead and several subs, though some of the work performed by the subs does not seem particularly relevant to the overall project.

- This project has a strong team, including Nel Hydrogen, UCI, NREL, De Nora, and ORNL. It is not clear what the role of De Nora is.
- The ORNL work needs to be better integrated into the project.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Development of improved PTLs is one of the greatest needs to enable low-cost, durable electrolyzers, and this project could potentially have a substantial impact in this area. If successful, the project could enable substantial reduction in Ir and Pt content, helping to accelerate widespread deployment.
- The project holds significant relevance in the development and manufacturing of PTLs with MPLs, as the project has the potential to enable low-cost electrolyzers by thrifting an expensive Ir catalyst by improving the contact between the catalyst layer and the MPL.
- This is high-impact work if a better MPL can be developed to enable lowering Ir by one order of magnitude.
- The project will be highly impactful if all the proposed tasks can be completed and milestones met.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- The planned work is reasonable and appropriate to meeting the project goals, though inclusion of more work scope that could provide improved understanding and thus benefit the larger electrolysis community outside the project team would be valuable.
- The proposed future work aligns with the project milestones. Adding a target for ex situ compressive and bending mechanical evaluation of the PTLs to future work should be considered.
- Generally, the project has a good future plan. The project needs to work on optimization of the MPL thickness, particle size, and porosity.
- Long-duration durability tests are planned.

Project strengths:

- This project has a strong team including Nel Hydrogen, UCI, NREL, De Nora, and ORNL. The PTL and interface with electrodes are important research areas. The project has demonstrated some good characterization data using x-ray CT. The project can reduce the Ir loading to 0.1 mg/cm^2 by adopting a new PTL design.
- Nel Hydrogen is a leader in water electrolysis, so the company's engagement in the Hydrogen Program through this project is of great value. The team includes fantastic expertise and can make a real impact on accelerating electrolyzer development and deployment.
- The project has a well-coordinated technical team that has developed PTLs with MPLs that show improved durability and performance, with a reduction in Ir loading in initial testing.
- The project has an excellent team, and MPL impact on performance is significant.

Project weaknesses:

- It is unclear how screening supported the Ir catalyst and how developing coating methods integrates into this project.
- Some proposed tasks—such as optimizations of the MPL thickness, particle size, and porosity—have not started.
- Some of the presented work seems irrelevant to the project goals.
- Long-term durability and stack testing are still lacking.

Recommendations for additions/deletions to project scope:

- The project needs to focus on effects on PTL properties, such as MPL thickness, particle size, and porosity. The project needs to investigate PTL manufacturing improvements. The project should operate cells at more standard conditions, such as 80°C, to make better comparisons with data from other projects.
- The project should explore the benefit of MPLs regarding the deformation of the catalyst layer and membrane at high-pressure operation. The project should consider testing the durability of the PTLs and the coating under cycling conditions.
- The work on catalyst characterization does not seem to fit in this project. The work on ink coating and ultra small angle X-ray scattering (USAXS) also seems to be of little relevance. The resources could be better spent focusing on the core PTL work.
- The project should integrate the ORNL catalyst work into the project or redirect to PTL/MPL work.

Project #P-199: Integrated Membrane Anode Assembly and Scale-up

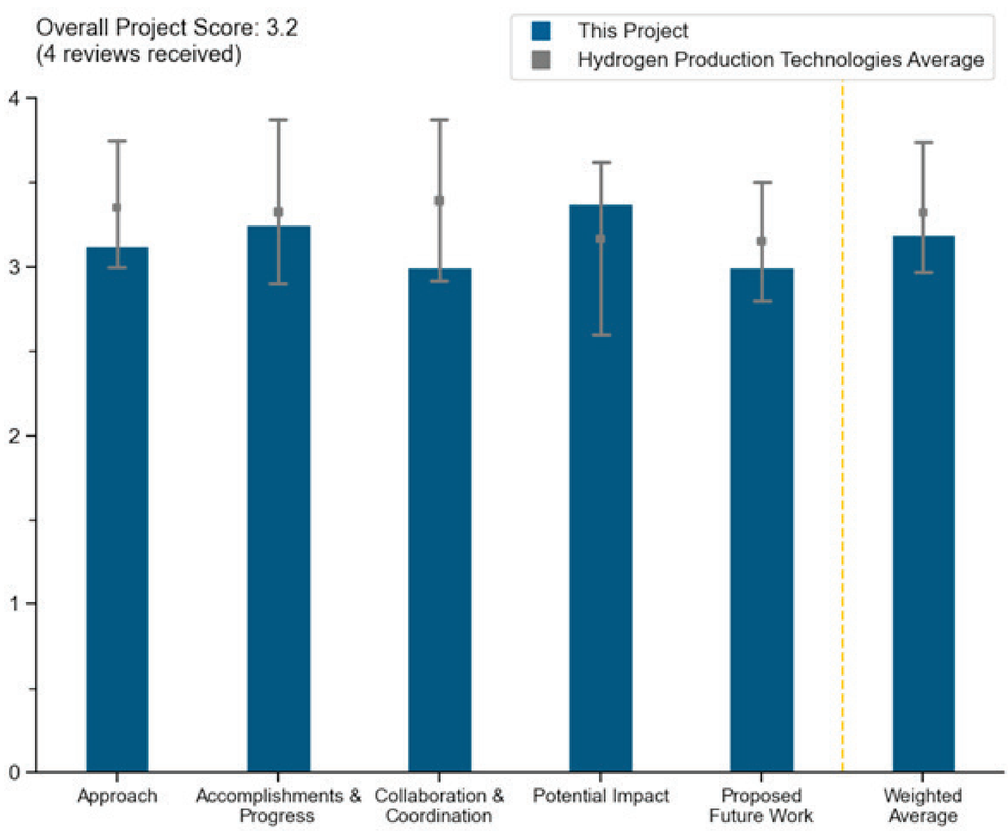
Adam Paxson, Plug Power Inc.

DOE Contract #	DE-EE0009236
Start and End Dates	8/1/2021–10/31/2024
Partners/Collaborators	University of Tennessee, Colorado School of Mines, Oak Ridge National Laboratory, National Renewable Energy Laboratory
Barriers Addressed	• Production volume • Component cost

Project Goal and Brief Summary

This project will develop and fabricate a single-piece, integrated membrane anode assembly with the aim of reducing electrolyzer capital costs. The status quo involves a time-consuming manufacturing process and expensive components. This project will implement innovative manufacturing processes and architectures to reduce the cost and fabrication time of the anode support structure and membrane electrode assembly (MEA), the most expensive components in an electrolyzer stack. Researchers will create a single-piece anode support structure (SPASS) and catalytic and ionomeric coatings. The coatings will be applied to the anode support structure's surface to form the integrated membrane anode assembly. The project will then scale up and demonstrate the production process.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project focuses on addressing key barriers to proton exchange membrane electrolyzer deployment through development of anode assemblies with reduced cost and increased performance. The exploration of multiple routes to improvement, including catalyst deposition through ink-based methods and electrodeposition directly on the porous transport layer (PTL), provides a promising route to increased performance, though an increased focus on reduction in Ir loading would be beneficial.
- The proposed approach of coating catalyst layer directly onto a PTL reduces the interfacial contact issues between the catalyst layer and PTL. Further coating of the intermediate ionomer layer with a gas recombination layer reduced the contact issues with the catalyst layer and membrane.
- It is not clear how the lattice Boltzman modeling ties to the rest of the project. It is unclear why Ru is being used since its long-term durability is known to be an issue. The SPASS design looks very promising in terms of lowering cost while improving performance over the baseline. The project needs to add membrane durability testing since the cast 2-mil membrane on a porous electrode will probably not have the mechanical strength of a similar free-standing membrane.
- The reviewer supports the innovative thinking behind the project, but it is not apparent how much this approach will impact the installed cost of an electrolyzer, much less the cost of hydrogen production. It is not clear whether the impact is through lower-cost materials or lower-cost manufacturing—and how much lower.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The project has demonstrated progress in development of methods for direct deposition of oxygen evolution reaction (OER) catalysts on the PTL, including extensive studies of the effects of alternate deposition methods. The excellent characterization results from Oak Ridge National Laboratory, which clearly show the morphology and elemental distribution of the resulting porous transport electrodes, are highly valuable. There was not enough data on durability, aside from the work on electrodeposited IrRu, which has known durability challenges.
- The project is on track to meet the project milestones after overcoming certain barriers related to ink penetration into the PTL. The project has the potential to reduce the interfacial resistance in MEAs while also reducing the manufacturing cost to meet the DOE Hydrogen Shot targets.
- This project has a challenging objective. The project seems to be behind in its timeline since it should have optimized and scaled up design at this point. The team may need to revise objectives to allow time to understand what is and is not working instead of pushing ahead to demonstration.
- The project has demonstrated good progress toward validating SPASS design. However, the baseline material seems to have the best performance in 50 cm^2 testing. This should be reconciled with the 5 cm^2 data showing improvements over the baseline.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- There is good collaboration with national laboratories for catalyst coating strategy and characterization. It is not clear how the University of Tennessee modeling contributes to the success of the project. If it is to guide a fundamental change in cell geometry (rather than reproducing the same geometry with a new manufacturing process), then more information needs to be provided.
- The project has overall good interactions between the team members, especially in the realm of characterization. The role of the modeling effort in driving progress on integrated anode assemblies is not very clear, though.

- The project has good collaboration between the partners but should tie the modeling better to the experimental work.
- The project included partners from national laboratories, with universities providing technical expertise needed to accomplish the project targets.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project is addressing some of the most important barriers and could have a large impact on electrolyzer development and deployment, though an increased focus on reducing Ir loading is needed to maximize the impact.
- The project has the potential to meet the large-scale manufacturing of the electrolyzer MEAs, which is also timely and necessary to meet the Hydrogen Program and DOE targets.
- It seems intuitive that simplifying the stack manufacturing process will lead to benefits, but a techno-economic analysis (TEA) is needed to validate and quantify this view.
- High project impact can lower manufacturing cost while improving performance and durability.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The proposed future work is well structured for overcoming the barriers and meeting the milestones.
- Most of the future work makes sense, but there was no mention of the catalyst electrodeposition effort or the plans for durability testing. A more detailed description of future work is recommended.
- Minimizing bleed through demonstrating 300 cm^2 stack performance will be critical to the success of this project.
- Moving to scale-up and demonstration at this point is not the best way to prove the utility of an integrated assembly, based on the remaining fundamental challenges that have been found to date.

Project strengths:

- Plug Power Inc. is one of the leaders in electrolyzer development, so engaging the company in the Hydrogen Program through this project is highly valuable. The strong efforts in development of catalyst deposition methods, as well as the excellent characterization, are key strengths.
- If all the milestones are met, the project has the potential to reduce the cost of MEA manufacturing, leading to low-cost electrolyzers.
- The project is ambitious, with an innovative idea to make a step change in stack design.
- The project has a good team with a very strong approach.

Project weaknesses:

- A stronger focus on Ir loading reduction and durability improvement is needed. While increasing OER activity and decreasing Ir loading through incorporation of Ru could be attractive, development of an approach to stabilized Ru is needed, given the well-known instability of Ru on electrolyzer anodes.
- Integration of the computational model to the SPASS is unclear, and durability improvement of conventional catalyst-coated membranes over SPASS is not well presented.
- The project has not conducted a TEA to calibrate the impact of innovations.
- The project’s modeling is not tied into experiments.

Recommendations for additions/deletions to project scope:

- The project should de-emphasize multiphase transport modeling or clarify why this aspect of the project is on the critical path for success. Potential tradeoffs with efficiency and/or durability should be addressed.
- The role of the modeling work is not very clear; shifting the associated resources to support other parts of the project should be considered.
- Membrane durability needs to be demonstrated with some on/off experiments.
- Stability of the catalyst layer coatings at high-pressure operation should be explored.

Project #P-200: Low-Cost Manufacturing of High-Temperature Electrolysis Stacks

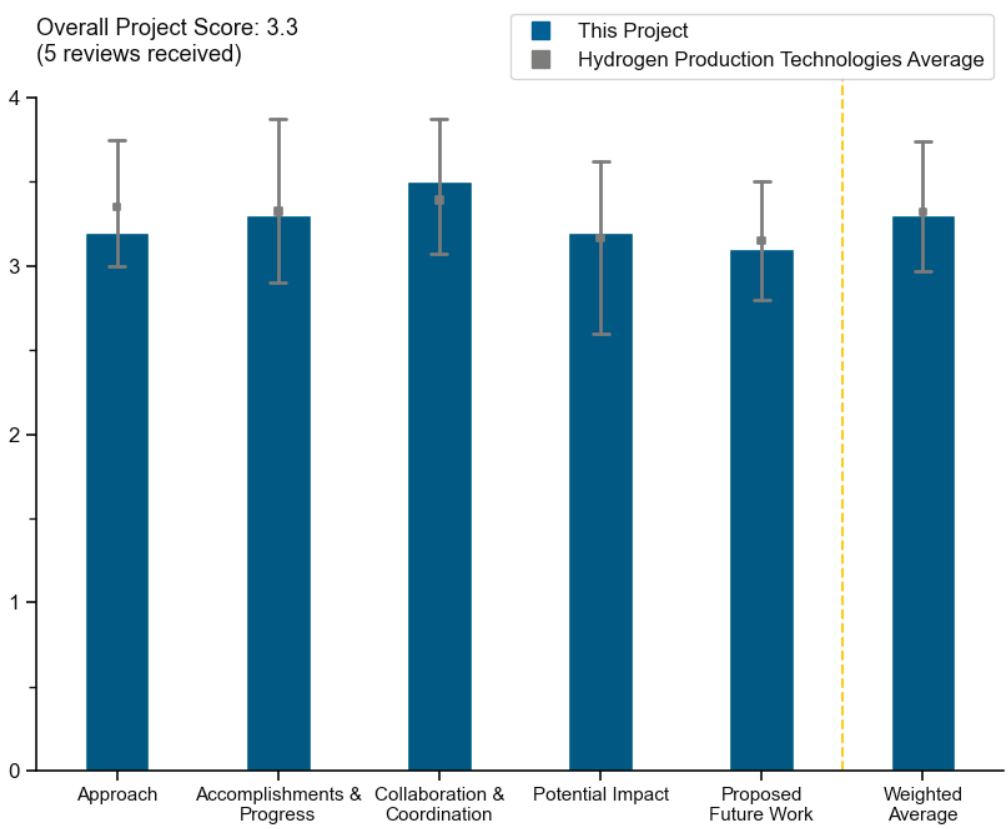
Scott Swartz, Nextech Materials, Ltd.

DOE Contract #	DE-EE0009621
Start and End Dates	4/1/2022–3/31/2022
Partners/Collaborators	Idaho National Laboratory, Strategic Analysis, Inc.
Barriers Addressed	• High-temperature electrolyzer stack cost • High-temperature electrolyzer electrical efficiency • High-temperature electrolyzer stack durability • Hydrogen production cost

Project Goal and Brief Summary

The project's goal is to develop cell and stack manufacturing technologies for high-temperature electrolysis (HTE) stacks. The primary objective is to achieve stack manufacturing costs below $100 per kilowatt, with a 15% reduction in cell costs through design optimization. The project will address key barriers, including high-temperature electrolyzer stack cost, electrical efficiency, and durability, by enhancing cell performance, stack durability, and manufacturability. The approach involves developing innovative cell and stack designs, reducing manufacturing costs, and conducting rigorous testing and analysis. Work in the second year encompasses updating baseline cost models, reducing electrolyte thickness to improve cell performance, implementing two stack cost reduction approaches, and testing stacks.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approaches that have been proposed and employed to reduce the solid oxide electrolyzer cell (SOEC) manufacturing cost are reasonable and feasible. It is very good to recycle the materials to further reduce the cost. The team also demonstrated that recycling materials can reduce the cost.
- In this project, the team identified several key areas that can reduce the cost of SOECs: changing electrolyte materials, recycling the tapes, and changing interconnect alloys. If the project is successful, the stack cost can be significantly reduced.
- The approach of conducting the cost study, performing various activities to reduce cell material and manufacturing costs, and confirming cost reduction via third-party validation is effective, and the work is well coordinated.
- The cost reduction processes are generally reasonable. However, the operating temperature (800°C) is still too high for metal interconnect loaded stacks. This could lead to fast performance decay. The team should consider ways to improve the cell performance to lower the temperature in the future. The approach involves tasks to reduce cell and stack cost on the Nexceris FlexCell. Many aspects will be addressed: validate low-cost interconnect alloy material, conduct long-term stack durability testing, reduce the number of components in the stack repeat unit, and automate stack component manufacturing. Nexceris is not an established solid oxide cell developer/marketer with competitive cell/stack performance, even after many years of DOE support. There is no competitive commercial prototype/product from Nexceris. For this project, it can only be hoped the FlexCell results from Nexceris can be useable across the solid oxide fuel cell (SOFC) industry.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The team has validated the proposed work and demonstrated the proposed methods for reducing SOEC manufacturing cost.
- Excellent progress has been made toward meeting the project objectives and targets.
- The project has demonstrated good progress on the three aspects of the proposed work.
- Progress was modest. Supply chain issues hindered progress of the effort. In the words of the speaker, only the best results were shown. The largest cost reduction opportunity is replacing scandia-stabilized zirconia (ScSZ-6) with yttria-stabilized zirconia (YSZ-3) in the support layer. The second largest opportunity is green tape recycling. The high area-specific resistance (ASR) of 0.65–0.70 $\Omega\text{-cm}^2$ is totally unacceptable. The claimed high current of 2 A/cm^2 is not presented—and not presented over the long term anywhere at the cell level.
- The team seems to have found a way to lower the cost, but the high operating temperature could jeopardize the lifetime of the stack. The 10-cell “rainbow” stack testing results were shown only with the best set of voltage readings. The team should report the other nine cells’ voltages, too.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- There was good collaboration. Pacific Northwest National Laboratory (PNNL) helped do post-test analysis. Testing is planned at Idaho National Laboratory (INL).
- There was good collaboration with project partners INL and Strategic Analysis, Inc.
- Collaborations with national laboratories and industry are noted.
- PNNL is doing the scanning electron microscopy (SEM)/energy dispersive spectroscopy (EDS) for the Nexceris stack after a 4,000-hour test, which was funded by the DOE Office of Fossil Energy and Carbon Management. It is unclear whether this is part of proposed activities for the DOE Office of Energy

Efficiency and Renewable Energy (EERE) project. If so, it is unclear whether this should be considered baseline results or new findings from the EERE project.

- It would be better if the team could collaborate with additional institutions, for example, universities and national laboratories, to better understand the materials and manufacturing processes.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The achievements and proposed work are very important for reducing SOEC manufacturing cost. It will certainly help to achieve the DOE targets and goals.
- The project focuses on cost reduction for stack manufacturing, thus aligning well with the Hydrogen Program.
- If successful, the project can make great progress on reducing Nexceris' SOEC stack costs.
- The project will help achieve the Hydrogen and Fuel Cells Technology Office (HFTO) goals if the manufacturing knowledge gained can be transferred to an established developer and commercializer. HFTO must be the integrator. In general, the company is excellent in generating/supplying powders and will sell cells for others to stack and test. It is not desirable to create yet another SOEC manufacturer/marketer. DOE has driven three or four fuel cell technologies to market. Historically, the cost of developing a fuel cell corporate technology to the demonstration stage has taken at least a $1 billion and decade(s) per technology. There are eight years left to 2030 and only limited funding to reach the Hydrogen Program goals.
- Without further reducing the operating temperature, it would be a challenge to improve the lifetime of the stack, which is a critical barrier for HTE technology.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The near-term plans are good: (1) exercise Strategic Analysis' cell and stack cost models to identify additional cost reduction opportunities, (2) build and deliver an HTE stack for validation testing at INL, and (3) conduct a 1,000-hour stack test to close out the first go/no-go milestone. However, there are only eight years left to 2030 and only limited funding to reach the Hydrogen Program goals. Funding yet another SOFC developer/marketer may be impossible. The impact of this technology will not impact the 2026 or 2030 goals.
- The proposed future work is feasible and important. It would be better if the project could do a better study of the interconnect materials.
- Degradation studies should be proposed. Ways to reduce the operating temperature should be investigated.
- The proposed future work is broad, lacking specifics, e.g., "to identify additional cost reduction opportunities."

Project strengths:

- The project strength mainly relates to the approach to conduct detailed cost analysis to identify appropriate cost reduction opportunities.
- The entity has the capability to partner well with the national lab complex, especially PNNL and INL. The work is very valuable to Nexceris.
- The team has all necessary expertise to conduct the proposed work. The researchers have demonstrated good progress on research and development.
- Recycling the materials reduces the SOEC manufacturing cost.
- Some ways to lower the cost have been identified.

Project weaknesses:

- The project needs transformative (rather than incremental) approaches/ideas to further reduce stack costs.
- Instead of weaknesses, the reviewer poses two points for clarification:
  - Cost estimation: Slide 4 shows the Nexceris stack cost was $426/kW (as of the proposal), and it can be reduced to <$100/kW if this project is successful. In the later slides, it shows the stack cost will be $123/kW. With all the estimated savings presented in the slides, it seems like the cost and cost-saving numbers do not add up.
  - Interconnect ASRs: Slide 18 shows the new alloy's ASR was continuously reduced from ~400 hours until the end of the test, and since this is after 400 hours, it was not the so-called "burn-in" effect. An investigation into what happened will be really useful.
- Cost reduction and manufacturing knowledge gained may be too specific to be widely useable by the industry.
- No intentions have been shown to further reduce the operating temperature to improve the stability.
- No weakness was identified.

Recommendations for additions/deletions to project scope:

- It would be better if the team could perform additional work to study the interconnect materials.
- The project should study ways to lower the operating temperature.
- There are no recommendations for additions or deletions to project scope.

Project #P-201: Automation of Solid Oxide Electrolyzer Cell and Stack Assembly

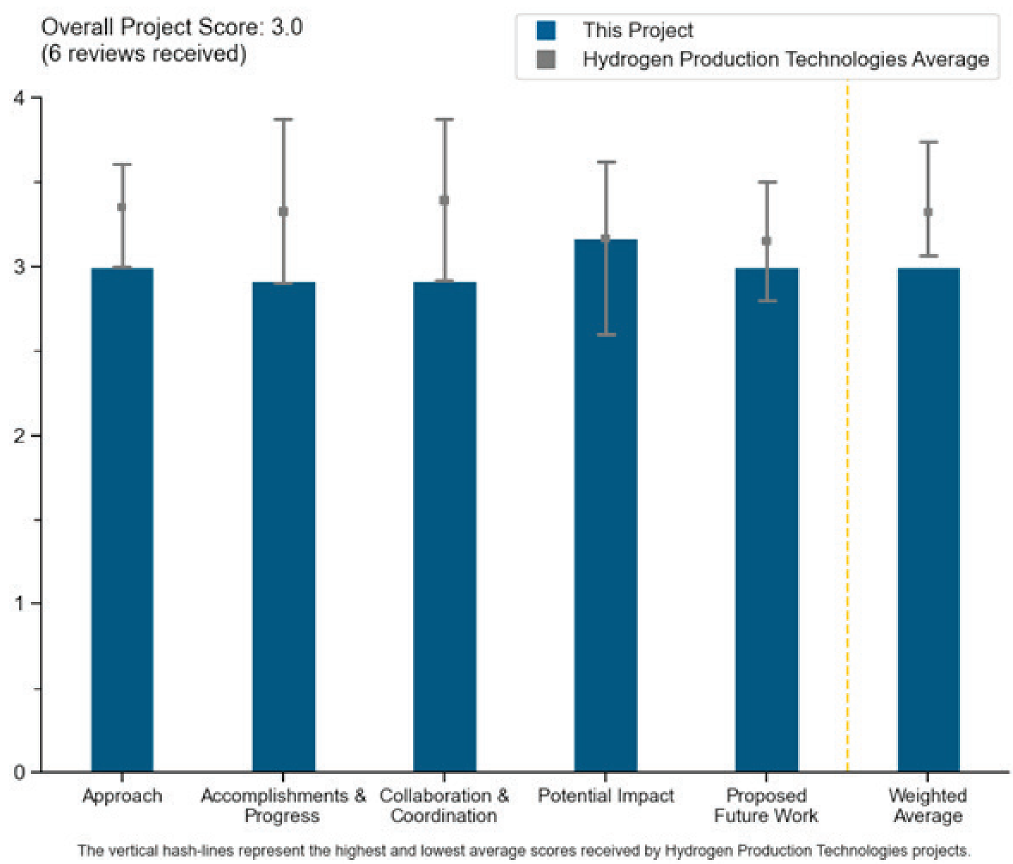
Todd Striker, Cummins Inc.

DOE Contract #	DE-EE0009622
Start and End Dates	8/1/2022–1/31/2025
Partners/Collaborators	
Barriers Addressed	• Traceability: processes corrupt barcodes • Meeting capital investment budget • Space: the solutions provided fit within 15 ft^2/MW

Project Goal and Brief Summary

The goal of this project is to develop high-volume manufacturing and quality control processes for solid oxide electrolyzer cells (SOECs) and stacks. The project aims to achieve targets such as an 85% reduction in direct labor, a 63% decrease in cycle time, and a 15 ft^2/MW annual capacity, which will contribute to reducing the cost of goods sold and support the Hydrogen Shot "111" goal. The project's accomplishments include baseline and preliminary requirements, process and gauge developments, automation development, traceability improvements, and equipment down-select. The next steps involve risk reduction, equipment installation, facility integration, commissioning, and steady-state operation to demonstrate project manufacturing targets.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project is at its early stages, and unfortunately, the principal investigator could not attend the Annual Merit Review. Stack production and assembly automation is imperative to reducing overall stack costs. The reviewer is looking forward to future updates. Perhaps the team could consider including the following for the next update:
  - A description of the equipment (to the extent possible) and the complexity of identifying equipment that can be bought off the shelf versus equipment that needs to be designed with vendors for a specific application.
  - The major differences, if any, for automation of an SOEC production line versus a solid oxide fuel cell (SOFC) production line. For example, scale of systems/stacks might play a major role in the difference of equipment needed.
  - The equipment that is the most complex to incorporate, why, and how such risks could be reduced through design and installation.
- The Cummins Inc. (Cummins) team has identified key areas to reduce the SOEC stack manufacturing cost through automation.
- Cummins will leverage its limited SOFC experience. However, the project will utilize Cummins' core manufacturing competence, expertise, initiatives, and supply chain and will emphasize quality control and traceability for a predictable product.
- Standard industrial automation processes have been designed, and quality control procedures have been documented. It is unclear how many cells have actually been processed to test out the automation and quality control systems.
- One important aspect of this project is large-scale manufacturing demonstration. However, more details, especially on process operation and integration, should be given on barriers and approaches to overcome those barriers.
- The presentation is very general (or superficial) and lacks specific details for technical evaluation. The fabrication processes/steps seem to be routine and reasonable. The uniqueness and advantages of the fabrication process were not well articulated, nor were the critical barriers/challenges and the proposed approaches to overcome them. There is room for improvement in sharpening the focus on critical challenges.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and DOE goals.

- The manufacturing improvements work is clearly not tied to SOEC performance. SOEC performance, even short-term, is not presented at either the cell or stack level. Lack of SOEC performance makes the SOEC manufacturing work possibly drop into the categories of "the irrelevant." The project may become a mere manufacturing exercise. Cummins appears to be committed to the underlying solid oxide cell (SOC) technology, and DOE welcomes such commitment. With excellent facilities and a large number of experts with diverse expertise within Cummins, Cummins could easily become a major SOEC player if the company is open-minded to different SOEC technologies. Indeed, Cummins is an important electrolyzer player in proton exchange membrane electrolyzer cell technology and could be in SOECs if its efforts are connected to a successful underlying technology that establishes SOC performance.
- It appears that some reasonable progress has been presented. However, it is not clear how the cells or stacks produced by the automated fabrication processes may perform under typical operating conditions. Perhaps it is still too early to ask this type of question since only a small amount of the budget (~$331,000 of $5 million) has been spent on the project so far.
- During budget period (BP) 1, the team did the analysis and identified key supplies, which is the go/no-go point.

- Significant accomplishments and progress are reported on process development; however, it is not clear how these contribute toward the overall project and DOE goals.
- The project's slow progress was caused mainly by supply chain blockage.

Question 3: Collaboration and coordination

This project was rated **2.9** for its engagement with and coordination of project partners and interaction with other entities.

- The presentation did not cover this topic, other than to state that vendors and equipment have been identified, so collaboration is difficult to evaluate.
- The project has limited collaboration, with no subrecipients on this award. Domestic suppliers have been engaged where and when possible.
- Although the project has no subrecipients, no information or discussion was provided on how the project activities are coordinated and how various suppliers are engaged.
- It seems that Cummins does not have a partner institution for this project.
- The slides did not mention external collaborations.
- The project has no collaborations.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- If successful, the automated fabrication process developed may reduce the capital cost of cells and cell stacks, thus contributing to achieving the Hydrogen Shot "111" goal.
- The project's new automation and quality control systems could benefit cost-effective mass production of cells in the future.
- The project focuses on large-volume manufacturing demonstration and cost reduction, and most aspects support the Hydrogen Program objectives.
- Automation is a very important aspect of SOEC/SOFC production. The wider audience would appreciate a more detailed description of equipment and the fabrication line so that lessons learned by Cummins can be applied across the industry.
- If successful, the Cummins stack cost would be significantly reduced.
- The manufacturing improvements are clearly not tied to SOEC performance, which limits relevance and impact.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- Reasonable tasks have been outlined for future work, and proper approaches have been proposed to address the remaining challenges and barriers. Examining the electrochemical performance of the fabricated cells and stacks to ensure that their quality is sufficient for cost-effective commercialization would be beneficial.
- Project lead times are still turbulent, as the schedule will have some dependence on equipment delivery. Integrating equipment with reliable traceability and integrating with the manufacturing execution system still carry some risk. Most of the project's work will be dominated by execution when equipment arrives. Cummins is still exploring materials and process development to reduce the drying space required.
- The proposed future work lacks specifics (e.g., ship equipment in 2024 does not have any information on the key pieces of equipment or estimated shipment date).
- It is unknown when the supply chain issue can be resolved.

Project strengths:

- The project's automation and quality control systems for mass production of electrolysis cells, stacks, and systems are its greatest strengths.
- The project will utilize Cummins' core manufacturing competence and expertise, initiatives, and supply chain and emphasize quality control and traceability for a predictable product.
- Automation of the fabrication process has the potential to reduce the cost of SOCs and stacks, although many challenges seem to remain.
- The strengths of this project include high-volume manufacturing demonstration, quality control, and cycle time improvements.
- Cummins is utilizing its strength in the manufacturing and automation of SOEC manufacturing.

Project weaknesses:

- During BP 1 (nine months), the team spent ~$331,000, which is about 6%–7% of the budget. During the question-and-answer session, if understood correctly, the presented indicated that the majority of the Phase II budget will be on equipment purchasing. It would be helpful to know the total cost of the equipment.
- The project is still in the early stages, so it is difficult to assess the degree of the project's success. It seems there is still a long way to achieving the project goals.
- The manufacturing improvements are not tied to SOEC performance, which limits relevance and impact.
- The project lacks testing of the designed automation system because of the backlog of parts.
- The project lacks innovations and appears to rely on conventional approaches for process improvement.

Recommendations for additions/deletions to project scope:

- Careful evaluation or inspection of the electrochemical performance of the fabricated cells/stacks would be helpful to quality control of the automated fabrication processes.
- The project should commission and qualify the designed systems with a sufficient number of cells.
- There are no recommendations for additions or deletions to project scope.

Project #P-202: Novel Microbial Electrolysis Cell Design for Efficient Hydrogen Generation from Wastewaters

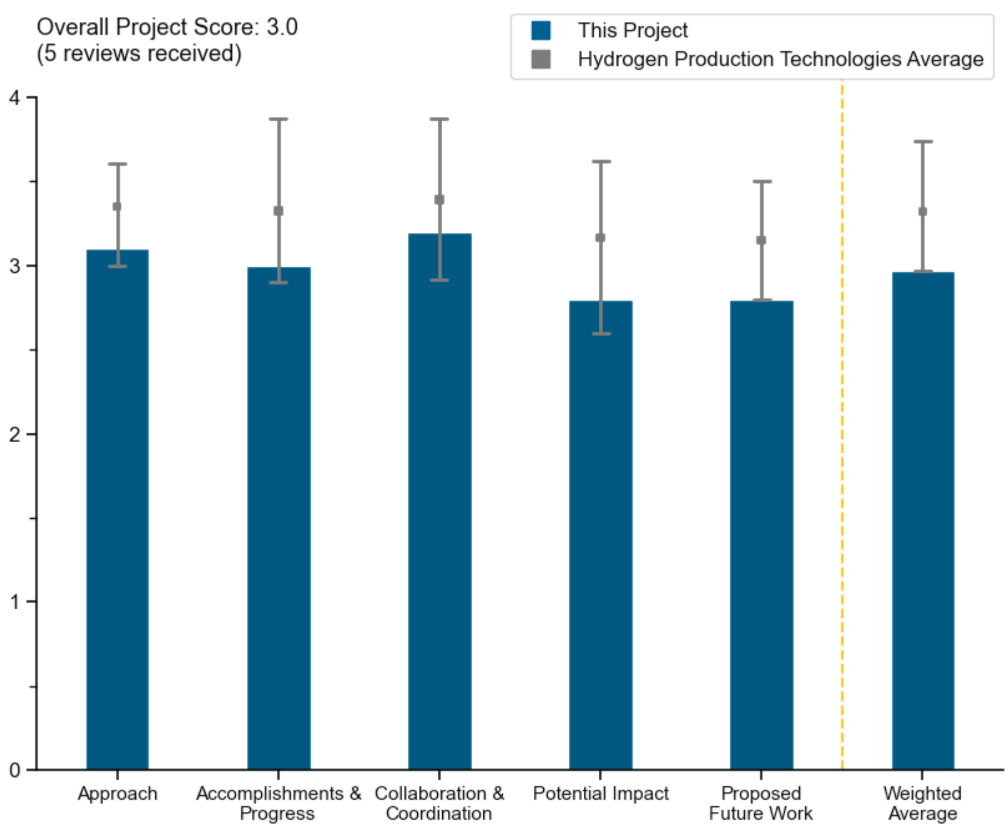
Bruce Logan, The Pennsylvania State University

DOE Contract #	DE-EE0009623
Start and End Dates	9/1/2021–9/30/2024
Partners/Collaborators	Johns Hopkins University, National Renewable Energy Laboratory, Island Water Technologies
Barriers Addressed	• Low cell efficiency • Small current density • High cathode cost and poor H_2 production

Project Goal and Brief Summary

This project seeks to offer a cost-effective method to generate hydrogen, utilizing wastewater as a renewable resource while reducing feedstock costs and environmental impact. The primary objective is to develop a novel design for a zero-gap bench-scale (100 cm^2) microbial electrolysis cell (MEC) that efficiently produces high-rate hydrogen from wastewaters. The innovation involves combining an anion exchange membrane (AEM) and eliminating the use of a liquid catholyte, resulting in improved current density, hydrogen production rates, and pH stability. Activities include testing hydrogen production from various feedstocks and optimizing the fermentation process, as well as validating and optimizing MEC performance. Additionally, researchers will prepare cathodes free of platinum group metals (PGMs). The ultimate aim is to demonstrate a pathway for hydrogen production at scale using wastewater feedstock, while addressing cost, performance, durability, and scalability challenges.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The Pennsylvania State University (Penn State) has clearly identified the critical barriers for a microbial approach to generating hydrogen at a cost of $1/kg H_2. There is some confusion as to whether the DOE goal is $1 or $2/kg H_2 for hydrogen generation via microbial pathways. This should be clarified at the next Annual Merit Review (AMR). The Penn State milestone schedule indicates the project is well designed and feasible. Partnering with Island Water Technologies (IWT) gives Penn State a pathway to developing an off-take customer for hydrogen, as wastewater treatment plants are being developed for both renewable natural gas and hydrogen generation. The wastewater treatment plant could have a direct path to placing the hydrogen in pipelines.
- The project uses a novel MEC design strategy (a zero-gap membrane with vapor feed at the cathode), which is a different approach that should definitely be explored. The results could change the game for MECs.
- The project team is going to a vapor feed for the anode, which is a good choice and should lower overall cell potential. The research on a non-PGM catalyst for an alkali system seems very reasonable. The AEM membrane research will be difficult. There is not a stable AEM for regular water electrolysis, and this system will be harder. There will likely be reactant crossover (ethanol, formate, lactate, etc.), which could be a potential problem. The separation of the formate, ethanol, and lactate from the fermentation broth will likely be very expensive. A cost analysis should be done. It is surprising that Hydrogen Analysis (H2A) was not included in the approach. The approach adds a second separation for the buffer recycling. Addition of two new unit operations may increase the cost.
- There was great demonstration of the progress achieved so far, for an innovative new idea. The performance of the system indicated an encouraging high hydrogen productivity but at a small scale. It appears that the system has limitations in the concentration of certain organic compounds, but the presentation did not provide any indication of the effect or how it changes with the concentration. The project also did not discuss whether the same compounds affect the alternative configuration.
- The project is developing a zero-gap MEC cell with a PGM-free cathode and with vapor feed to the cathode to replace liquid catholyte. From the presented concept and results, it is not clear how the vapor feed for the cathode will be generated and how vapor condensing within the cell will be avoided. The expected performance conditions—temperature, pressure, and flow rate—should be reported, as well as a schematic process flow diagram (PFD) for the whole system integrating the MEC.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- Penn State is making good progress toward achieving the project objectives. The team has well-defined metrics and good comparisons to other existing microbial electrochemical cells. Greater discussion on off-take pathways might allow for better assessment of achieving DOE goals for microbial hydrogen generation, specifically in estimating production cost. At an estimated program execution of 58%, this project may be underspent. It is proposed that project spending be reviewed at the next AMR.
- By separating out the formate, lactate, and ethanol from the broth and using only those organics, this is now very similar to other work in electrolysis reported elsewhere. The separations cost may be significant. The DOE Bioenergy Technologies Office program has a consortium dedicated to separations. The identification of the NiMo catalyst was a good accomplishment. Identifying a good buffer for the MEC is an important accomplishment. The use of a buffer may increase the operating and manufacturing (O&M) costs. At the voltages applied and with the carbon felt (which is a catalyst), the project may be doing electrochemical destruction of the organics. The principal investigator reported high durability. This may be a bit premature since the technology has not run for long periods. Long-duration (1,000+ hours) needs to be done to ensure no biofouling. It would be interesting if the project could report the half-cell potentials; since the project has a reference electrode, this should be easily done. An impedance spectroscopy is recommended to better understand the limits of the cell.

- The project is a contribution toward the goals of the DOE Hydrogen Program and has achieved and exceeded the productivity target—but only at small scale so far. Moreover, there was no estimate on how this productivity gain, but in a different system, will affect the cost of the produced hydrogen.
- The project performance has been delayed by Dr. Rossi's moving from Penn State to Johns Hopkins University (JHU). The necessary project modifications have been completed, and the work should be resumed at JHU. High current density for the MEC performance has been observed, though testing was done with very small cells, and it is not clear how much this performance can be sustained for larger cell size and for multiple cell stacks.
- It would have been good to see at least initial attempts at getting results on a real wastewater feed at this point in the timeline. The project should make sure to do so before the next AMR, as outlined in Future Work.

Question 3: Collaboration and coordination

This project was rated **3.2** for its engagement with and coordination of project partners and interaction with other entities.

- Penn State has shown good collaboration with the National Renewable Energy Laboratory (NREL) in developing biological buffers for microbial feedstock. Discussions about the status with IWT could be helpful in determining the project's impact. The project could engage IWT to outline possible hydrogen off-take pathways. This may have been addressed in the proposal and could perhaps be provided in the backup slides at the next AMR.
- The team has well-defined roles, the members have worked together before, and they seem to be doing well.
- Good collaboration is established between Penn State and JHU and NREL. The project is also working with IWT for wastewater supply for testing and for technology commercialization.
- It is nice that the project is working with NREL, but so far, it is only to obtain a model wastewater feed and advice. The project has not yet benefitted from collaboration with IWT.
- The project appears to have good collaboration, at least on paper.

Question 4: Potential impact

This project was rated **2.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project led by Penn State has an excellent alignment with the Hydrogen Program and DOE research, development, and demonstration (RD&D) objectives and has the potential to advance progress toward DOE RD&D goals and objectives. Per the discussion on the team, IWT has been identified to promote the technology. It might be beneficial for IWT to outline a hydrogen off-take pathway. If successful, this project may advance progress toward the DOE RD&D goal of hydrogen production of $1 or $2/kg H_2.
- The objectives of the project appear to align with the Hydrogen Program goals and the DOE RD&D goals. The outcome will likely enhance knowledge and understanding of the process, even if at the end, the proposed system will be abandoned. However, the presentation did not provide any indication of how the system could move toward the cost targets that have been set. Thus, it is difficult to fully characterize the alignment with the totality of the goals.
- MECs will be a niche production pathway for hydrogen, but within this space, the project is novel and has the potential to maximize the utility of MECs.
- Production of hydrogen from fermentation of waste streams fits within the Hydrogen and Fuel Cell Technologies Office portfolio. By adding additional unit operations, the researchers have lost the simplicity of the original MEC. The new unit operations (there are two separation steps, one for the substrate and one for buffer recycle), along with the buffer, will likely add cost and may make it difficult to achieve the goal of low-cost hydrogen. The Remaining Challenges slide states that acetate is the ideal substrate and that the ethanol, formic acid, and lactic acid are difficult. The team's mitigation of this is dependency on other projects to genetically engineer strains to increase the acetate and minimize the other compounds. This seems to say that the success of this project is dependent on other projects. The other projects have been working on genetically engineering strains to eliminate production of the other compounds for a long time.

- The project needs to conduct a techno-economic analysis (TEA) to determine cost of hydrogen production. Apparently, most revenue for the system operation would arrive from the credit for wastewater cleanup and treatment. A TEA should determine what the contributions are of the wastewater cleanup, the MEC system cost, and the consumed power in the cost of hydrogen. It is likely that MEC technology would be primarily applicable to cleaning small-size water streams, and it is not clear how much the technology can be scaled up to match the available feed streams. It is not clear how pure the hydrogen produced by the MEC is and how the requirement for further purification would affect the cost of hydrogen.

Question 5: Proposed future work

This project was rated **2.8** for effective and logical planning.

- Penn State has effectively planned the project to address the DOE goals for hydrogen production through biological methods. The program has been executed well against its project plan. The proposed solutions for the remaining challenges and barriers may be successful. There is some concern the approach to TEA may not be inclusive of all costs. The project is asked to outline the factors to the TEA at the next AMR. If a TEA task does not exist in the project, perhaps it can be added with support from the national laboratories.
- On the positive, the presentation indicated that the team has identified barriers to the success of the product, such as the variability of buffer concentration in a real system, the presence of organic compounds that could affect system productivity, and the requirement of a pretreatment step to remove solids. It seems that the team plans to test some solutions to these issues, but the presentation provides only milestones and should clarify the target stability. It is not clear whether the advantages of zero-gap MECs will hold in a real system. It is not clear how stability/lifetime will be evaluated or how the buffer variation will be simulated.
- The project needs to add an H2A analysis and show a reasonable pathway to achieving the hydrogen cost targets. The project team does not mention the challenge of biofouling, which has historically been a challenge to MECs, and should clarify whether the problem has been solved. Long-duration flow-through tests are needed. The AEM fouling needs to be studied. In addition, there may be crossover of the substrates. The impact of crossover (if it is happening) needs to be understood.
- The focus on moving to real wastewater feeds from NREL and IWT is commendable.
- The proposed future work is reasonable on continuing technology development.

Project strengths:

- The team is very strong and includes industry, as well as academia and a national laboratory. The project has identified a non-PGM catalyst. The approach has the potential to use a very low-cost, perhaps even free, feed stream. The use of an AEM has potential to lower costs.
- The project adequately studies MEC operational parameters on performance (although from the presentation, it is unclear why these parameters, and not others, are being studied). The convincing comparison with other studies seems to document the advantages of the system at lab scale.
- The project strengths are highlighted by the teaming between Penn State and IWT. The connection to NREL is also prized and could grow if a TEA is also pursued.
- The project has a novel approach and a fundamental understanding.
- The project made good progress in demonstrating high-current-density operation.

Project weaknesses:

- The path to \$2/kg H_2 is not identified. This is particularly important since the project is adding several unit operations. In chemical processing plants, separations are the most energy-intensive process. The addition of the AEM may work, but the principal investigators did not mention the risk of biofouling or substrate crossover with the membrane or electrolysis work. AEMs have not had excellent durability. The project's success seems to be dependent on the success of other projects to genetically modify strains to increase the titer of the desired substrates and the development of stable AEMs.

- Per discussions during the reviewer questions at the AMR, there are questions as to the performance of the microbial electrochemical cell. Carbon corrosion could be skewing the energy consumption. A greater weakness may be the need for buffering. The cost of buffering should be reviewed, as it might have a big impact on achieving the DOE cost targets.
- The project is small-scale at the moment, and there is no indication of longer-term operation/lifetime. The industrial partner's contribution is unclear. The project has no quantification of the effect of higher productivity on the final cost.
- The novel approach may lead to wastewater quality specifications that limit the range of wastewater feeds that can be used. The question of how broadly applicable the approach can be, should be addressed soon—if not in this project, in the next.
- The project is still in a very low technology readiness level, and it is not clear how much commercial interest there would be for technology application.

Recommendations for additions/deletions to project scope:

- The project should provide data to quantify the effect of organic compounds at different concentrations. Perhaps the system is more sensitive than alternatives to these compounds. With a target of 20 L H_2/L-reactor·day and achieved productivity of 70 L H_2/L-day, it seems that there might be some room to give. The study of the design at a larger scale should be done quickly (if indeed that is the projected size) to demonstrate that the advantages will hold at that scale.
- The project should develop a PFD for the hydrogen production system that would integrate the MEC stack and analyze the mass and heat balance, particularly associated with vapor generation. A detailed TEA should be performed to estimate the cost of hydrogen production.
- An H2A analysis is needed, with reasonable (not overly optimistic) assumptions for the capital and O&M costs of adding the additional unit operations and the cost of buffers.
- The project should outline the factors to the TEA so it can be added with support from the national laboratories.
- The project should consider exploring the potential to pressurize the vapor on the cathode side, as mentioned in the question-and-answer session.

Project #P-203: Novel Microbial Electrolysis System for Conversion of Biowastes into Low-Cost Renewable Hydrogen

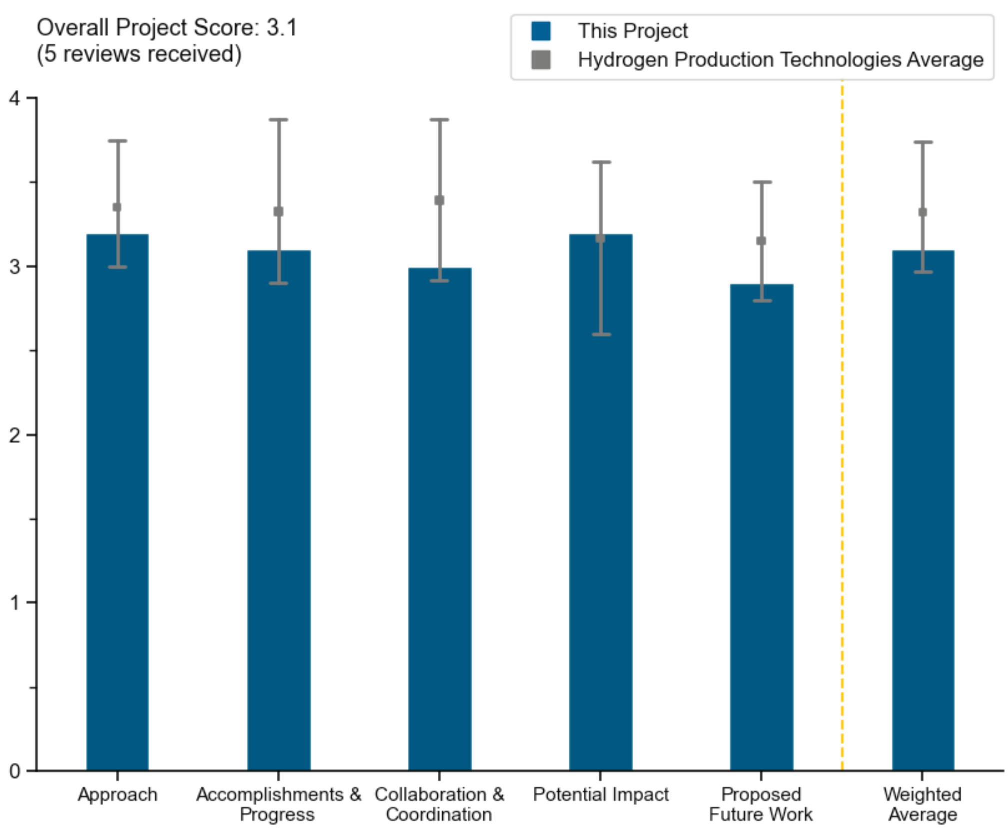
Noah Meeks, Southern Company Services, Inc.

DOE Contract #	DE-EE0009624
Start and End Dates	11/1/2022–10/31/2025
Partners/Collaborators	Electro-Active Technologies, Inc., T2M Global
Barriers Addressed	• Scale-up • Performance • Durability • System/process engineering

Project Goal and Brief Summary

The project aims to identify critical scale-up parameters and develop a microbial electrolysis cell (MEC) stack to achieve target hydrogen productivity (>20 L/L-day). It also focuses on demonstrating the stability and durability of MEC technology and developing an integrated waste-to-hydrogen system using commercial food waste. The project seeks to enable distributed hydrogen production, increase hydrogen yields in MECs (>40%), and provide a renewable source of hydrogen while abating waste management costs. By the end of the project, the project team will demonstrate an integrated waste-to-hydrogen system using commercial food waste to produce hydrogen with end use in fuel cells.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Southern Company Services, Inc. (Southern Company) has proposed an effective approach to overcoming the barriers of hydrogen production via a microbial pathway. Some of the data reviewed needs further explanation—specifically, the drop in efficiency and current density as the microbial electrochemical cell is scaled to 10 L. The team being led by Southern Company has strong analysis, technology partnership, and off-take in Southern Company Gas.
- The project focuses on scale-up and commercialization of hydrogen production by MCE technology previously demonstrated by Oak Ridge National Laboratory (ORNL) and Electro-Active Technologies, Inc. Conducting detailed techno-economic analysis (TEA) and life cycle analysis (LCA) and understanding biomass yield and degradation mechanisms will be a significant part of the project. The project outlines all the important parameters in the process that will be optimized throughout the period of performance.
- The project team is demonstrating a scale-up approach for a specific MEC system. Unfortunately, the system factors are not included (catalyst, anode/cathode material, etc.). It is unclear from the presentation whether the results shown are applicable to other systems (smaller cell size with multi-cell systems) or whether other systems simply have to follow a similar (to this project) approach to determine their optimal configuration. Thus, the work presented does not seem to "Identify critical scale-up parameters and development of MEC stack to achieve target hydrogen productivity," which is listed as the objective of this phase. The authors are clearly aware of the various parameters affecting MEC biofilm optimization and MEC optimization, as some introductory slides demonstrate, but the presentation (at least) does not show how the team identified the critical parameters through the project. Instead, the presentation gives the impression that the team followed a predetermined scale-up approach (which is useful on its own but as a demonstration).
- The team is using Hydrogen Analysis (H2A) to help determine a pathway to low-cost hydrogen. The team is licensing a fermentation technology, which means it is more mature than having to start with trying to discover or genetically engineer one. The scope is ambitious for the budget. The project does not include the biofilm fouling of the membrane. The use of the membrane with food wastes will likely result in biofilms. It is not clear that the approach has work scope to address or mitigate this risk. The team is planning on subcontracting out the TEA and LCA to another company and will do it based upon some scale-up, which will result in a better TEA.
- The main barrier this project seems to be addressing is demonstration of a commercially viable continuous MEC system. In this regard, it appears the focus is to engineer an MEC system. The plans to do this seem reasonable, but it is hard to tell how robust they are. The target waste stream (generically referred to as food waste) is unclear.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- The project team has made excellent progress, considering the project started in the fall of 2022, and has identified some optimal operating conditions. The high hydrogen recovery in the 2,000 ml and 10,000 ml reactors suggests that the project team is splitting water and may want to talk with some electrochemists. There may be simple designs that would eliminate this. The selection of 80 ml volume cells may result in stacks with a large number of cells in a real system, which is significant because it will result in higher manufacturing costs than if larger-volume cells were used. There is a reason the fuel cells and electrolyzers are scaling their active area to reduce costs. Slide 12 has the target impedance of <0.8 dkohm-cm^2, and it is not clear that the project team has validated this. For slide 10, it is not clear how long the system was operated ore what the operation conditions were. There are additional questions: whether the feed was recycled, what the temperature was, and what the flow rate was. In addition, the project is asked to define cathode efficiency. For slide 11, for the impedance, the project is asked to explain why the impedance increased with volume, i.e., perhaps it was an increase in ohmic. It is not clear what the mass transfer was. It would be helpful for the project to integrate a reference electrode to run the impedance and other tests. There is no data on lifetime operation. It is not clear how the performance changes.

- Although the presentation does not seem to fully address the project objectives, the work is quite useful as a practical demonstration of the scale-up of the MEC systems. The drawback is that there is no explanation (in the presentation) of why the criteria were selected (maybe an explanation will be shown in a later report) and how/if the approach should be followed at each MEC system. Irrespective, this work could be used by other programs, based on laboratory results, to test and understand scale-up. Although (after trying multiple scales) this project seemed to settle in a multicell 80 ml system, other projects in the Hydrogen Program (the Program) are targeting the higher scale. It probably suggests a gap in the knowledge transfer among the Program's projects.
- The project started about two quarters ago and has developed scale-up strategy and demonstrated cell scale-up by about a factor of 125. Significant decrease in cathode efficiency and hydrogen production per liter reactor was reported for larger reactor volumes, which suggests that uniformity of the reactant and current distribution across the cell remains a challenge. The project needs to carefully analyze the scaling-up factors to resolve this issue.
- Southern Company is making good progress toward achieving the project objectives. The project has well-defined metrics. Southern Company could include a summary chart to better highlight the milestones and progress on tasks.
- The project has reasonable progress for the first six months, with components being built and tested.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- Southern Company has good collaboration with its partners. Southern Company has enabled Electro-Active Technologies to scale up the project technology and provided a pathway to off-take hydrogen when production is available. Southern Company has also partnered with T2M Global (T2M) and a consulting company for the environmental resources management to support the TEA and provide the levelized cost of hydrogen being produced from the microbial system.
- There is no indication of a less-than-good collaboration. The team seems quite familiar with work in the area and builds on that.
- Close collaboration between Southern Company, Electro-Active Technologies, and T2M should lead to fast commercialization of the technology if design performance is demonstrated.
- It is not clear how Southern Company is involved, while Electro-Active Technologies is doing most of the work. The reviewer is looking forward to seeing the TEA from collaboration with T2M.
- The team includes a system manufacturer and end users; however, the roles and responsibilities are not clearly presented.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project led by Southern Company has excellent alignment with the Program and DOE research, development, and demonstration (RD&D) objectives and has the potential to advance progress toward DOE RD&D goals and objectives. The TEA should provide DOE with a clear status as to the maturity of microbial pathways for hydrogen production.
- Commercialization of an MEC system has the potential to provide two-pronged societal benefits of abating waste management costs, while producing a renewable local source of hydrogen for use in fuel cell equipment. While conducting TEA and LCA, the project should focus on determining the optimal scale at which the MEC technology could be deployed and commercialized, what types of waste streams can be processed, how much hydrogen can be produced, and how much downstream purification would be required.
- The project aligns with the Hydrogen and Fuel Cell Technologies Office's goals. The project will co-produce CO_2. There will be competition for the food waste since food waste can be converted to biocrude via hydrothermal liquefaction, which can then be made into products such as bioplastics and other bioproducts.

- Investigating and demonstrating how lab-scale results can hold up upon scale-up is crucial in the development of this and any technology. To that end, this is a useful project in the overall Program, particularly around MEC.
- Inherently, MEC will be a niche production pathway for hydrogen. This project meets DOE objectives of accelerating deployment of new technologies.

Question 5: Proposed future work

This project was rated **2.9** for effective and logical planning.

- A Gantt chart or some critical path for the future work, rather than "execute on the remaining scope," would be helpful to see. The project is doing an H2A analysis. The future work would benefit from using the H2A analysis to identify the research and development areas that would make the largest cost reductions. The project does not include the biofilm build-up on the membranes as a potential risk. In other work in this area, formation of biofilms has fouled the systems, which is even worse for units that use a separation membrane. The use of the membrane with food wastes will likely result in biofilms. The project needs to report on long-term operation.
- The proposed future work described in slides 16 and 17 of the presentation raises the right questions (durability, different feedstocks) but lacks specificity. This gap makes it very difficult to comment on whether the project has effectively planned its future. For example, the project could clarify which feedstocks can test or "stress-test" the "stability and durability of MEC technology" and how they will be selected. The project should also clarify whether the size of the cell (selected on impedance analysis) is the optimal scale for durability. The future plan could address this question.
- The project's presentation was thin on plans for future work, so it was hard to judge. It is good to see that Southern Company will get more involved. If future work indeed includes looking at landfill gas as a feedstock (an odd choice), the project will need to compare other ways to utilize this feedstock to make hydrogen, such as modular reforming or pyrolysis.
- The future work is centered around evaluating business cases around specific Southern Company projects, which should promote fast-track commercialization of the technology.
- As this project is in an early stage, Southern Company is focused on executing on project scope. It is assumed risk analysis and risk mitigation will be available as the demonstrations progress.

Project strengths:

- The project has made excellent progress. The work scope looks like the project team is focused on the correct areas. The project team has included an H2A TEA analysis. The team has a manufacturer and end users. Electro-Active Technologies is a spin-out from ORNL, developed in the I-Corps program. This program would give Electro-Active Technologies a good foundation upon which to build.
- The project strengths are in identifying an off-take for hydrogen and the focus on the TEA.
- The project is practical and has useful demonstration data on system performance at different scales.
- The project focuses on demonstrating commercial viability of MECs.
- The project has a strong commercialization component.

Project weaknesses:

- There are no project weaknesses at this stage of execution. There is concern issues can exist with microbial reactor scaling. More discussions are suggested as to the decrease in performance when scaling from 16 mL to 10 L.
- It is recommended a reference electrode is used in the electrochemical tests to better understand the performance of the cells. The reference electrode can inform on which reaction is limiting, if the limits are due to kinetics or mass transfer, and better elucidate failure mechanisms.
- The project does not indicate whether the project findings on "optimal scale" are universally applied. It would have been useful to discuss/explain the rapid deterioration of the system performance with scale. An

estimate of the economics of the hydrogen based on the findings is missing (there is a graph from a reference paper but not a direct estimate from the findings here).

- The project needs to address the biofouling and mitigation. Long-term operation needs to be reported. The TEA and LCA need to be completed.
- There is a potential for fundamental challenges (e.g., feedstock heterogeneity, fouling, hydrogen separations) to derail the project.
- The project just started, and it is difficult to evaluate the results obtained up to date. Initial results on MEC scale-up suggest significant loss of efficiency at larger scales, which may be a challenge.

Recommendations for additions/deletions to project scope:

- A close inspection of the current densities listed in table 10 (dimensionless) and comparison with the estimated current densities (by cell area and current) on slide 12 show that they are not the same (for the same scale). The project should clarify if these are different sets of experiments and why. The data in slides 10, 11, and 12 for the 80 ml volume are all different. In fact, the 30 A/m^2 at an 80 mL scale is not achieved in slides 10 and 12. Some discussion is necessary since achieving this current density is shown as the key selection factor for the cell size. On slide 10, summary results are seen at five scales, but there is no attempt to discuss the dependency of the responses to the scale or what would be a way to develop some predictive approaches, which would be a useful contribution. Moreover, simple inspection of the data in slide 12 shows that in addition to the scale, the five experiments have different cell area-to-volume ratio (~2.5 cm^2 per ml at small scales to 1.25 cm^2 per ml at the higher volumes). The project does not discuss whether the ratio has an effect and, if yes, how this ratio will be used during system performance optimization. Discussion is needed. At least, one would have expected that the ratio should have stayed constant upon scale-up. Although the four cells in the photographs on slide 10 appear to be similar in the relative ratios of their dimensions (avoiding any additional complication in the interpretation of the results), it is quite possible that the exact dimensions of the cell (height, width, depth) may be important (instead of the volume alone). It would have been nice to have some commentary on that. An estimate of the economics of the hydrogen based on the findings is missing (there is a graph from a reference paper but not a comparison with the findings here).
- The project needs to address the biofouling and mitigation. Long-term operation needs to be reported. The TEA and LCA need to be completed. It is recommended that the team use a reference electrode in electrochemical tests to better understand the performance of the cells. The reference electrode can inform on which reaction is limiting, if the limits are due to kinetics or mass transfer, and better elucidate failure mechanisms.
- The project could consider how the hydrogen will be used locally, or brought to market, if production units remain at the scale being considered.
- No changes in scope are required.
- The reviewer has no additions or deletion to the current project scope.

Project #P-204: Hydrogen Production Cost and Performance Analysis

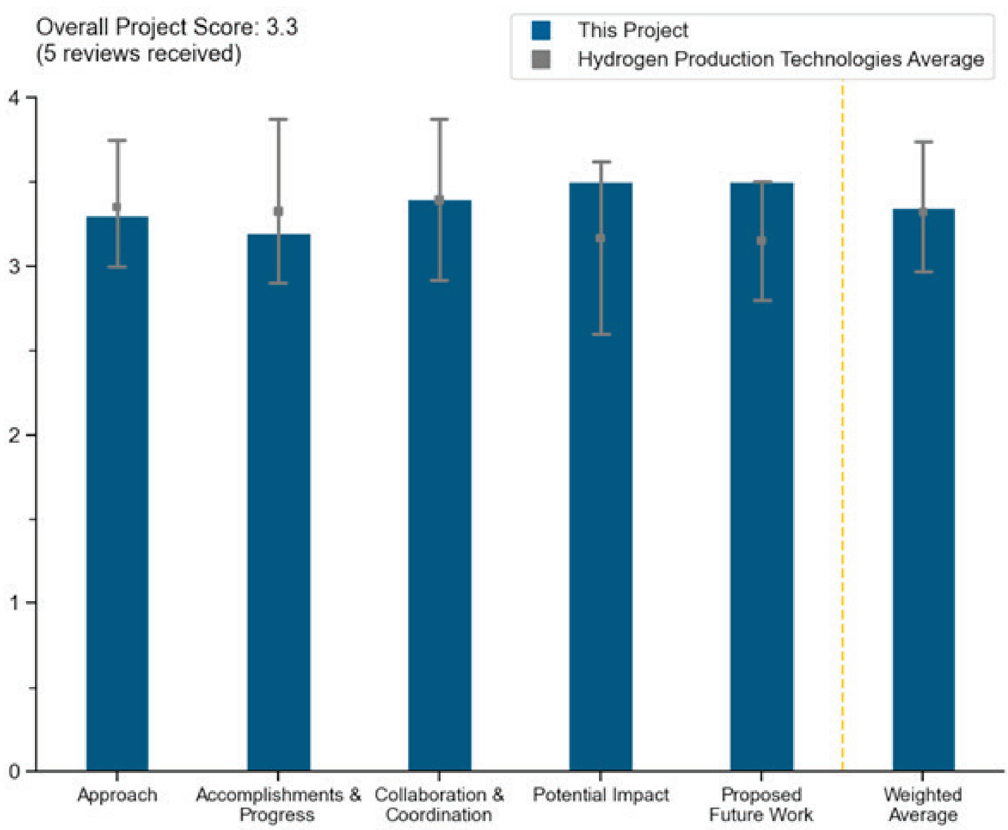
Brian James, Strategic Analysis, Inc.

DOE Contract #	DE-EE0009629
Start and End Dates	10/1/2021–9/30/2024
Partners/Collaborators	National Renewable Energy Laboratory, Idaho National Laboratory
Barriers Addressed	• Hydrogen generation by water electrolysis: • Capital cost • System efficiency and electricity cost • Manufacturing

Project Goal and Brief Summary

The project aims to conduct a techno-economic analysis (TEA) of various hydrogen production pathways, including electrolysis and photoelectrochemical methods, to evaluate the cost of hydrogen production. It utilizes Design for Manufacture and Assembly (DFMA®) techniques, heat and mass balances, and Hydrogen Analysis (H2A) discounted cash flow models. The goal is to estimate the cost of hydrogen production based on state-of-the-art technology at central production facilities (50–500 tons per day) and measure the cost impact of technological improvements in hydrogen production technologies. The project will provide a comprehensive pathway analysis, identify cost drivers, guide research and development efforts, and support the Hydrogen Shot goal of achieving $1/kg hydrogen production cost. The approach involves collecting data, conducting cost analysis of proton-conducting solid oxide electrolysis, and collaborating with experts and research institutions to ensure transparency and accuracy.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Production Technologies projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach to the analysis and objectives for the project, system boundaries, and operating parameters have been clearly identified. The approach to the analysis of the anion exchange membrane (AEM) water electrolysis is similar to the ones used in analysis of other hydrogen production technologies, which allows making consistent back-to-back comparisons of the cost of hydrogen production by different methods.
- This is a great effort in estimating the stack cost and deployment costs of alkaline electrolysis (ALK) hydrogen plants and comparing to proton exchange membrane (PEM) systems, mainly leveraging the National Renewable Energy Laboratory model. Perhaps the team could consider the following suggestions to further tighten/improve the models since the project has only one year remaining:
  - Incorporate capital expenditures (capex) for ALK systems deployed worldwide to date; verify the capex cost of PEM and ALK stacks and full systems, and do one-to-one comparisons in terms of balance-of-plant (BOP) (what is included and what is not to be allowed for accurate comparison).
  - Verify efficiency curves with electrolyzer original equipment manufacturers (both PEM and ALK) and BOP providers as function of production capacity.
  - Verify engineering, procurement, and construction (EPC) costs with Tier 1 EPC firms.
  - Conduct sensitivity analysis for higher electricity costs, different electrolyzer and balance-of-stack availability, utilization, etc.

  Furthermore, ALK is mature technology that has been deployed in gigawatts worldwide; it would be valuable to explain why it is more expensive than PEMs, which are lagging in maturity, supply chain maturity, and deployment scales.
- This is a good approach that has proved to work well in the past. The approach is a to do a bottom-up analysis, which raises questions about whether some of the assumptions are bottom-up or top-down. The assumptions on slide 6 for future performance need to be validated. Where they came from is not clear. The assumption for degradation that the AEMs will approach PEM performance degradation does not seem to be realistic, given that these are very different systems (one is acidic, and the other is alkaline) and that AEM degradation mechanisms are different from Nafion™ membrane degradation mechanisms. It would be better if performance could be tied to a scientific reason that would allow for overcoming degradation mechanisms rather than "industry thinks we can do this..." The same is true for slides 7, 10, and 14. It is not clear why the performance improvements in the future case were chosen.
- TEA is critical to keep DOE focused on the most important challenges. Strategic Analysis takes a rigorous, mostly transparent approach to developing benchmark costs with industry input. The exceptions are when that industry input needs to be protected (e.g., polarization curves) or when engineering judgement is required because of lack of data (e.g., EPC costs).
- There is a well-defined approach for cost analysis. Assumptions are clear. The approach is aligned with the project goals.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- Significant accomplishment toward goals is demonstrated. Numerous scenarios were explored and cost representations created to show major influences for dollar-per-kilogram reductions. Trades were conducted between low-temperature electrolysis (LTE) hydrogen generation technologies.
- The project made very good progress in evaluating cost of hydrogen production by AEM operating with KOH and with a water feed. Comparison with other technologies has been made, and the crucial cost factors have been identified.
- The TEA identified priority focus areas for AEM systems to lower the cost of hydrogen production.
- The current state of AEM performance seems optimistic, especially the AEM water scenario. It is not clear where the data is coming from because there are no commercial stacks to use as a reference. If the team is referring to literature data, then it would be better to put some references in the document. The DFMA and

flow sheeting were well done, assuming the assumptions that were used are correct. The projected AEM current–voltage (I-V) curves seem optimistic. The solid oxide electrolysis cell (SOEC) current density on slide 24 is low. SOEC Hydrogen and Fuel Cell Technologies Office (HFTO) work has shown SOEC current densities in excess of 1 A/cm^2 (see various past Annual Merit Review presentations by FuelCell Energy and others on SOECs). It was unclear why the current life was projected to be 35,000 hours (slide 8) when slide 25 says it is less than 9,000 hours. It was unclear whether the performance assumptions were for end of life or beginning of life—in other words, whether the stack will operate at 3 A/cm^2 at 1.8 V for the 90,000 hours.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- The project collaborates with all major stakeholders in water electrolysis development: DOE, national laboratories, electrolyzer developers, and manufacturers.
- There is a good combination of labs and industry to get at real costs, operating conditions/parameters, and degradation rates.
- Strategic Analysis obtains feedback from commercial manufacturers, which is critical to this type of analysis.
- The team has well-defined activities and contributions.
- Close collaboration with EPC firms and vendors could help tighten the model.

Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has significant impact on development of the Hydrogen Program through accurate comparison of the cost of hydrogen production by different technologies and through identification of the most critical cost components that require further development efforts.
- Cost breakout for stack and system subcomponents was done well and provides guidance for areas to focus for the largest cost-reduction opportunities. It is important for researchers to understand so they know the highest-value areas to explore and improve.
- The projected performance predicts one set of targets that would enable AEM to achieve the cost targets.
- Interest in AEM will only grow. DOE-sponsored analysis like this will be taken as a benchmark.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- Next steps planned for the project, conducting cost sensitivity analysis and coming up with strategies for reducing stack cost and operating costs, are well defined and provide logical continuation for the project.
- Proposed future work shows follow-up for incomplete AEM scenarios. Efforts are also realigned to see the viability of achieving $1/kg targets established for electrolysis after project start.
- There are plans to publish the H2A case and DOE record (the latter is important because it allows a deeper explanation of the analysis). The team should show the sensitivity of results to input assumptions. DOE has a low-grade reputation for optimistic cost assumptions, so the sensitivity analyses are important, including those where more than one variable is changed at a time. The cross-comparison of LTE options published is recommended as well. Preparation of the proposed Hydrogen Shot scoping study is strongly recommended. It may be best to show that as a standalone study, but DOE should rapidly shift to a total-cost-of-supply metric, including storage, transmission, and distribution.
- The future work seems appropriate.

Project strengths:

- The project provides analysis of new and rapidly developing AEM water electrolysis technology for hydrogen production. Many new hydrogen projects and startup companies have recently been formed to develop and commercialize the technology. Providing publicly available TEA and performance metrics for the technology will allow for better comparisons of different commercial systems and will provide targets for system development and assessment by DOE.
- This is very important work. It is needed for HFTO to create appropriate performance targets. It is imperative that Strategic Analysis provide very honest and transparent analysis. Strategic Analysis has an excellent process for doing this and well-qualified staff.
- The project has a strong prime contractor in this area of research who is well regarded in the field. Good collaboration is shown between national laboratories and the prime contractor. The industry partner input adds validity to modeling efforts.
- Rigorous bottom-up analysis is a strength. Assumptions are transparent; work is published.

Project weaknesses:

- The team needs to provide more documentation on the current and future performance metrics. Saying "we found this in the literature" should be accompanied with the literature references. If the team surveyed industry, there should be error bars showing the variation between responses. The team has done this in the past, so it was surprising not to see it in this presentation or in the background information.
- Optimistic assumptions are made about EPC costs. The team should talk to EPC vendors. It is not clear whether the analysis actually does guide DOE decisions on research and development to fund. If possible, the team could show evidence of the impact of past analyses.
- It would be nice to get similar input from industries in the comparison technologies and not just AEM. It is possible this was done, but that was not clear in the presentation.
- No specific weaknesses were identified.

Recommendations for additions/deletions to project scope:

- The project needs to more fully document its assumptions. Currently, it looks like the future performance targets were selected to achieve the DOE goals (top-down) and not based upon a bottom-up analysis of what the physics says can be reasonably done. Stating that AEM target durability can be achieved because PEM can do it is not a strong argument.
- It would be good (and does not seem difficult) to show the projection of future costs compared to a learning curve approach. It would complement Strategic Analysis's bottom-up approach and help some stakeholders put the results in context.
- No modifications to the scope of the project are recommended.

Project #P-190: A Multifunctional Isostructural Bilayer Oxygen Evolution Electrode for Durable Intermediate-Temperature Electrochemical Water Splitting

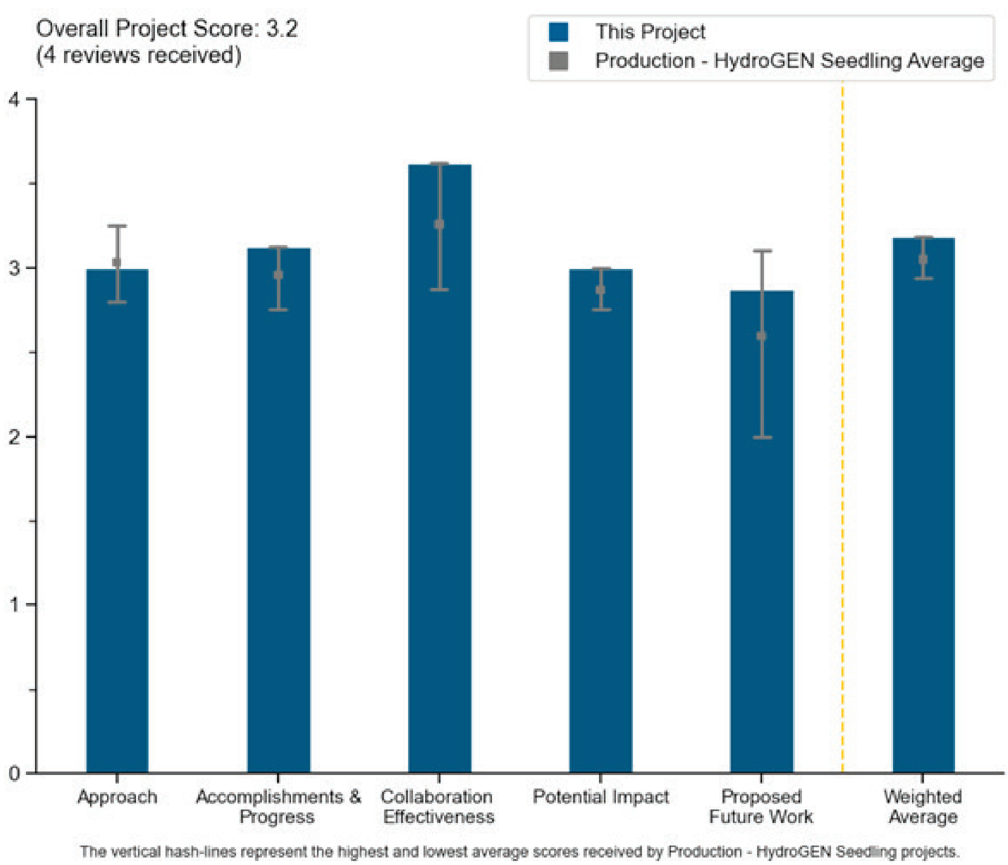
Kevin Huang, University of South Carolina

DOE Contract #	DE-EE0008842
Start and End Dates	4/1/2020–3/31/2024
Partners/Collaborators	University of Massachusetts at Lowell, Idaho National Laboratory, National Renewable Energy Laboratory
Barriers Addressed	• Delamination and chromium poisoning of oxygen electrodes

Project Goal and Brief Summary

The two leading causes for oxide ion conducting solid oxide electrolysis cell (O-SOEC) performance degradation are delamination and chromium poisoning of oxygen electrodes. This project seeks to address these issues through materials innovation and theoretical modeling. The final product will be a highly active, delamination-resistant, and chromium-resistant oxygen electrode for durable, high-efficiency, and high-rate hydrogen production via intermediate-temperature SOECs (≤700° Celsius).

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.0** for identifying barriers and addressing them through project innovation, as well as for project design and feasibility.

- It is always a pleasure to listen to Dr. Huang's presentations, and new ideas keep coming. The project's use of the required presentation template for the updates is appreciated. In general, the work in Europe has shown that electrode delamination, which many groups have addressed, is mainly a function of processing and application on cells. Likewise, major electrolyzer original equipment manufacturers (domestic and abroad) demonstrated long operation in solid oxide fuel cell (SOFC)/SOEC/reversible solid oxide cell (rSOC) stacks/systems without oxygen electrode delamination. The following comments are shared in the hopes of helping to guide current and future work with a more focused approach:
    - Perovskites and composites are well-known oxygen electrodes operated in large systems (in Europe and the United States) for extensive periods without any major delamination issues. The principal investigator (PI) also mentioned no delamination was observed when measured in fuel cells. However, delamination does occur in symmetric cells; thus, perhaps it is worth considering whether symmetric cells are the right tool to measure electrode delamination or any kind of long-term electrochemical operation. Perhaps it would be worth questioning how or if such data/behavior could be reproduced in full cells.
    - The SCT (strontium cobalt tantalum, or $SrCo_{0.9}Ta_{0.1}O_{3-\delta}$) coat is an interesting approach to help with electronic conduction and as Cr getter. It would be helpful to understand whether it is economically more feasible to coat all cells with SCT or apply scaled, well-understood, manufactured-at-scale, Cr-resistive coatings to bipolar plates. Perhaps it is worth considering whether application of SCT (an additional cost) is necessary if there are Cr-resistive coatings on the stack and doing the job. If SCT's primary role is to serve as a current-collecting paste and will replace another current-collecting paste, then further investigations are warranted.
    - On slide 14, the baseline lanthanum strontium cobalt ferrite–gadolinium-doped ceria (LSCF-GDC) cell shows extremely low performance, while there are many literature sources clearly showing that such electrodes perform at least 2x to 4x better (commercial inks). Perhaps it would be beneficial to explain why such a low-performing cell was used for comparison against the highest-performing cell with LSCF-GDC/SCT. If another highly conductive current collective paste (e.g., lanthanum strontium cobalt [LSC]) is used for a baseline cell, then it would be helpful to know the difference in cell performance. Perhaps it would be beneficial to conduct such a study to ensure an accurate one-to-one comparison.
    - Using the same materials in planar cell configuration leads to substantially lower degradation than in tubular cell configuration. Perhaps it would be beneficial to explain this difference.
- Cr tolerance of oxygen electrodes is an important degradation mechanism that needs to be resolved. The project considers a Cr-tolerant coating over the LSCF-GDC electrode. The selected coating layer has excellent oxygen exchange properties, as discussed by the PI. The symmetrical electrode test method is a good approach to measuring the exchange current density and is skillfully used to monitor the change in the exchange current density over time.
- Both experimental and computational methods are employed to study the oxygen electrode, which provides a clear and deep understanding of the novel electrode the project developed.
- The approach is adequate except for operating at too low of currents. Delamination and Cr poisoning of oxygen electrodes are the two leading causes for the performance degradation of SOECs.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals, as well as the HydroGEN Consortium mission.

- The team has validated that the bilayer oxygen electrode can help to improve performance and durability. Both experimental and computational studies have been conducted to confirm the results. The accomplishments meet the proposed goals.

- Time to delamination is calculated empirically based on change in exchange current density with time. Combining multi-physics modeling, materials process development for coating, and experimental validation shows the well-rounded approach of the project's research group.
- The project's progress is adequate but appears slow.

Question 3: Collaboration effectiveness

This project was rated **3.6** for its collaboration and coordination with HydroGEN and other research entities.

- The project is working with two national laboratories. It shows that combining the strengths of the university with the core capabilities of two laboratories is beneficial.
- The team has very good collaborations with universities and national laboratories.
- The project has excellent collaboration, with five national laboratories supporting the effort.

Question 4: Potential impact

This project was rated **3.0** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN Consortium mission.

- The overall objective is good. Adding another layer over the oxygen electrode appears to provide Cr tolerance and reduce delamination. Many groups seem to have addressed the delamination problem (to the extent it is published), but extending the solution for high-current operation as an objective is worthy of exploration. It is somewhat unclear whether the coating needs to be continuous to gain the Cr tolerance and whether the top layer has the same functionality as the underlying LSCF-GDC opposite. Testing the concept on commercial tubular cells is a good approach, although the cycle-to-cycle degradation seems high, but a solution will help the industry.
- Even in the reversible mode, currents of 3 A/cm^2 or higher for SOECs will be needed. The tubular technology, whatever advantages it may have, has inherently lower current designs. The effort is concentrating on tubular SOFCs, which has no industrial partner in the forefront of development. It is uncertain whether the project should continue to be pursued, other than as an academic curiosity. DOE has driven three or four fuel cell technologies to demonstration/market. The cost of developing a technology to the demonstration stage has taken at least $1 billion and decade(s) per technology. There are eight years left and limited funding to reach the Hydrogen Program goals to indulge every distraction. Developing to demonstration or market such a technology (tubular SOECs) will take a billion dollars and decade(s). It may be too late for these Seedling projects to impact DOE 2030 goals.
- The success of this project will certainly advance the SOEC program at DOE and help to achieve durable SOEC cells, stacks, and systems.

Question 5: Proposed future work

This project was rated **2.9** for effective and logical planning.

- The project has a good approach and plan.
- The project should complete the work at the highest currents possible.
- The proposed future work is reasonable.
- Perhaps it would be beneficial to consider experimental direction change.

Project strengths:

- This project addresses two common degradation mechanisms, namely Cr poisoning and oxygen electrode delamination. The project understands the mechanisms and formulates solutions elegantly.
- Both experimental and computational methods are employed to understand the bilayered electrodes.
- The research is an excellent academic contribution with important commercial SOFC experience.

Project weaknesses:

- It appears the project's effort is avoiding degradation, delamination issues, and exploration by operating at low currents. Even in the reversible mode, currents of 3 A/cm^2 or higher for SOECs will be needed. The tubular technology, whatever advantages it may have, has inherently lower current designs.
- It is unclear whether the layer needs to continuously cover the electrode and whether it needs to be uniform. It was stated that the isostructural layers will not delaminate at the interface, but the project needs to convincingly demonstrate this as fact.
- The project has no apparent weakness.

Recommendations for additions/deletions to project scope:

- Certain accelerated tests, such as rapid thermal cycling, will give a better understanding of the stability of the bilayer electrode. Perhaps an evaluation of a discontinuous or partially covered layer on its capability for Cr tolerance would be helpful.
- The project should operate at higher currents.

Project #P-191: Perovskite–Perovskite Tandem Photoelectrodes for Low-Cost Unassisted Photoelectrochemical Water Splitting

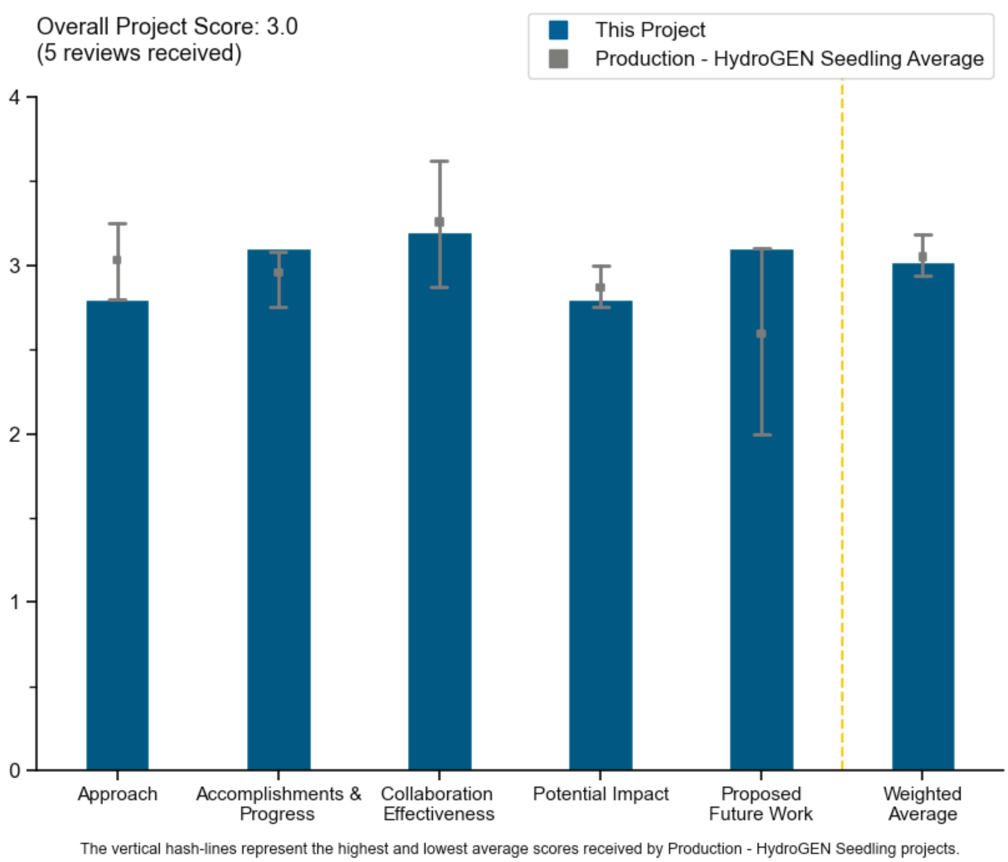
Yanfa Yan, The University of Toledo

DOE Contract #	DE-EE0008837
Start and End Dates	10/1/2019–9/30/2023
Partners/Collaborators	National Renewable Energy Laboratory, Lawrence Livermore National Laboratory
Barriers Addressed	• Materials Efficiency – Bulk and Interface: Identification of absorber composition and interfacial materials for efficient hydrogen generation • Materials Durability – Bulk and Interface: Investigation of intrinsic stability of perovskites; development of durable protection layers • Configurations: Tandem film stack and photoelectrode integration

Project Goal and Brief Summary

This project's goal is to enable cost-effective photoelectrochemical (PEC) water-splitting devices using monolithically integrated perovskite−perovskite tandem photoelectrodes, developed by the research team. If successful, the proposed PEC technology presents a significant technoeconomic advantage over the state-of-the-art spontaneous water-splitting devices. The team aims to demonstrate a high-efficiency and stable PEC system that shows potential to reduce PEC hydrogen generation costs to $1/kg. The University of Toledo is collaborating with the National Renewable Energy Laboratory (NREL) and Lawrence Livermore National Laboratory (LLNL) on this project as part of the HydroGEN Consortium.

Project Scoring



Question 1: Approach to performing the work

This project was rated **2.8** for identifying barriers and addressing them through project innovation, as well as for project design and feasibility.

- The team is focusing on improving the durability of low-cost perovskites for PEC water splitting. The solid-state efficiency of the proposed material class is already comparable to that of III-V systems while offering much lower manufacturing costs. The fact that narrow e_g perovskites do not possess the same intrinsic stability as wide e_g ones is a challenging issue, but ongoing research efforts in the photovoltaic (PV) community to address these problems, including in the principal investigator's group, will eventually translate to PEC systems.
- Tandem perovskite "photoelectrodes" offer an attractive approach to achieving high solar-to-hydrogen (STH) using potentially low-cost, solution-processed materials. The emphasis on durability tests is appreciated, as this is a critical barrier to overcome. Sealing the tandem perovskites behind a metal foil is also likely to be an effective approach to ensure those components are not exposed to the electrolyte. The performance of the perovskite photo-absorbers is impressive, but it is not obvious that Type III PEC devices (panel configurations) have a competitive advantage over PV electrolysis using PV panels made of the same photo-absorbers.
- The use of perovskites may enable low-cost materials. The project uses the HydroGEN nodes well. From slide 5, it looks like the project team is making a mixed hydrogen and oxygen gas, which is a separations and safety challenge. The project will be using a membrane to solve this problem, but this was outside the work scope. The membrane will increase the impedance, so the project will get lower STH efficiencies than reported. The project team needs to be testing the materials in a configuration that better simulates what the final device will be to truly understand the performance. The tandem configuration is a good approach.
- The project has a good approach that allows for inexpensive tandems for water splitting. There is a balance between detailed understanding and testing, although improvements are needed. It is not clear why a buried bandgap material is used in a PEC configuration compared to PV electrolysis. The project is focused on the photoelectrode, but the test cell should be a viable system that can be tested to ensure equitable comparisons.
- The project's vision projects an increase in efficiency (>20%), decrease in cost (<\$200/m^2), and durability of >1,000 hours. The current state of the art has 18% efficiency, a cost of \$20,000/m^2, and durability of 100 hours. The project suffers from a chronic stability problem with water-soluble materials. The project's targets are well stated, but it is clear that insufficient thought is given to some of the key issues with implementation. Highly effective PV cells do not necessarily make for cheap hydrogen if there are catalyst, stability, and engineering issues that are intractable.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals, as well as the HydroGEN Consortium mission.

- The project has made good progress in terms of understanding fundamental mechanisms for degradation and figuring out ways to overcome them. The project examined different metals and catalysts and obtained efficiencies that are relatively high (although not the highest reported). However, the system should be less expensive. The stability has improved, but the project still has a long way to go to be commercially competitive. There still appear to be significant challenges.
- The project has demonstrated impressive STH efficiencies for Type III PEC devices (>18.5%). The project has also demonstrated ~240 hours of stability, although the project is unlikely to achieve the 1,000-hour target, based on presented results. While significant progress has been made, it is not obvious that this approach presents a realistic pathway to achieving the DOE Hydrogen Shot goal of < \$1/kg H_2. The discussion about the perovskite stability challenges/mechanisms is appreciated.
- The project team was able to achieve high STH efficiency of >22%, but this was in a cell that produced stoichiometric H_2:O_2, which is not safe. The real STH will be lower when a membrane is used to prevent the stoichiometric H_2:O_2 gas generation. The project team was able to develop a suitable conductive paste. The project was able to achieve suitable performance of 280 hours. The open-circuit voltage of 2.13 V is very good and is suitable for water splitting. Overall, the project team made very good progress to exceed

the project goals. The team is using an IrO_x counter electrode, which is suitable for an experimental setup but is not going to be suitable for a commercial cell.

- The project benchmark to improve is the state of the art. The project should probably use silicon and proton exchange membrane (PEM) and not 3/5 PEC. The project has three months to go and has not achieved 500 hours with 80% activity retention. The PV curve looks good, with 28% power conversion efficiency and open circuit voltage of 2.13 V. The presenter did not say what catalysts are needed for the system. The advantage of Si and electrolyzers is intensification of the electrolysis step and lower platinum group metal (PGM) demand for hydrogen production. The implementation does not consider gas separation or scale-up and could refer to DOE studies.
- The project has made some good progress regarding STH efficiency. With respect to stability, T90 = 240 hours was demonstrated. It is not clear whether the T80 of 1,000 hours can be met using the current device architecture, especially considering the project is in its final year.

Question 3: Collaboration effectiveness

This project was rated **3.2** for its collaboration and coordination with HydroGEN and other research entities.

- The project has effective collaboration with NREL (PEC measurement, atomic layer deposition interconnection, and protection layers) and LLNL (x-ray analysis).
- The lead organization uses the HydroGEN nodes well.
- The project seems to be utilizing the capabilities in the network to address the perceived issues.
- Numerous Energy Materials Network nodes are listed on slide 4, and the interaction with NREL's perovskite team is apparent (with one joint paper published in *Science*). It was not clear whether STH efficiency values were validated by the NREL PEC node. The interaction with the LLNL group was limited to one figure on x-ray spectroscopy analysis on slide 24. More information on how these data are used to improve perovskite properties would have been welcome.
- The project is leveraging HydroGEN labs successfully, although additional interactions and modeling to inform future work would be good. The interactions were not really shown, though—just mentioned. The project should be leveraging test cells from HydroGEN in all testing.

Question 4: Potential impact

This project was rated **2.8** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN Consortium mission.

- The project has a good approach in terms of inexpensive materials for PEC. If the technology were to be widely deployed, PEC could perhaps meet the goal, but it still needs improvement in terms of stability and scale-up. The test cells are not viable or representative, so it is hard to judge actual impact.
- Perovskites are clearly dominating the PV field and could have a huge potential for low-cost PEC hydrogen production, assuming durability issues (let alone in dry conditions) can be solved.
- The project presents a good introduction to why perovskites are of interest and has a simple solution-based film deposition.
- High-efficiency demonstrations and long-term durability tests are very valuable to the field. One of the biggest risks is long-term stability. Degradation of lead halide perovskites themselves is the biggest concern. This is especially concerning for some of the more exotic wide bandgap perovskites needed for the tandem designs. Some techno-economic analysis (TEA) work was carried out, but it was not clear that there is a realistic pathway toward <$2/kg or inherent techno-economic advantage of these device concepts compared to decoupled PV electrolysis (e.g., a PV-PEM electrolyzer). Specifically, achieving a 10-year lifetime is a major reach. It is concerning the TEA on slide 21 appears to have not taken into account the cost of the membrane. It is great that the projected photoelectrode cost might have a pathway to <$30/m^2, but the membrane that will be required to separate the O_2 and H_2 should also be considered. Mass-produced cation exchange membranes are often >$300/m^2. Utilizing these membranes at a current density of only 15–20 mA/cm^2 makes this alone an unfavorable proposition versus a PEM electrolyzer using the same/a similar membrane but with two orders of magnitude higher current density per area of the membrane.

- To meet the long-term goals of >$2/kg H_2, the project will need to use a counter electrode different from IrO_x and increase STH efficiency and durability. The mixed gas generation is a very significant challenge. The use of a membrane may solve the mixed gas challenge, but it will lower the STH efficiency. Mixed H_2 and O_2 gas generation is a safety issue.
- The project's understanding of the required performance seems adequate, but the cost of system components (especially the catalyst) is not really considered. It is hard to see how this could hit $1/kg with the complex fabrication, PGM dependency, and limited lifetime that seems inherent with such materials.

Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- Measuring temperature-dependent performance and running tests with separated cell compartments are both interesting and important analyses to perform. Demonstrating durability up to 1,000 hours is also key; however, it is not clear what changes will be made to the tandem structure to achieve this goal. With the current structure, the perovskite cells are physically isolated from the electrolyte, and loss in performance may come from the materials themselves, not the electrochemical process.
- The focus on long-term stability tests and TEA is appropriate during the remaining two to three months.
- The 1,000-hour test is a good experiment. The Hydrogen Analysis (H2A) production model would be useful to determine what the current projected cost of hydrogen would be with the device. The project needs to do testing with a membrane to better simulate a real cell to measure true STH efficiency.
- It is clear there is a way to go to achieve the project performance target in a rather limited remaining time, but this is at least understood.
- The project is ending, but there are still significant things to get done to prove stability.

Project strengths:

- The cells the team has produced can clearly generate the current densities required for high STH efficiencies. The team also has excellent knowledge in the physical and chemical properties of the class and is participating in efforts to improve the durability not only for PEC but also PV applications.
- The project focuses on stability of perovskites, which can be a less expensive tandem with high efficiency. The project has made good progress, although in more ideal cases, and has a good focus on the fundamental understanding that can be leveraged into improvements.
- High-efficiency PEC demonstrations and long-term durability tests are very valuable to the field. The perovskite tandem cells might have commercial potential in the PV field.
- The project looks at materials with high STH potential.
- There is nice progress on PV performance.

Project weaknesses:

- It was not clear that there is a realistic pathway toward <$2/kg or inherent techno-economic advantage of these device concepts compared to decoupled PV electrolysis (e.g., a PV-PEM electrolyzer). Also, long-term (5- to 10-year) stability of wide-bandgap perovskites is a major technical risk. While there was nice progress related to perovskite materials/photoelectrodes, efforts related to incorporating photoelectrodes into devices and thinking about scale-up considerations were underwhelming.
- The materials the project uses are sensitive to water. The project team is testing the cells in a configuration that is not representative of what a final device will look like, which results in higher performance than what will be seen in a real cell. The project has not done an H2A or other TEA analysis. The project uses IrO_x, which is extremely expensive, and there will be considerable competition for this valuable critical material.
- The test conditions were ideal, so it was hard to judge the actual efficiencies with practical cells and non-photoelectrode materials. The stability is still not sufficient. There are still major barriers in the various materials, and detailed strategies to overcome them were not presented.

- In terms of cell design, it is unclear why metal foils are bonded to the back of the cell, instead of coating catalysts via direct deposition (physical vapor deposition or chemical vapor deposition). The use of conductive paste and resulting gaps between the cell back side and foil could be a point of ingress, leading to degradation.
- Multiple issues still exist, implementation issues are not considered, and no consideration is given to the catalyst.

Recommendations for additions/deletions to project scope:

- If this work were to be extended, the cost of fabrication should be realistically assessed to establish meaningful targets. It is likely to be a long time before PEC is a viable technology; this a low technology readiness level. The assertion that the $1/kg target is achievable with this technology is questionable, and the assumed cost of electricity for PEM to achieve $1/kg is not achievable at the required capacity factor. Maybe $2/kg could be acceptable, but there should be some realism about what might be possible instead of unsubstantiated claims of what is achievable without any TEA being provided to inform the key performance metrics.
- The project is ending. The project could use HydroGEN cell testing and validation of PV electrolysis versus PEC because of stability issues.
- The project needs to do a TEA. The researchers need to do their tests with a membrane to separate the O_2 and H_2 production. The project needs to identify a better material than IrO_x.

Project #P-192: Development of Composite Photocatalyst Materials That Are Highly Selective for Solar Hydrogen Production and Their Evaluation in Z-Scheme Reactor Designs

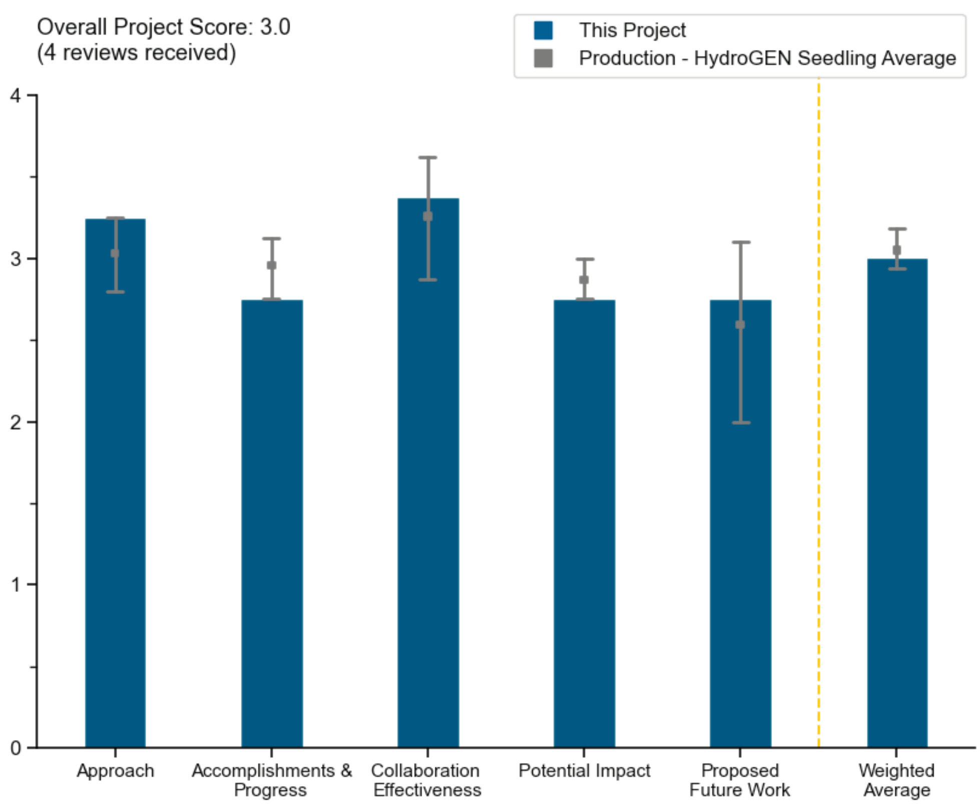
Shane Ardo, University of California, Irvine

DOE Contract #	DE-EE0008838
Start and End Dates	10/1/2019–10/31/2023
Partners/Collaborators	University of Michigan, Columbia University, National Renewable Energy Laboratory, Lawrence Livermore National Laboratory, Sandia National Laboratories, Strategic Analysis, Inc., Lawrence Berkeley National Laboratory, California Institute of Technology, Tokyo University Science, Shinshu University
Barriers Addressed	• Few composite particles that selectively evolve H_2 and O_2 instead of performing undesired redox shuttle back reactions • Design of ultrathin oxide coatings for selective reactivity and reactor dimensions for natural convective mixing, guided by empirical and numerical results

Project Goal and Brief Summary

This project aims to develop new photocatalyst particles and ultrathin oxide coatings for photocatalytic solar water splitting that can enable demonstration of the interim DOE target of 3% solar-to-hydrogen efficiency. The goal is to demonstrate a selective ultrathin oxide coating on particles that results in a ≥10 times larger hydrogen evolution quantum yield than for uncoated particles. Using an intrinsically safe tandem (Z-scheme) dual-bed particle suspension reactor design, the project also aims to validate high-efficiency and techno-economically viable photocatalyst reactors for solar water splitting.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Production - HydroGEN Seedling projects.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying barriers and addressing them through project innovation, as well as for project design and feasibility.

- The project aims at solving important challenges in PEC water splitting using so-called Type II (Z-scheme) reactors with suspended nanoparticles. Specifically, the team has targeted two key issues: reaction selectivity and the development of a low-cost reaction shuttle mixing process. Reactor design is driven from advanced modeling and simulations covering multiple physical (e.g., photon flux, particle diffusion) and chemical (reaction kinetics) steps. Overall, the approach and results presented are impressive. The team has clearly identified the main technological barriers with the technology and established clever solutions to address them.
- The approach uses Ir-doped $SrTiO_3$. Ir is extremely expensive, with limited supply, making it unlikely to be used at high volumes. In addition, there is a growing demand for Ir for other applications. Photoelectrochemical (PEC) particles in a Type II design is one pathway that has been proposed that has the potential to come close to \$2/kg H_2. The approach assumes the ability to keep the particles suspended. It also assumes natural convection for mixing, which is unlikely, given the diurnal mode of operation of this system and for the cases of multiple days without much sunlight (cloudy days, rainy or snowy days, etc.). The project needs to assume heating from the sun. The project may need to include cooling to ensure material integrity. The improved design increases the area for the ion transport between the oxygen evolution reaction and hydrogen evolution reaction (HER), which is vital for the success of this approach.
- The project may achieve 10% target efficiency. The particles need to remain suspended if not fixed film, which requires a good mixing of redox species. The project uses iridium-doped $SrTiO_3$. The project also uses two light-absorbing particle chambers. The redox shuttle species needs to diffuse/migrate through a barrier. There is a small area for redox shuttle to allow gas collection; perhaps there is a concentration gradient around this. The project could consider raceway tubes with larger ion bridges (slide 7). The project has undesirable back reactions and could consider Pt and IrO_x co-catalysts to help avoid other reactions on redox shuttle (Fe[III] reduction). The project team arguably has a good understanding of some of the key issues, although the practical implementation aspect, including catalyst loading, is conveniently ignored.
- This project seeks to develop high-yield photocatalysis with high selectivity. The project uses two separate catalysts for hydrogen, and oxygen evolution is studied.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals, as well as the HydroGEN Consortium mission.

- Great progress has been made in the project. For example, a coating that can prevent back reactions has been experimentally validated and backed up by simulations. Dopant discovery for strontium titanate has been successfully implemented via high-throughput screening. Characterization of a single particle with scanning electron microscopy is a noteworthy accomplishment. Demonstration of durability over 8 hours of testing is also reported.
- This project was started in 2019, so the lack of experimental data is a very significant failure. There were many simulations to aid in the selective coatings' selection. The simulations predict that solar-to-hydrogen efficiency of up to 10% may be achieved. The simulations were done at room temperature, but the temperature in the Type II configuration is likely to be substantially higher than room temperature because of the configuration and needs to be included in the calculations. The simulations assume the particles will remain in suspension. The suspension of particles for long periods of time has not been demonstrated and is unlikely to be achieved without some sort of mechanically induced mixing. The project is using Ir and/or Pt, which are critical materials; it is recommended that the project develop alternatives for both. Slide 12 seems to indicate that Rh was the preferred dopant, but the principal investigators (PIs) clarified that Ir was the best. The PIs needs to be clearer on what the best materials are, as this important finding is not clearly stated in the presentation. All the project slides need to clearly state what materials and conditions are used. The coating work is very encouraging. The idea of specific coating of the active sites is interesting but may be cost-prohibitive for manufacturing at large scale. The atomic layer deposition is an interesting approach, but its use for nanoparticles in high-volume manufacturing while keeping costs down may be a

challenge. The photo-deposition option may be better. The project did not do direct measurements but translated quantum yields through models. The project really needs to do direct measurements. For the proposed membrane, the project did not measure cross-over; the team only did calculations. The project needs to do more measurements to back up the calculations.

- The combinatorial screening looks really nice, but there are significant barriers to the success of the project, and it would seem that the targets are not going to be reached. The overall target (≥10 times larger H_2 evolution quantum yield than for uncoated particles) is not really enough to ensure this is a realistic technology and seems a bit narrow. Catalyst usage is not really addressed, although some thought is given to the design of a system.
- The project's accomplishments include rapid screening of catalysts and coating to suppress side reactions by using model and experimental validation.

Question 3: Collaboration effectiveness

This project was rated **3.6** for its collaboration and coordination with HydroGEN and other research entities.

- The project mentioned external partners early, and there seems to be a good deal of activity at different places. The combinatorial screening looks fantastic. The funds might be too thinly spread for effective work at each institution; coordination of such a large team would perhaps also be difficult.
- The team is supported by several Energy Materials Network (EMN) nodes, as well as international experts (Kudo and Hisatomi). Several joint publications include national laboratory scientists as co-authors. Overall, collaborations with external partners are effective and well-coordinated.
- The use of HydroGEN nodes was well done. The roles and responsibilities of the team members are not clear.
- The project appears to be interacting with various lab personnel and the research community.

Question 4: Potential impact

This project was rated **2.8** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN Consortium mission.

- The work performed so far is impressive. Although the project is focused on the development of particles and coatings, the milestones and go/no-gos have been established considering the whole Z-scheme process.
- Overall, the project is challenging, but success will provide another option for hydrogen production.
- The project simulations indicate possibly attaining $2/kg, but it is unlikely that the project will be able to get to a projected cost of $1/kg. The extremely critical material, Ir, is essential for the success of this technology. The project assumes that the materials can be suspended for long periods, which has never been demonstrated. The project team presented a good deal of calculations and modeling but not very much experimental data. This project was started in 2019, so the lack of experimental data is a very significant failure.
- It is not clear how this can lead to a workable system. Pumping was identified as a significant cost/energy penalty, and natural convection was postulated as a possible solution, but it is not clear how this would work on start-up/shutdown and intermittent insolation. The project's catalyst loadings could be enormous. The project has too much emphasis on modeling versus experiments.

Question 5: Proposed future work

This project was rated **2.8** for effective and logical planning.

- The proposed work seems a reasonable pathway to complete the work.
- The project seems to be coming to a close without really clear outcomes. "Continue to work with collaborators to obtain high-quality materials and evaluate particle properties using our suite of experimental tools, to support pathways to high-efficiency photocatalysis" and "continue to work with co-PIs/EMN project node experts to deposit ultrathin oxide coatings on nanoparticles and evaluate selectivity via HER quantum yield, to support pathways to high-efficiency photocatalysis" are too vague. The project

should really focus on what the key metrics are to meet a $2/kg goal and what the next stage would look like if the investigators feel this is a concept with merit.

- The proposed plan for future work is consistent with the project objectives.
- The project is ending this year.

Project strengths:

- The PI has identified two important barriers for PEC water splitting using Z-scheme Type II reactors. A team of experts with complementary knowledge has been assembled, and great progress has been made so far. The number of high-quality publications that resulted from this project is impressive. Good science will come out of this project.
- The project's concept provides a way to evolve hydrogen and oxygen in separate chambers. The use of coating is a good approach to limit secondary reaction.
- The project has a very interesting approach that avoids the limitations of the more common planar PEC configurations, and the modeling work was very interesting.
- The project is engaging with many people (25 researchers), is arguably creating many opportunities for scientific knowledge, and has some nice techniques.

Project weaknesses:

- There is nothing to report. The reviewer is looking forward to hearing how improvements made on particles and coatings will translate into a standalone Type II reactor efficiency in the near future.
- The project is unclear on crossover of hydrogen. Regarding extinction/transmission of light, the depth of reaction has very low quantum yields at 405 nm, which is less than 0.1%. The quantum yield target might be irrelevant if the percentage conversion is ridiculously low. Regarding single wavelength, it is not clear how this would translate to full spectrum. The project considers particle-scale effects but not the broader diffusion and light extinction/transmission issues. The project needs to build and operate something, as it is currently all calculation-based.
- The project did a poor job validating calculations with experimental work. The project assumed that natural convection would be sufficient to keep the particles suspended for long durations (years) without any other agitation, but this must be validated. It is an extremely unlikely scenario given the diurnal nature of the system and the obvious scenarios of cloudy days that would happen even in deserts.
- Selective deposition of coating will be challenging to implement.

Recommendations for additions/deletions to project scope:

- There are no specific recommendations. The team is capable, but it will be challenging to accomplish all the targets. Suspending particles needs more consideration in terms of particle size and surface characteristics. It is understandable if the project is hampered by limited time and other tasks take priority.
- The project must do experiments to validate the calculations. The project must prove that the assumptions on natural convection are sufficient to cause mixing, which must include start-up from when the particles are all on the bottom of the reactor. The project needs to find alternative materials to Pt and Ir, as these are expensive critical materials and there is tremendous competition among many industries, not just hydrogen production.
- Techno-economic analysis and experimental demonstration will be critical to the project's outcomes.

Project #P-193: Highly Efficient Solar Water Splitting Using Three-Dimensional/Two-Dimensional Hydrophobic Perovskites with Corrosion-Resistant Barriers

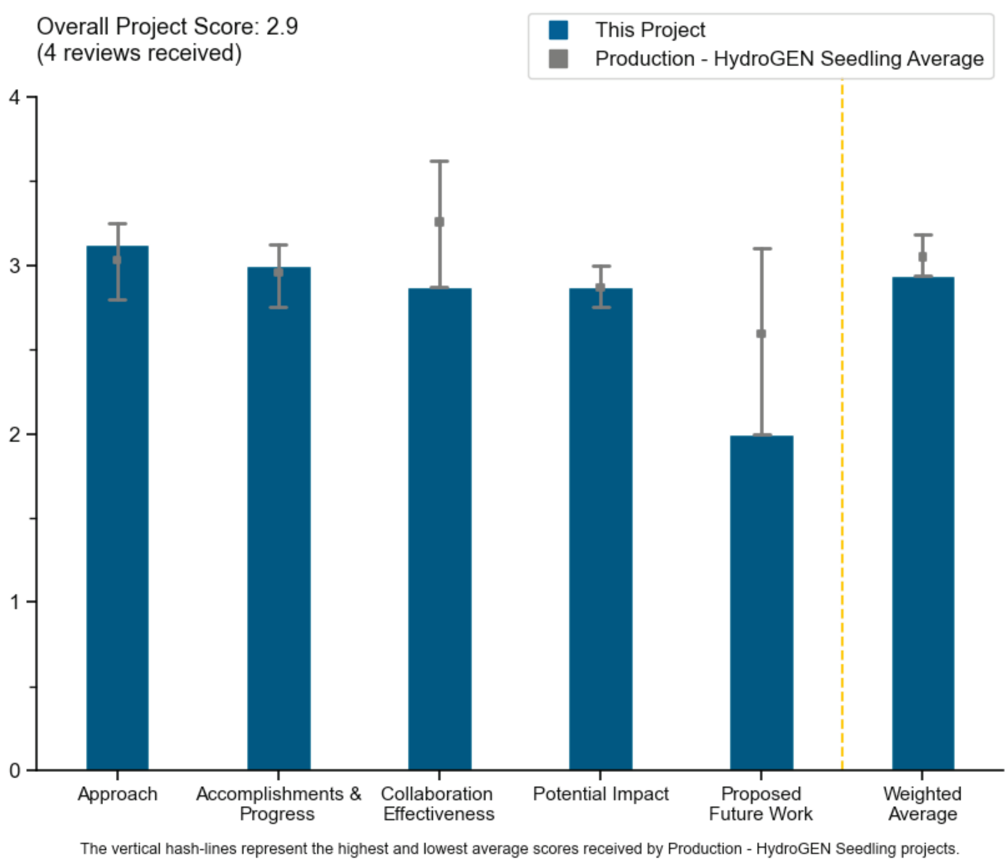
Aditya D. Mohite, William Marsh Rice University

DOE Contract #	DE-EE0008843
Start and End Dates	1/1/2020–1/1/2023
Partners/Collaborators	Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory
Barriers Addressed	• Stability of perovskite solar cells in aqueous media • Development of corrosion-resistant layers that are electronically transparent

Project Goal and Brief Summary

Rice University aims to demonstrate an innovative concept with advanced materials for photoelectrochemical (PEC) cells based on direct water splitting to produce hydrogen fuel. The project team is combining high-efficiency, low-cost halide perovskite (HaP) solar cells with hydrogen evolution reaction and oxygen evolution reaction catalysts to demonstrate an integrated HaP-PEC cell with 20% solar-to-hydrogen (STH) efficiency and 500 hours of operational durability. If successful, this project, in collaboration with Lawrence Berkeley National Laboratory (LBNL) and the National Renewable Energy Laboratory (NREL) through the HydroGEN Consortium, will demonstrate a durable and efficient water-splitting system that can produce hydrogen at scale using low-cost, abundant materials.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.1** for identifying barriers and addressing them through project innovation, as well as for project design and feasibility.

- Tandem perovskite photoelectrodes offer an attractive approach to achieving high STH using low-cost, solution-processed materials. The recyclability of the substrate and active components is also very attractive. The project incorporated a nice combination of materials development, device testing, and techno-economic analysis (TEA) that leveraged expertise at national labs.
- The project seems the most focused of the three PEC presentations. The project had the best articulation of the performance goals: 20% STH and 500-hour stability of HaP, this time using hydrophobic termination. Other photons can heat up the electrolyte and improve kinetics. (It is good that Sophia Haussener was mentioned.)
- The team is focusing on earth-abundant perovskite materials for PEC water splitting. Despite the material class's being notoriously unstable, the team managed to achieve good stability (~100 hours) with tandem structures.
- The team's approach investigates the major challenges for the technology. The plan has included a cost analysis portion to aid in the development. The water-stabile perovskites were an important focus.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals, as well as the HydroGEN Consortium mission.

- The project demonstrated record STH efficiencies for Type III PEC devices. The project demonstrated a recyclable platform, which is great to see from a lifecycle analysis standpoint, and very nice device demonstrations using a concept that is scalable, in principle. The project demonstrated ~100 hours of stability, although it is unlikely to achieve the 500-hour target, based on presented results.
- The project achieved high STH (15%) and life (100 hours), which was a little lower than the stated goal of 20% for 500 hours. The project should refrain from referring to 100 hours as "long life" when >40,000 hours will be needed for a technology to be considered. The degradation rate is still too high. The project needs to continue to better understand the degradation (delamination) challenge. The team is trying to decrease the use of Ir and other critical materials, which will be necessary for a commercially viable device. The conductive-adhesive layer accomplishment was very important and is a key enabler. The project team is working on scaling up the system size—the first time this has been seen. The heat harvesting to improve the efficiency is a novel approach. The demonstration of recycling the materials was a nice add-on to the work and is very interesting. The degradation rate is still too high, but 100 hours is progress. The researchers need to find alternatives to IrO_x. Ir is a critical material, and limited amounts are available. The researchers are looking at Ru with Ir, but these are not earth-abundant catalysts. The principal investigator claimed very good stability of the Ni and Ru in the acidic solution; however, this is unlikely for Ni. The project needs to look for the species in the solution.
- The project has made progress toward earth-abundant catalysts, recyclable components through solution-based extraction, a lifetime up to 2,000 hours, 98% conversion of electric energy to chemical energy, and Pt and IrO_x catalysts (slide 12). The technology shows 5- to 10-hour failure from ingress of ambient moisture, not from solution. Slide 17 shows progress with Ag. Slide 18 shows STH from 20.8% to 12.5%—not 15%, as stated in the presentation. Slide 21 shows results from IrO_2 catalyst delamination studies.
- Clearly, the team can produce high-efficiency solid-state tandem perovskite solar cells, and at face value, the STH efficiencies reported are impressive. However, it is apparent that no hydrogen has been collected so far at the system level. No information on the catalysts used for Faradaic efficiency calculations was provided. Also, it appears that this study was done on thin film catalysts, not the tandem cell. As such, STH values (calculated by multiplying current density x 1.23 V) constitute only the upper STH efficiency limit of the system. Also, for Year 2, the go/no-go decision point was a 15% STH for 100 hours; however, based on data provided (slide 15), it looks like efficiency dropped below 15% at around 50 hours.

Question 3: Collaboration effectiveness

This project was rated **2.9** for its collaboration and coordination with HydroGEN and other research entities.

- The project has effective collaboration with LBNL (degradation studies) and especially NREL (efficiency benchmarking/protocols, strategies for scale-up, input on TEA).
- The team members have well-defined roles. The lead organization effectively uses the HydroGEN nodes.
- The Energy Materials Network partners are LBNL and NREL. In the presentation, LBNL is credited once for the Faradaic efficiency calculation. LBNL is mentioned on slide 16 ("understanding of degradation"), but no data was included. Also, based on this presentation, it appears that the NREL node was not solicited for device benchmarking, despite being a part of the project. The latter is problematic, considering the high STH values reported by the team.
- The project's collaboration is satisfactory. The project has involvement from LBNL and NREL (slide 6) but may not connect as broadly with the HydroGEN community as other projects.

Question 4: Potential impact

This project was rated **2.9** for supporting and advancing progress toward DOE Hydrogen Program goals and the HydroGEN Consortium mission.

- The potential impact of perovskites on PV and PEC is undeniable.
- High-efficiency demonstrations and long-term durability tests are very valuable to the field. One of the biggest risks is long-term stability; this project highlights some challenges associated with delamination/ degradation of catalyst and encapsulation layers, but the biggest concern is degradation of lead HaPs themselves (even in the absence of contact with the electrolyte). This is especially concerning for some of the more exotic wide-bandgap perovskites needed for the tandems. Some TEA work was carried out, but it was not clear that there is a realistic pathway toward <$2/kg or inherent techno-economic advantage of these device concepts compared to decoupled photovoltaic (PV)-electrolysis (e.g., a PV-proton exchange membrane [PEM] electrolyzer), even if electrolysis is carried out with earth-abundant electrocatalysts in an alkaline environment. Specifically, achieving a 10-year lifetime is a major reach, and it is not clear from the presented results that membranes were taken into account (it appears not).
- The reviewer does not recall what the statement "need 1000x times less material to absorb solar radiation" was using as the counterfactual, but this feels like hyperbole. Also, it is unclear why there are two charts for STH efficiency versus panel costs. The left one looks more credible, though from the presentation, it appears that some of the balance-of-plant costs were overlooked. It is not clear that any system requiring a low-iron glass can be realistically produced at or below $\$50/m^2$.
- The team is trying to identify a viable pathway to $2/kg H2 and proposed an ambitious pathway that may achieve $1/kg H_2. The technology requires significant development such that it is unlikely to provide a pathway to $2/kg H_2, let alone $1/kg H_2, within the timeframe DOE states as its mandate.

Question 5: Proposed future work

This project was rated **2.0** for effective and logical planning.

- The project seems to be out of time (January 1, 2023, end date) with a number of objectives unmet.
- The project did not include a "Future Work" section.
- The project is ending this year.

Project strengths:

- The project has high-efficiency demonstrations and long-term durability tests and is very valuable to the field. The recyclability of the substrate and active materials is very attractive. The project incorporated a nice combination of materials development, device testing, and TEA that leveraged expertise at national laboratories.
- The project is looking at some very interesting materials that would decrease or eliminate the use of critical materials (Ir) and achieve longer lifetimes.

- The project appears to understand the broader implementation issues around pumping and platinum group metals.
- The project is based on high-efficiency solid-state and low-cost materials. Economical hydrogen PEC production could be achieved with perovskite, assuming durability can be addressed.

Project weaknesses:

- The cost of the membrane is unclear. Alkaline systems rates will decrease substantially. Ru is soluble in 1 M sulfuric acid; the project needs to check the solution chemistry: 200 mA/cm^2, p22 - 3 suns. Regarding the heat transfer from solar cell to electrolyte, some key operating conditions were omitted from the slides; it matters whether there is concentration or one sun. It is not clear what the next steps could or should be. This is fundamentally a tough technology to make work, and there is nothing here that shows a clear path to impact.
- It is not clear that there is a realistic pathway toward <$2/kg or inherent techno-economic advantage of these device concepts compared to decoupled PV-electrolysis (e.g., a PV-PEM electrolyzer). Long-term (5- to 10-year) stability of wide-bandgap perovskites is a major technical risk.
- The previous analysis done by Systems Analysis, Inc., for the Hydrogen and Fuel Cell Technologies Office suggests that it will be difficult for the planar design for PEC to achieve the low hydrogen cost targets DOE mandates.
- The project would greatly benefit from more rigorous PEC testing, which could add credibility to the technology.

Recommendations for additions/deletions to project scope:

- The “what next” was lacking.
- The project is ending.