Technology Acceleration – 2021

Subprogram Overview

Introduction

Technology Acceleration aims to address technology barriers, systems and systems-integration challenges, and other crosscutting activities to enable the H2@Scale vision and support the Hydrogen Energy Earthshot. The subprogram pursues these aims by:

- Identifying hydrogen applications and system configurations that can provide more affordable and more reliable clean energy
- Validating and testing integrated system development
- Bridging the gaps between component-level research, development, and demonstration (RD&D) and industry's role in commercialization by integrating technologies into functional systems, reducing costs, and overcoming other barriers to deployment.

Demonstrations conducted during verification and validation activities provide valuable data feedback to research and development conducted through the U.S. Department of Energy's (DOE's) Hydrogen Program subprograms. The data are also used in technoeconomic assessments of various market scenarios to provide essential information regarding market readiness to manufacturers, investors, and potential end users. The remaining subprogram activities—including manufacturing RD&D; safety, codes and standards RD&D; and workforce development—fill out an integrated portfolio that addresses other significant barriers.

The Technology Acceleration subprogram focuses its activities on key emerging markets (or technology applications) based on preliminary findings of the Systems Analysis subprogram, which identifies technologies and markets with the potential to enable economies of scale for hydrogen and fuel cell systems in alignment with the H2@Scale vision. Based on this analysis, the Technology Acceleration subprogram is currently focused on four technology application areas:

- **Grid energy storage and power generation** applications focus on grid integration and renewable hybrid systems, nuclear hybrid systems, and distributed and back-up power generation. Projects are designed to produce low-cost green hydrogen from intermittent and curtailed renewable sources, provide grid reliability, demonstrate dynamic response to match grid demands, support market penetration of renewable energy systems such as wind and solar, and provide additional revenue streams for nuclear power plants.
- **Chemical and industrial processes** are focused on decarbonizing hard-to-decarbonize industrial sectors through integration of hydrogen technologies. These end uses include iron- and steelmaking and ammonia, fuel, and chemicals production, among others. The integration of green hydrogen will reduce greenhouse gas emissions, add jobs, and provide environmental justice in these energy-intensive processes.
- **Transportation** includes medium- and heavy-duty trucks, maritime, rail, and other emerging applications such as construction, mining, and agriculture. The focus for heavy-duty vehicles is to demonstrate and validate fuel cell durability and performance under real-world conditions. Projects will also demonstrate and validate high-flow fueling to support these vehicles. Maritime projects aim to develop and validate power supply systems and hydrogen infrastructure at ports, portside power to supply oceangoing vessels, and onboard hydrogen/carrier storage systems. Demonstrations for rail and other emerging applications focus on the integration of hydrogen production, storage, distribution, and refueling infrastructure.
- **Enabling activities** include manufacturing RD&D; safety, codes and standards RD&D; and workforce development. Manufacturing RD&D projects aim to identify and pursue high-value processing routes to accelerate scaling and to develop techniques to produce advanced components and sub-systems to enable multi-megawatt-scale hydrogen systems at high production volumes. These demonstrations also focus on developing technology and analysis tools for quality control and reliability issues. The Safety, Codes and Standards activity area develops codes and standards to enable bulk utilization of hydrogen, as well as safety and permitting guidance to enable deployment of hydrogen for novel applications (see the Safety, Codes and Standards section of this report for more details). Workforce development activities support the development of training programs to enable the safe and effective deployment, use, and maintenance of hydrogen and fuel cell technologies across various applications.

Goals

The overarching goal of the Technology Acceleration subprogram is to identify new and promising hydrogen end users, expedite the commercialization of hydrogen and fuel cell systems by the private sector, validate the performance of these systems, and achieve economies of scale as envisioned in the H2@Scale initiative.

Key Milestones

Key milestones for the Technology Acceleration subprogram are summarized below.

Grid Energy Storage and Power Generation

- Validate large-scale electrolysis systems for energy storage, grid stabilization, resilience, and dispatch management of electric grid systems with high renewable energy penetration.
- Validate efficiency, costs, and benefits of hydrogen production systems integrated with nuclear power.
- Validate 90% efficiency for high-temperature electrolysis systems operating at nuclear plants utilizing onsite waste thermal energy.
- Validate an integrated distributed and back-up power generation system in real-world operations for power demands up to 2 MW.

Chemical and Industrial Processes

- Validate 100,000-hour electrolyzer durability and verify green hydrogen system cost and technical performance comparable with incumbent technologies for metals production.
- Validate 100,000-hour electrolyzer durability and demonstrate green ammonia production processes for emission reductions; verify costs and validate technical performance.
- Integrate emerging concepts with industrial processes for production of synthetic fuels and chemicals; verify costs and validate technical performance.

Transportation

- Validate 25,000-hour durability and 68% peak efficiency for fuel cells in in heavy-duty truck applications.
- Validate integrated portside power systems, and validate a 35,000-hour durability target for ferry boat shipboard applications.
- Validate onboard hydrogen storage and locomotive power systems for long-distance trains, including a 35,000-hour durability target.
- Validate technical and economic potential of hydrogen and fuel cells for off-road applications.

Enabling Activities

- Develop manufacturing and supply innovations to commercialize multi-megawatt-scale electrolyzers that can produce hydrogen at <$1/kg.
- Develop crosscutting low-cost manufacturing processes with scalability in mind to support domestic supply chains.
- Identify ways to reduce the siting burdens that prohibit expansion of hydrogen fueling stations by using hydrogen research and development that enables a 40% reduction in station footprint, as compared to the 2016 baseline of 18,000 square feet, by 2022.
- Validate hydrogen sensor technology capable of detection speeds of less than one minute, with <$1,000 annual operating cost.
- Initiate at least three new non-automotive-related applied risk assessment and modeling efforts pertaining to large-scale hydrogen deployment applications.
- Establish a skilled workforce to effectively respond to the expected growth in hydrogen-supported industries.

Fiscal Year 2021 Accomplishments

Subprogram-Level Accomplishments

Technology Acceleration fiscal year (FY) 2021 accomplishments are summarized below.

Grid Energy Storage and Power Generation

- Awarded the world's first large-scale hydrogen-fuel-cell-powered data center project (Caterpillar Inc.).
- Established an integrated megawatt-scale hydrogen production, storage, and fuel cell system at the Advanced Research on Integrated Energy Systems (ARIES) facility (National Renewable Energy Laboratory).
- Validated two high-temperature electrolyzers from industry, including a 25 kW stack that surpassed 4,000 hours with <0.5% degradation per 1,000 hours (Idaho National Laboratory).
- Released H2@Scale cooperative research and development agreement (CRADA) call supporting ARIES in FY 2021, focused on integrated hydrogen energy system testing and validation.

Chemical and Industrial Processes

- Initiated two first-of-their-kind hydrogen for steel ("HySteel") projects in the United States to demonstrate use of hydrogen to decarbonize iron and steel production (University of California, Irvine, and Missouri University of Science & Technology).
- Hosted the H2@Scale Workshop focused on ammonia as a viable clean-hydrogen carrier serving diverse end uses.

Transportation

- Awarded the world's first renewable hydrogen production refueling barge to fuel the first hydrogen passenger ferry in the western hemisphere (Hornblower).
- Initiated a CRADA project on high-flow fueling protocol, in concert with the international Protocol for Heavy-duty Hydrogen Refueling (PRHYDE) project (National Renewable Energy Laboratory).
- Released the SuperTruck III funding opportunity announcement (FOA) in collaboration with the Vehicle Technologies Office.
- Supported the launch of Mission Innovation's hydrogen-related missions: the Shipping initiative, which is an international effort focused on decarbonizing marine applications, and the Clean Hydrogen Mission, which included hosting a workshop on hydrogen for mining, agriculture, and construction equipment/vehicles.
- Hosted the H2@Airports Workshop focused on hydrogen use in aviation.

Enabling Activities

- Initiated the Hydrogen Education for a Decarbonized Global Economy (H2EDGE) workforce development project (Electric Power Research Institute).
- Hosted an international workshop on quality control for electrolysis and fuel cells with the National Research Council of Canada and Germany's Fraunhofer Institute for Solar Energy Systems (National Renewable Energy Laboratory).
- Released the first-ever federal regulatory map report to identify hydrogen-infrastructure-related status and gaps across federal agencies (Sandia National Laboratories).
- Released the H2@Scale CRADA Call, which was focused on applied risk assessment and modeling for H2@Scale applications as well as next-generation sensor technologies.
- Accelerated progress on safety, codes and standards (see Safety, Codes and Standards section for specific program- and project-level accomplishments).

Project-Level Accomplishments

Grid Energy Storage and Power Generation

Frontier Energy partnered with several industry stakeholders on an integrated hydrogen demonstration project in Texas. The main objective was to determine how hydrogen production costs can be minimized by using multiple generation sources and by co-locating multiple end uses (stationary power generation and hydrogen vehicle fueling). A five-year plan was also developed for the Port of Houston. Site plans have been completed, and one years' worth of load data (modeled with hydrogen and fuel cell power) have been collected. In support of the plan for the Port of Houston, a preliminary model with supply and demand hubs was developed.

Plug Power partnered with several industry stakeholders to develop an integrated demonstration project in Florida that leverages intermittently available, low-cost electricity from renewables to provide hydrogen in multiple value streams (vehicles, emergency back-up power, and grid). The required storage system was sized to meet various (stationary and vehicular) hydrogen delivery demands. Site and integrated system design, dynamic power simulations, and technoeconomic analyses are under way. Initial deliveries of system equipment were completed.

Exelon Corporation plans to install a 1.2 MW polymer electrolyte membrane (PEM) electrolyzer at a nuclear power plant to provide low-cost supply of in-house hydrogen (used for cooling) and to simulate operation of a larger electrolyzer in nuclear power markets. Nine Mile Point in New York was selected as the demonstration site. Initial engineering design is under way, while an electrolyzer supplied by Nel Hydrogen has gone through acceptance testing (by the National Renewable Energy Laboratory [NREL]), demonstrating less than 0.1% degradation over 500 hours of operation. Initial market demand analysis for similar deployments at various sites was conducted by Argonne National Laboratory. Moreover, Idaho National Laboratory (INL) developed a front-end controller for optimal electrolyzer dispatching.

FuelCell Energy—in partnership with INL and Versa Power Systems—plans to demonstrate the integration of a 250 kW solid oxide electrolyzer with a nuclear plant emulator at INL to validate a high-efficiency and low-cost pathway for production of hydrogen using electricity and waste heat from the nuclear power plant. The project is newly under way but aims to increase operating flexibility and provide an additional revenue stream for nuclear plants by switching between power and hydrogen generation.

Idaho National Laboratory developed a high-temperature electrolysis test stand integrated with a nuclear power plant emulator to accelerate solid oxide electrolyzer competitiveness in the United States, independently validate stack performance, and provide nuclear-simulated integration and testing. The project plans to validate commercial stack performance from industry partners, including Bloom, Nexceris, OxEon, FuelCell Energy, and Haldor Topsoe. To date, two electrolyzer stacks have been tested, including a 25 kW stack that was tested for over 4,000 hours with degradation levels less than 0.5% per 1,000 hours of operation, and three more stacks are being prepared for testing and validation.

Pacific Northwest National Laboratory, in partnership with INL, is collaborating with industry to solve cost and degradation issues through membrane electrode assembly development, modeling, post-mortem analysis, accelerated stress testing development, and manufacturing. A process to produce 300 cm^2 active-area solid oxide electrolyzer cells was developed, and cell performance was validated in multiple single cells. Several cells were tested over 2,800 hours at 750°C and 1.3 V to confirm minimal degradation. A stack repeat unit fabrication process was established, and two 1 kW short stacks were assembled and tested with a goal of building and testing a 5 kW stack.

The ***National Renewable Energy Laboratory***, through the ARIES initiative, is designing and commissioning a 1.25 MW PEM electrolyzer, 600 kg hydrogen storage system, and 1 MW fuel cell generator at NREL's Flatirons Campus to support H2@Scale goals. The system is designed as a testbed to demonstrate systems integration, grid services, energy storage, direct renewable hydrogen production, and innovative end-use applications such as heavy-duty transportation and natural gas blending. Overall site layout and safety reviews have been completed, and most key pieces of equipment have been ordered. Systems integration (controllable grid interface, thermal, water, gas, electrical) is under way.

Caterpillar Inc. was awarded funds to install the world's first large-scale hydrogen-fuel-cell-powered data center—⊖a 1.5 MW stationary fuel cell at a Microsoft data center in Washington state. It will provide 48 hours of liquid hydrogen onsite and increase confidence in hydrogen and fuel cells for the information technology industry by performing technoeconomic analyses, modeling, and simulation to identify data requirements and gaps.

Chemical and Industrial Processes

Missouri University of Science and Technology is developing and demonstrating a grid-interactive steel production system that combines a hydrogen-direct-reduction furnace for ironmaking and electric melting for steelmaking. The system will use variable hydrogen/natural gas content, with one-ton-per-week iron production capacity. The reactor model will then be scaled up to simulate a production pilot facility with a planned capacity of 5,000 tons per day.

University of California, Irvine, is demonstrating and optimizing a thermally and chemically integrated solid oxide electrolysis cell system, as co-producer of hydrogen and oxygen, with a direct reduction iron plant at one ton per week of product scale, scaling up to capacity of two million tons per year.

Transportation

The ***Center for Transportation and the Environment*** partnered with UPS and others to demonstrate fuel cell hybrid electric delivery vans with fuel cell range extenders (75- to >125-mile range), thereby reducing petroleum consumption and related emissions and increasing the commercial viability of electric drive medium-duty trucks. Five trucks have been built and are undergoing testing (a 169-mile max range test was completed), while ten more trucks are currently in various stages of assembly, with expected completion in 2021. The UPS trucks will operate in a disadvantaged community in California and provide benefits aligned with the Biden administration's emphasis on environmental justice.

The ***National Renewable Energy Laboratory*** continues its fuel cell electric bus (FCEB) evaluations to validate performance and cost using real-world data. Of the 38 FCEBs tracked, 12 of them surpassed 25,000 hours of operation, while one FCEB demonstrated over 32,000 hours of durability. The average fuel economy of these FCEBs was found to be approximately 9 miles per diesel gallon equivalent (mpdge) (up to two times greater than fuel economy for compressed natural gas or diesel buses), and a range of approximately 300 miles was achieved with the buses running on 37.5 kg of hydrogen.

Hornblower Energy, LLC, was awarded funds to develop the world's first maritime hydrogen refueling infrastructure on water (at the San Francisco waterfront), with refueling capabilities of up to 530 kg H_2/day. This will be an integrated system of green hydrogen production via electrolysis (to fuel hydrogen fuel cell marine vessels) and power generation via fuel cell (to charge hybrid electric vessels), both mounted on a barge, bringing commercial hydrogen technology to the maritime sector. Hornblower is collaborating with the Port of San Francisco, Sandia National Laboratories, and various industry stakeholders to evaluate the performance, efficiency, and feasibility of such a system, while developing related safety protocols.

Argonne National Laboratory is conducting total cost of ownership analyses to determine how hydrogen and fuel cells compare with incumbent technology in applications in rail, maritime, and aviation and what performance metrics are needed for them to be able to compete on a cost of ownership basis. Results showed that fuel cost dominates total cost of ownership for heavy-duty applications. In one example, it was determined that achieving a fuel cell cost of $60/kW and liquid hydrogen bunkered cost of $4/kg H_2 would likely make hydrogen fuel cell ferries cost-competitive with incumbent technologies. In another example, Argonne found that multiple-unit hydrogen electric locomotives are likely to be cost-competitive at a fuel cell cost of $60/kW and liquid hydrogen cost of $3.50/kg H_2.

Electricore is working on developing a high-pressure, high-flow-rate dispenser and nozzle (100 kg H_2 in 10 minutes at 70 MPa) for heavy-duty vehicles. The system will be demonstrated at NREL. An industry survey of 27 organizations was completed, with the objective of determining specifications. The project team also conducted initial design work, including component selection, computational fluid dynamics analysis, and failure modes and effects analysis. Nozzle technology provider WEH Technologies Inc. and dispenser technology provider Bennett Pump Company are collaborating with Electricore on this effort.

Electricore is also developing an advanced mobile hydrogen refueler capable of fueling 20–40 vehicles per day (70 MPa at -40°C, 3–5-minute fill, 200 kg H_2). The refueler can operate without remote power connections, is modular for easy transport and deployment, and can provide expanded daily capacity and multi-day operations using delivered gaseous hydrogen. The design, assembly, and initial testing are complete, and the refueler is soon to be available for public fueling in Ontario, California. Fueling data will be sent to NREL's Technology Validation team for analysis.

New Project Selections

In FY 2020, the subprogram added projects through FOAs. FY 2021 selections are pending from the Office of Nuclear Energy industry FOA, the SuperTruck III FOA, and the H2@Scale CRADA Call supporting ARIES.

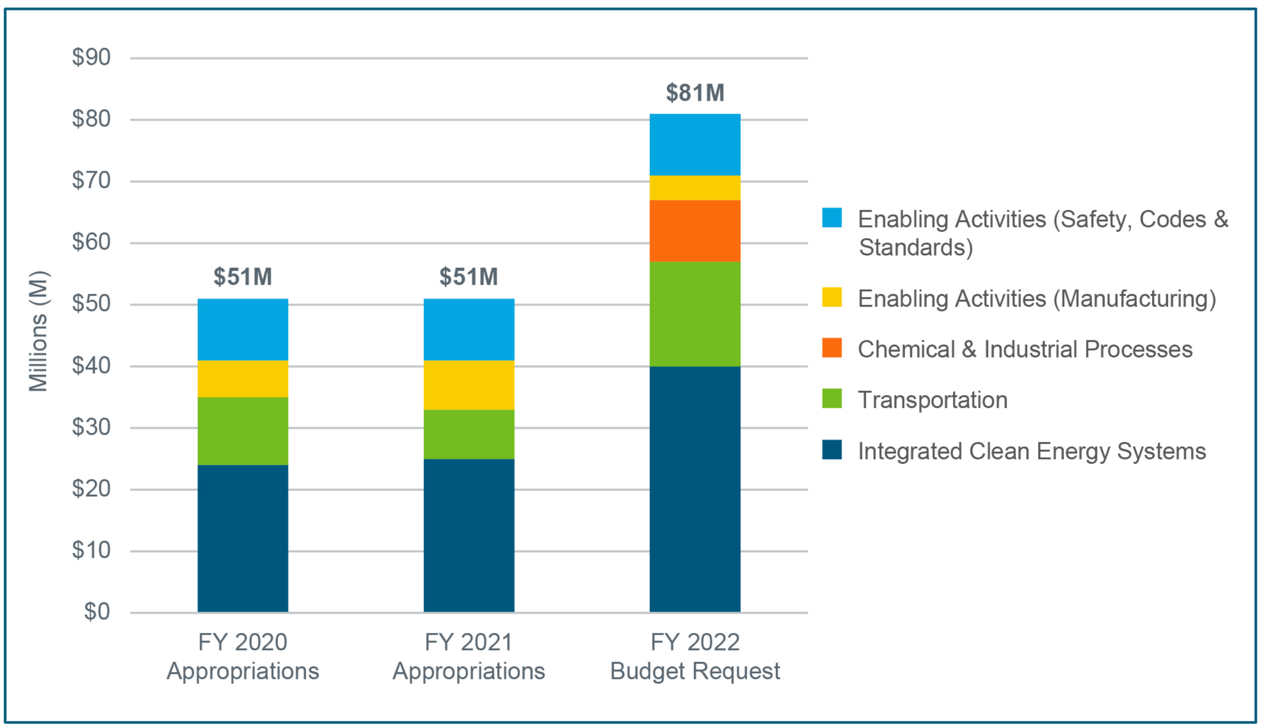
FY 2020 selections included the following:

- FuelCell Energy, Inc. – Solid Oxide Electrolysis System Demonstration
- University of California, Irvine – Solid Oxide Electrolysis Cells Integrated with Direct Reduced Iron Plants for Producing Green Steel
- University of Missouri System – Grid-Interactive Steelmaking with Hydrogen
- Hornblower Energy, LLC – San Francisco Waterfront Maritime Hydrogen Demonstration Project
- Caterpillar Inc. – 1.5 MW Polymer Electrolyte Membrane Fuel Cell for Data Center Power: Development and Demonstration
- Electric Power Research Institute, Inc. – Developing a Workforce for a Hydrogen Technology Economy

Budget

The budget for the Technology Acceleration subprogram remained constant in FY 2020 and FY 2021 at $51 million. The FY 2022 budget request includes a significant increase of $30 million to accelerate efforts to demonstrate, validate, and integrate low-cost hydrogen production with various end uses to enable decarbonization and support the H2@Scale vision. Subject to appropriations and congressional direction, the FY 2022 distribution of funds in key application areas is shown below.

Technology Acceleration RD&D Funding



*$8 million in FY 2020 funding for HySteel projects is now managed under Technology Acceleration – Chemical and Industrial Processes.

Annual Merit Review of the Technology Acceleration Subprogram

Summary of Technology Acceleration Subprogram Reviewer Comments

The Hydrogen Program (the Program) reviewers applauded the Program's development of facilities to validate and integrate hydrogen and fuel cell systems, noting the value of these facilities in de-risking implementation and commercialization and lowering capital risk. Reviewers commended the Program's recent shift toward RD&D on hydrogen applications in decarbonizing CO_2-intensive industries, such as iron, steel, refining, concrete, and fertilizer, as well as RD&D on energy storage applications and blending hydrogen with natural gas. Program reviewers also expressed support for projects that integrate hydrogen applications, such as green steelmaking and transportation applications. However, reviewers also expressed concern that the Program's shift in focus away from light-duty vehicle applications is premature, noting that light-duty transportation applications still require RD&D.

Program reviewers recommended increasing the funding levels for Technology Acceleration activities to enable deployment of mobile and stationary fuel cell systems and hydrogen infrastructure. Reviewers suggested increasing both the number and scope of Technology Acceleration projects, establishing a Technology Acceleration tech team or industry advisory group, and prioritizing end-use demonstrations for hydrogen production. Reviewers supported the use of prizes like the H2 Prize to accelerate technology implementation but cautioned that prizes should be limited in size and scope, focused on outcomes that industry would not achieve without the prize, awarded only if all the prize criteria are met, and used for novel applications or needed integration of existing technologies.

Program reviewers highlighted the need for efforts to accelerate technology commercialization and market acceptance, such as increased engagement with regional, state, and local stakeholders and more education and outreach activities. The Program was encouraged to increase international leadership and cooperation, industry collaboration, partnerships, and environmental justice efforts. The value of collaboration across various DOE offices and federal agencies to Technology Acceleration efforts was also emphasized, with specific mention of the U.S. Department of Defense, DOE's Office of Basic Sciences, DOE's Advanced Manufacturing Office, and the National Science Foundation.

In addition to the Program reviews, project reviewers evaluated 26 individual Technology Acceleration projects during the 2021 Annual Merit Review. The projects received scores ranging from 2.8 to 3.6, with an average score of 3.3.

Project reviewers described the Technology Acceleration activities as well-coordinated and well-managed, relevant, potentially impactful to market readiness and/or market acceptance of the technology, aligned to key DOE objectives, and focused on eliminating the most important barriers. Many projects were commended for their flexibility and excellent progress during the COVID-19 pandemic. Project teams were described as strong and were praised for their choice of partners; the quality of the research facilities was admired. Project reviewers appreciated methodical, systematic approaches and projects with balanced approaches that included experimental, characterization, and numeric/modeling components. There was praise for demonstration and deployment projects that included input and/or hydrogen offtake commitments from potential end users, as well as projects developing versatile systems or components with broad applicability across applications, sites, etc. Projects were lauded for leveraging past experience, other DOE-funded projects, and industry input.

Across the Technology Acceleration activities, reviewers identified a need to conduct technoeconomic analysis to demonstrate the competitiveness of the technologies, compare costs and performance to those of conventional incumbent technologies and alternative competing technologies, and validate the economic models with real-world data and industry input. Reviewers expressed concern for material costs, the scalability of some of the technologies, and the viability for high-volume manufacturing. Data challenges faced by some of the projects were recognized, and projects were encouraged to formally document and publicly share their lessons learned and best practices, as well as to identify codes and standards needs and limitations.

Following this subprogram introduction are individual project reports for each of the projects reviewed. Each report contains a summary of the project, the project's overall score and score by question, and the project-level reviewer comments.

Project Reviews

Project #TA-001: Membrane Electrode Assembly Manufacturing Research and Development

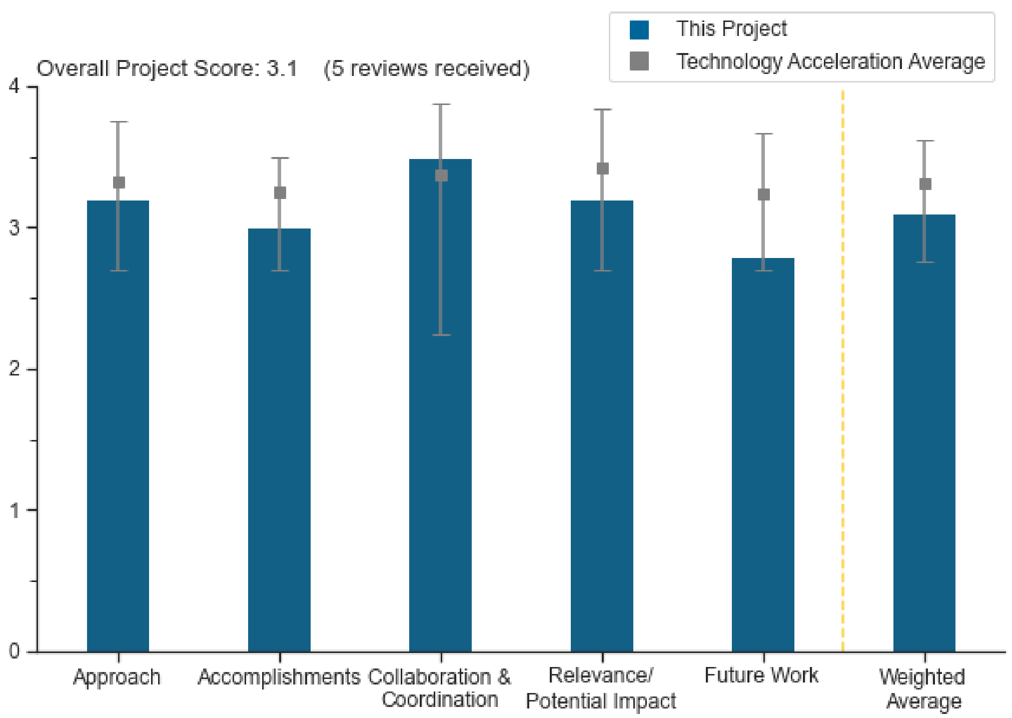
Michael Ulsh, National Renewable Energy Laboratory

DOE Contract #	WBS 10.1.0.501
Start and End Dates	7/1/2007
Partners/Collaborators	General Motors, Mainstream Engineering, Gore, 3M, Nel/Proton, Giner, Inc., Plug Power, AvCarb, Lawrence Berkeley National Laboratory, Colorado School of Mines, National Research Council–Canada, Fraunhofer-ISE
Barriers Addressed	• Lack of improved methods of final inspection of membrane electrode assemblies • Low levels of quality control

Project Goal and Brief Summary

The objectives of this project are to (1) understand quality control (QC) needs from industry partners and forums, (2) develop diagnostics by using modeling to guide development and in situ testing to understand the effects of defects, (3) validate diagnostics in-line, and (4) transfer technology to industry partners.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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.

- Fourier transform analysis for the Nafion™ HP (high-performance) membrane using a hyperspectral image of new/unhandled HP samples and measurements from both silicon (ultraviolet–visible) and InGaAs (near-infrared [IR]) fast spectrometers clearly identifies peaks associated with the membrane thickness, and the high-speed, low-heating case led to the least error and a good opportunity for the mapping method. Pinhole studies with reinforced membranes were done as accelerated stress tests with process-induced membrane irregularities (PIMs) for beginning-of-test (BOT) performance and other parameters.
- The optical hyperspectral approach for membrane electrode assembly (MEA) QC makes sense within the thickness limitations of the approach. Rapid MEA inspection is critical toward the development of durable fuel cells.
- QC is obviously a key indicator tool for lifetime, where the project understands the key failure modes expected through membrane failure.
- Objectives and barriers are defined; however, they are somewhat amorphous and lacking in quantifiable details. This is understandable, given that most industry partners are probably unwilling to share much in the way of confidential data.
- The project approach is focused on MEA manufacturing quality control and defect studies. The approach does not seem particularly innovative or likely to result in significant advancements. There is little evidence that this project can advance the state of the art in MEA manufacturing.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Multiple techniques have been evaluated successfully; it would be beneficial for the partners involved to do a cost comparison of the existing equipment and the cost savings due to the efforts within this project. The implications of a pinhole formed are clear and have been demonstrated with a hole made on purpose, but a key performance indicator that can be defined mathematically based on thickness consistency or overall surface quality would be beneficial, taking into account a variety of thinning spots within the produced membrane that may be the size of a pinhole but may not go all the way through the membrane. In other words, the possibility of quantifying the gray zone rather than doing black-and-white pinhole counting should be explored.
- Peaks associated with the membrane thickness were clearly identified, and the high-speed, low-heating case led to the least error and a good opportunity for the mapping method, but samples that are overly handled and in poor condition are difficult to characterize for thickness. Detectable BOT IR response was observed from laser-drilled pinholes of 20–100 µm, and cells with 100 µm pinholes failed reproducibly about 10 times faster than pristine MEAs. The project developed a modeling framework to understand the underlying mechanisms driving membrane degradation in the case of a membrane pinhole.
- The project has been ongoing since 2007. While there was a gap in funding and the COVID-19 pandemic limited work, progress was made toward correlating defect findings from the optical inspection with the durability of fuel cell MEAs.
- Key accomplishments were reported in membrane thickness mapping. There was also some progress in studying effects of defects on performance and durability. These results represent incremental progress, but it seems unlikely that this project is providing information not already known to MEA manufacturers.
- This project has been ongoing for some time now. The project should revisit the specific problem being addressed. It is unclear what has changed since the project started. A chart showing the impact of manufacturing-related defects on overall fuel cell cost (listed as barriers on slide 3) would be beneficial. It is unclear whether the current efforts are properly directed to address those manufacturing problems and how much of an impact the developed solutions have against those problems.

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 collaborates with the major MEA manufacturers, and the researchers actively drive the dialog through sponsored symposia of MEA quality assurance/QC. The project is also well-coordinated between the Tier 1 suppliers, experimentalists, and modelers.
- National laboratories are working closely with 3M, Nel Hydrogen/Proton, Giner, Inc., GM, Plug Power, and AvCarb to understand industry directions and challenges. Industry partners provide materials and QC requirements.
- It is impressive to see the number of international collaborations with partners. A general summary of shared interests and issues would provide more insight on the state of the art.
- The project clearly works with as many industrial partners as feasible, both on commercializing developed solutions and by pulling guidance from fuel cell manufacturing companies. While it is probably not realistic to expect industry to share detailed manufacturing defect and scrap data, this would be the best case for directing this project to the most relevant manufacturing problems.
- The project features valuable collaborations with W.L. Gore and General Motors (GM), among others.

Question 4: Relevance/potential impact

This project was rated **3.2** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Current results show correlation with crossover associated with pinhole formation (and thinning of membranes). There is obviously strong interest from the network of partners, and going forward, roll-to-roll processing will develop stronger dependency on in-line QC tooling. It is key to demonstrate that this work solves current (proprietary) industrial issues without revealing sensitive information.
- Membrane durability is a key issue for the widespread implementation of fuel cell technology. An understanding of the effects of membrane manufacturing defects on the overall fuel cell lifetimes is critical toward achievement of the aforementioned goal.
- National laboratories and industry partners give an effective way to identify key needs toward commercialization of fuel cells for specific applications.
- Fuel cell manufacturing industry data would help direct and validate the focus of this project.
- This project addresses MEA manufacturing, which on the surface is highly relevant, but it is not clear that the project is providing any real innovations. It seems unlikely to advance the state of the art or result in knowledge not already available to MEA manufacturers.

Question 5: Proposed future work

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

- The proposed future work is very strong. It might be good to have an additional effort that couples other inspection techniques, such as x-ray imaging and membrane permeability methods, to further correlate the validity of the work.
- The team is proposing to continue to work on a number of spectroscopic tools for new properties, such as opaque-layer thickness measurement, the effects of relevant defects on cell performance and lifetime, and the development and application of predictive models to assist in understanding the performance and lifetime impacts of defects. This work is needed, but the statement of future work is a little vague.
- The proposed future work on effects of defects could be valuable to improving understanding of MEA degradation mechanisms. The future work on manufacturing diagnostics does not seem as valuable, owing to lack of novelty.
- Perhaps updated data are available to help guide this project to best support fuel cell companies. It would be good to know the following:
    - Which current manufacturing defects the project needs to address next
    - What new materials are coming up (membrane, catalysts, gas diffusion layer [GDL], stack components), and how manufacturing defects and difficulties might change with those new

    - materials—for instance, alkaline membranes and polymer electrolyte membranes might have different sensitivities
    - How the project can use this topic area to address hydrogen generation.
- The future work is vaguely defined. A response was expected to the sense of urgency to scale up production volumes and extend lifetime at the same time, increasing the inherent necessity for QC analysis and data processing. The hydrogen industry is stepping up, and the QC expertise should ramp up accordingly.

Project strengths:

- The project has a world-class research team. There is excellent coordination between industry and national laboratories. There is a viable method for rapid materials inspection.
- There is huge potential to lift the hydrogen industry to a higher level of manufacturing readiness by having good control over QC at higher line speeds.
- The project has good interaction with industry and uses National Renewable Energy Laboratory capabilities in MEA manufacturing.
- There is teaming and a straightforward approach.
- There is continued effort to pull involvement from industry. There is transfer of developments to commercialization.

Project weaknesses:

- As the presenter commented in response to one of the questions, most of the detailed analysis techniques are not on the coating line. Therefore, the application is connected to manual activity to execute deeper investigations into individual trouble areas. Findings would be more valuable if they translated back to in-line damage severity assessment.
- The project needs more correlation studies between defect types as detected by hyperspectral imaging and MEA durability. The technique is not able to characterize the GDL–MEA interface characteristics. There are limitations of thickness measurements by optical measurements.
- There is little innovation or potential for more than incremental advances in this project. It seems unlikely to move the needle in MEA manufacturing.
- There is a lack of hard data to link these efforts to actual impact on fuel cell cost.
- Innovation is limited.

Recommendations for additions/deletions to project scope:

- Project scope should include more in-depth characterization of MEA defects detected by the optical method. This could include transmission electron microscopy (TEM), scanning electron microscopy (SEM), Raman microscopy, and x-ray imaging.
- The attempt to bring QC on different thickness membranes under the same common denominator may actually indicate that different approaches are needed. The project should consider future trends to anticipate market requirements.
- The project should consider hydrogen generation, such as manufacturing of new electrolysis materials. It is unclear how difficult it will be to manufacture alkaline membranes (compared to polymer electrolyte membranes) or catalysts—or to control quality.
- A more science-based approach or a more innovative work scope with respect to developing novel manufacturing methods would make the project more valuable.

Project #TA-005: In-Line Quality Control of Polymer Electrolyte Membrane Materials

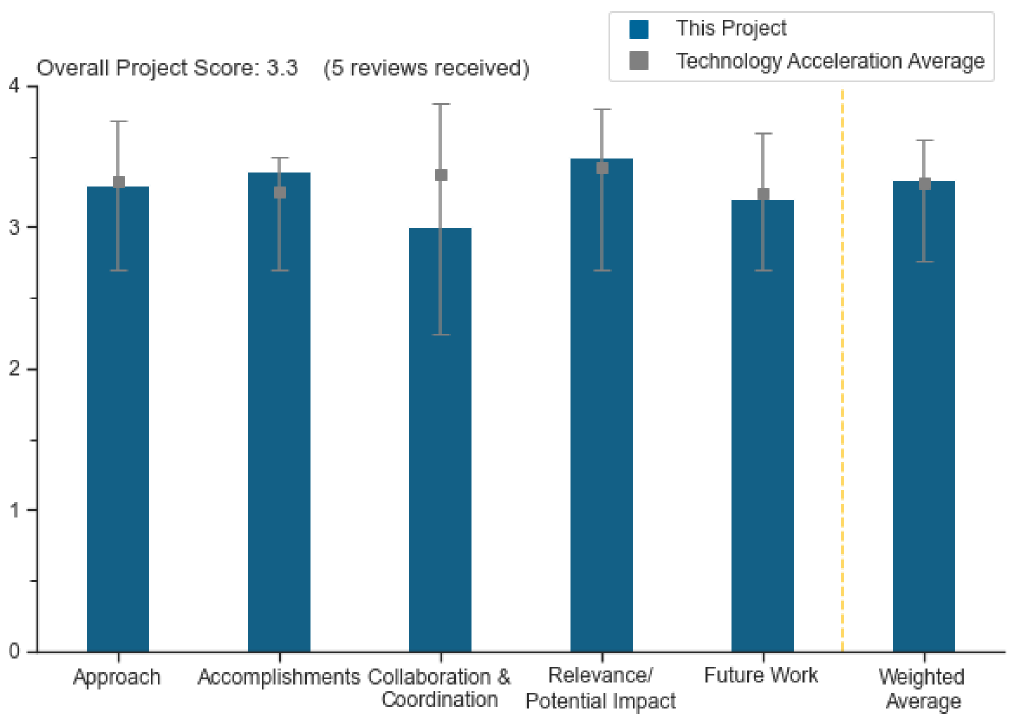
Andrew Wagner, Mainstream Engineering

DOE Contract #	DE-SC0013774
Start and End Dates	8/21/2020 to 8/21/2022
Partners/Collaborators	Ionomr Innovations Inc.
Barriers Addressed	• Lack of improved methods of final inspection of membrane electrode assemblies • Low levels of quality control

Project Goal and Brief Summary

With the goal of improving the reliability and reducing the cost of automotive fuel cell stacks, Mainstream Engineering (Mainstream) seeks to improve in-line quality control technologies that are used in the manufacture of polymer electrolyte membrane (PEM) materials. To achieve this goal, the project team will build a prototype system capable of simultaneously measuring defects in a moving membrane web and membrane thickness over the full web width. The developed system will scan the manufactured membrane with 100% coverage, marking and logging defective regions.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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 is well-managed. The project participants are skilled. This is a continuation of a multiyear endeavor to pioneer the fuel cell/electrolyzer future. The national laboratories provide technical horsepower and continuity. As new U.S. companies join this path, the necessary key technology base is there. This plan is excellent.

- The approach is clear, with efforts directed at eliminating the barriers associated with high-volume production and reducing fabrication costs via automation. The integration with the National Renewable Energy Laboratory (NREL) on defect specifications is especially encouraging and appears to be a solid collaboration. The approach of creating a continuous inspection line that can also be used on piece parts is very good for the current market.
- Methods have made good progress since earlier reviews, such as accuracy, capability, speed, etc. This project is critical in terms of increasing manufacturing speeds based on the need to concurrently increase inspection speed.
- This project employs a great approach to addressing an objective that some component manufacturers may value (others may prefer to develop this in-house instead).
- The approach is appropriate for bringing a commercial system to market.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There is good technical progress on loading distribution on gas diffusion electrodes or catalyst-coated membranes (CCMs) and ability to tune the method based on the ink formula. In addition, commercially required elements such as manuals, training material, and calibration procedures are being defined.
- The Mainstream team has shown significant progress in defect detection and marking, as well as putting together training documentation. The system is versatile and can be used for many different products ranging from CCMs to gas diffusion layers. The catalyst loading and continuous thickness mapping ability is a strong addition to the defect inspection procedure. One area of concern with the current design is the ability to process large rolls of delicate materials. For instance, some materials (such as rollable paper gas diffusion layers [GDLs]) cannot be wound around three-inch rollers, and the current design does not allow for 1,000-meter-long rolls, which can be over three feet in diameter. Overall, the design looks very promising for demonstration and moderate-volume production but will need adjustment for true volume production predicted within the next three to seven years.
- The project has achieved excellent results; the team has developed equipment with more capabilities than expected.
- Manufacturing quality improvement has a direct impact on reliability and cost. The best step in accomplishments and progress will be market acceptance/sales and use. The data leading the team to identify the need for these specific inspection points were not shown. It is unclear how many of each defect have previously escaped manufacturing. The cost associated with those defects (both scrap and downstream costs at the system and field levels) is unknown. It is unclear how much this machine will save in those areas.
- The team made good progress on manufacturing details. Details such as particle size, etc., are critical, and data show good progress. Even so, many of the details are not described. There is no mention of test specimens or samples with proscribed damage.

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.

- The very evident partnerships are well-described and show thoughtful selection to assign responsibility among the participants. There are excellent modeling results of dynamics during the coating processes. The presentation stresses the collaboration, and such success is absolutely necessary.
- This project is a good example of government funds being used to produce a useful technology (thanks to national laboratory and industry partners, which will hopefully lead to customers for the machine).
- This small project really allows for only one collaborator, but most usefulness would be gained by incorporating multiple collaborators in similar industries but using different materials to show the translatability of the methods. These collaborations are being discussed but do not appear to be formalized yet.
- There is good collaboration with NREL and Ionomr Innovations, but additional industrial partners should be involved in this process. It is promising that there have been multiple demonstrations and discussions

with various large-scale and small-scale manufacturers, but reaching a universal standard will require additional input about material widths, roll diameters, tensioning requirements, etc. It would be interesting to have at least one high-volume industrial partner for each critical market (e.g., membranes/CCMs, GDLs/gas diffusion electrodes, and electrolyzers) for improved handling definitions and limits to make such a product truly universal.

- It is good that the project now has one highly engaged partner, Ionomr Innovations. However, this membrane developer is unlikely to "be at scale where automated [quality control] outweighs man-hours" anytime soon. The team needs to engage with developers who are at, or near, this scale, e.g., Plug Power or IRD Fuel Cells (for CCMs) and DuPont or W.L. Gore (for membranes).

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Inspection will be a critical piece in meeting DOE objectives, since roll-to-roll coating and similar methods will need rapid feedback on coating quality to avoid generating significant scrap. In addition, at high manufacturing capacity, slow, labor-intensive inspection methods will become a major bottleneck in stack production.
- There is a strong need for consistent defect definition and automated inspection with defect marking in the very near future based on the projected volumes in these markets. Currently, manufacturers are left working with each customer independently to define different defect parameters based on different system configurations, and most visual inspection is done manually. If the project is successful, and the information generated from this work is made widely available, then this project could have a large potential impact in advancing the learning curve for next-generation manufacturing best practices.
- There is no assurance that the "best" technology will be developed using the described approach. However, there is one clear way to make progress: by learning and perfecting the processing steps. This dedicated "long and hard" activity is critical. It is also critical that the processing steps are well-documented so that replication is possible. There is no assurance that any of this will have commercial value, but there is absolutely no way to hope for such success without having a skilled and dedicated team, such as the one here, involved. The missing step is any mention of the "competition."
- Commercialization and sales will be the best indicator of relevance. It will be interesting to see how well the machine moves into the market in coming years.
- This is not a critical barrier, but it is a good contribution at a very modest budget.

Question 5: Proposed future work

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

- The milestones for the demonstration seem appropriate and relevant for industrial applications. Expansion of partnerships will also provide more accurate assessment of the potential for the instrumentation and applicability to other industries (flow batteries, etc.).
- The proposed future work for this project is adequate for demonstration of capability on the current line. It seems like it would be beneficial also to conceptualize how such a design could be expanded for real production volumes (widths ≥ 1 m and lengths ≥ 1,000 m). A cost–benefit analysis of the installation of such a system versus the cost of manual labor and the risk of defects reaching final production would be helpful as well.
- The project has good future plans. Emphasis should be placed on expanding manufacturing partners.
- The future remains mysterious. Clearly, manufacturing engineering remains a critical task. New components, such as membranes and catalysts, will be introduced. However, this team has critical skills, and that knowledge is a U.S. asset. A sensible federally funded activity would include detailed analysis of competing products. This team might also have tasks to evaluate degradation mechanisms, working always to achieve long device life. Those who know how something is made are those who can evaluate how something fails. There is emphasis on hardware from a single vendor. Technical efforts in fuel cells are global in extent. It would make sense to review and document the state of the art in PEM electrochemical hardware quality control. Certainly, the auto manufacturers in, for example, Japan or Korea are not going to waste platinum by building faulty hardware. It would be useful to have this team do a review—maybe one week of travel and one week to document—of global quality control technology, both physical instrumentation and software, now being utilized in the commercial sector. (Decades ago, the primary Nafion™ fabricator would lay sheets

of polymer on a light table and look for “fish eyes” in the material. These came from Teflon™-like regions that resulted during the polymer synthesis, zones where the primary product was Teflon. Defective polymer was discarded. Therefore, optical scanning for PEM quality control was around in the 1980s.)

Project strengths:

- Overall, this is an interesting project that has a chance to provide a large benefit to the industry. There is great work done in defining defects; capturing real-time data, including thickness and catalyst loading; and setting up training documentation. This is a critical area that is needed for next-generation, large-scale production manufacturing.
- This task has been under way for years now. The NREL team provides insight and direction; the existing team is clearly a strength. The task seems essential as PEM technology progresses. An expensive system, such as a PEM fuel cell stack, involves considerable costs, materials, and labor. It really makes a huge difference, when you consider cost/mile driven, if the hardware has a lifetime of 50,000 miles or 5,000,000 miles. The team should scheme on “onboard diagnostics” that monitor degradation during testing.
- The team has the required capabilities. There is great technical progress.
- Improvements in accuracy and the breadth of parameters create additional value of the instrument for commercial use.
- Technology has been transferred out of the laboratory. The project has an industrial partner with interest in commercializing developments.

Project weaknesses:

- The task is rather well-defined. Once people are convinced that fuel cell systems will be deployed and many systems will be manufactured, quality control becomes critical. Some “tests” were meaningful but simple. For example, when stainless steel was used for bipolar plates, nickel dissolved and increased membrane electrical resistance. However, it was also possible to actually see that the membranes developed a pink color—clear as it can be. One weakness is that the project seems tightly focused on one instrument. Many other tools could provide additional information. Some efforts are needed to develop a larger scale. The challenge is to be able to identify isolated problem locations within a working stack.
- It is unclear how much market pull there is for the technology. Upfront data showing scrap rates, downstream failures, etc. and costs would be the best justification for the original developments transferred under this project.
- The industry collaboration is lacking and could be improved with the addition of new industry partners. The conceptual system is promising but does not have the flexibility required for softer materials or production-sized rolls.
- The project is limited in funds to be able to partner across multiple original equipment manufacturers.
- The project lacks engagement with potential customers.

Recommendations for additions/deletions to project scope:

- It would be beneficial to the industry as a whole if the defect definitions, vision parameters, and training documentation could be provided to the industry after the system is proven out over the next year. The project team should conceptualize next-generation designs, looking at increasing web width, using different roller diameters, and allowing excess space for longer production rolls (e.g., roll diameters ≥ 1 m). There needs to be more clarity on the cost–benefit analysis of system design and implementation versus labor costs associated with manual inspection and the potential cost of defects making it into final products. It would be beneficial to have at least one volume-producing industry partner consulted for each critical component associated with this vision system to make the design more versatile for the industry.
- DOE should help Mainstream find potential customers for this new product. This should obviously include the Hydrogen and Fuel Cell Technologies Office introducing the team to CCM, membrane electrode assembly, GDL, and membrane producers, but the project should also engage with other DOE offices (e.g., the Advanced Manufacturing Office and Vehicle Technologies Office) to try to identify other potential end users.
- Other scanning tests may be useful. This team should explore possibilities. Clearly, the roll-to-roll status is the last part of the stack build procedure where defects can be identified and managed (perhaps discarded). As the stack is assembled, the task is far more complex. Thermal imaging should be explored. Acoustic testing might be useful.

Project #TA-007: Roll-to-Roll Advanced Materials Manufacturing Lab Collaboration

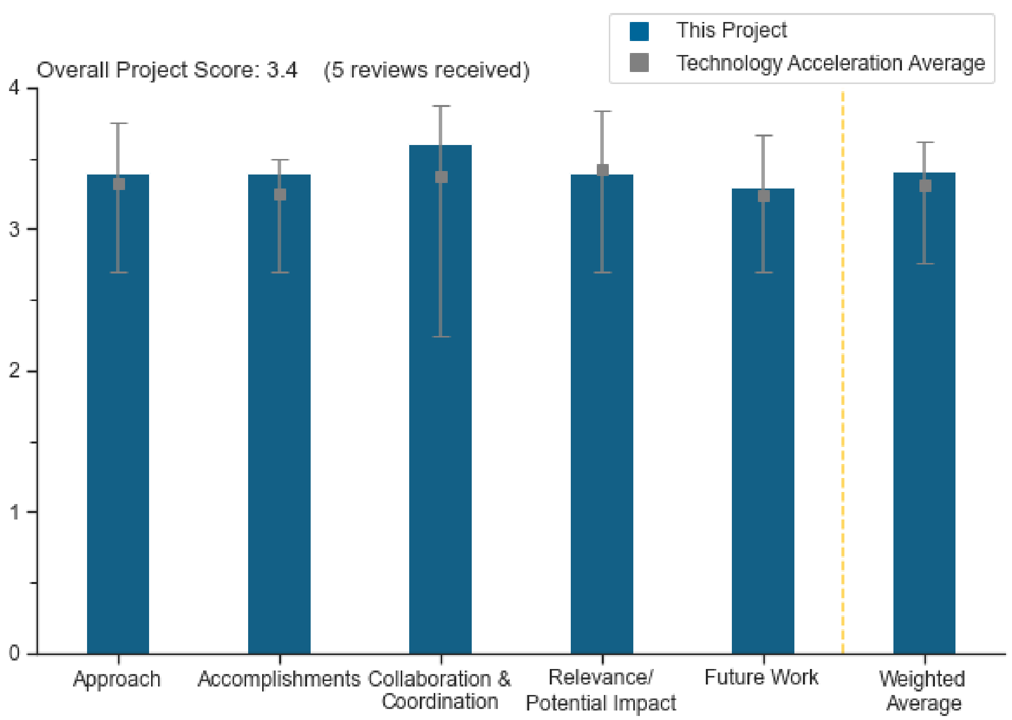
Yarom Polsky, Oak Ridge National Laboratory

DOE Contract #	WBS 10.2.0.604
Start and End Dates	4/1/2016
Partners/Collaborators	Nel Hydrogen, General Motors, Plug Power Inc.
Barriers Addressed	• Lack of high-volume membrane electrode assembly processes • Low levels of quality control

Project Goal and Brief Summary

All U.S. Department of Energy (DOE)-sponsored cost analyses for high-volume production of membrane electrode assemblies (MEAs)/cells assume roll-to-roll (R2R) processing will be used. The project objective is to develop R2R manufacturing techniques to reduce the cost of automotive fuel cell stacks at high volume (500,000 units/year) from the 2008 value of \$38/kW to \$20/kW by 2025. The project goals (depending on technology area) are to (1) increase throughput by 5 times and reduce production footprint, (2) reduce energy consumption by 2 times, (3) increase production yield by 2 times, and (4) enable a substantial shift of manufacturing to the United States by assisting in the development of a domestic supply chain.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The task is to pioneer R2R manufacturing techniques for electrochemical devices, especially for polymer electrolyte membrane devices. This activity integrates a DOE-based team that is carefully coupled to several quality U.S. firms in a focused, detailed study of the manufacturing of electrochemical hardware. Various specific steps are required, and the identification of new processes is assigned to various participants so that one effort can support others. The planning is excellent. The National Renewable Energy Laboratory (NREL) is the lead lab. The project has a large distributed team. There are many tasks. There are many variables for each task. It is a multiyear project. There are many challenges. It is apparent that the approach has proven successful. The project is well-managed and -integrated. It is well-done.
- The approach across all tasks is coordinated for maximum efficiency. The project covers several different approaches (anode, cathode, catalyst-coated membrane [CCM], gas diffusion layer [GDL], etc.), which is appropriate, given the uncertainty as to which approach will be optimal for commercialization.
- The overall approach is good for developing CCMs. The coordination between the two different projects (Advanced Manufacturing Office [AMO] and Hydrogen and Fuel Cell Technologies Office [HFTO]) is good, and the fact that the team presented both during the peer review is greatly appreciated. However, there is no focus on the ultimate component that most fuel cell and electrolyzer developers would like, which is a five- or seven-layer MEA (sometimes called a unitized electrode assembly [UEA]). This is the CCM integrated with the GDLs and often includes a perimeter feature for interfacial sealing. The principal investigator did not seem to be familiar with this component, which is not good. It is not clear how engaged NREL is with industry.
- Developing R2R manufacturing is needed for fuel cell commercialization, and the team is studying various processing approaches for MEA-making.
- The approach discusses two national laboratories working on the project but is not totally clear about how they coordinate their efforts. It appears they are working independently, with one laboratory (AMO) reporting the results.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- R2R manufacturing is critical for meeting the hydrogen production cost targets. The project shows good progress in understanding factors for achieving uniform coatings and the impact of ink rheology.
- Considerable progress is apparent. In some ways, it looks like the results were “harder than we thought,” but much has been accomplished. Clearly, on the globe, this team is as good as any.
- Accomplishments include the rheology model and slot die and experiments-validated model. Slide flow studies are very informative, and the concept of lower surface tension for the top layer should be directly applied to multilayer coating. Spectrometry-based metrology is making great progress. An in-line method for simultaneously measuring thickness and loading will be very useful. Active thermal scanning for half-MEA roll materials is reported to be successful, but a statement of what was needed was not presented. Plug Power inputs on high-shear mixing are very applicable, but overnight low-velocity mixing is reported mostly defect-free, and it is unclear what “mostly” indicates. It would be helpful to know how many defects can be tolerated. For the wrapping of the microporous layer, the target diameter roller is unclear. Nel Hydrogen (Nel) developed a methodology for direct gravure coating onto a membrane. Work at AMO reports slot-die modeling. It is unclear if the difference in coating techniques is important. It is unclear whether the AMO slot-die effort will help Nel.
- The project has demonstrated reproducible R2R deposition of anode and cathode layers on membranes.
- There are some good accomplishments here, although the project could reasonably be expected to be further advanced than it is, considering the AMO work started in 2016 and the project’s annual budget is large.

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 management is just about collaboration and coordination. The cast is large and distributed. There are federal people, academics, and industrial folks. The project has made considerable progress. As the United States develops its industrial base in electrochemical devices, this team knows the territory. Nobody knows the end results, but it is apparent that the results are good enough to begin performance, then cost, then durability. The results are not in yet, but the work has started well.
- This is a well-integrated and comprehensive effort of five national laboratories: Oak Ridge National Laboratory, Argonne National Laboratory, NREL, Lawrence Berkeley National Laboratory, and Sandia National Laboratories.
- Five national laboratories are working together, and an industrial cooperative research and development agreement complements the efforts.
- This is good with the HFTO work, since collaboration with fuel cell and electrolyzer developers seems to be the primary focus of this newer project. It is not evident that much engagement is done in the AMO project, either with potential customers for this work or with R2R experts in industry.
- There is good collaboration with industrial partners, with real-world components analyzed using developed techniques. In the short time allotted for the presentation, it was difficult to tell what the major contributions of the laboratories besides NREL are.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Electrochemical devices are high-volume products. Fuel cells and electrolyzers will be made in high volumes and made throughout the globe. This project was designed to pioneer techniques and processes for that high-volume manufacturing. Unlike batteries, these newer devices are meant to be long-duration hardware. It is critical to have excellent manufacturing engineering. This project is how that happens.
- R2R manufacturing is recognized as a process to meet DOE cost and volume targets for MEAs. It is important to have this effort going forward and working with (U.S.) industrial partners. This effort should be a valuable assist to U.S. manufacturers' competitiveness.
- Critical mass for R2R processing within the U.S. community is needed to advance these methods to commercialization. Having significant laboratory effort in this area, in conjunction with key U.S. industries, provides a good mix of applied trials with fundamental understanding of the underlying physics for accelerated development.
- R2R methods are important. A way to make a seven-layer membrane, anode layer, cathode layer, anode GDL, and cathode GDL is most relevant to manufacturers.
- The project is well-aligned with key DOE objectives, but the results are disappointing, and the lack of attention to (or even knowledge of) what components are ultimately needed/desired here is quite disappointing.

Question 5: Proposed future work

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

- Heavy emphasis on industrial engagement and technology transfer is appropriate for this area. Coordination with Hydrogen from Next-generation Electrolyzers of Water (H2NEW) partners and industry is extremely important, especially as H2NEW gains momentum.
- The team is continuing to improve the quality of deposited layers in R2Rs being made.
- The team is working on the last year of an extended project. There is still much to do. Platinum management is an example. Platinum is a rare element, and it remains expensive, perhaps in part because of the existing global cartel that manages demand and supply. It makes sense for future work to consider the platinum supply, budget, and management. If the MEA has an endurance issue, after that duration, the platinum needs to be recovered. That technology needs consideration. There are environmental concerns with the perfluorosulfonic acids, and the management of those materials needs to be done carefully. It

might make sense for the electrochemical hardware, "fuel cell," to be leased to the owner; and at the end of its useful life, it gets returned to the "owner," who manages recycle and disposal.

- Proposed future work for the AMO core laboratory activity includes the following statement: "Leverage application agnostic process for development of fuel cell and electrolysis MEA challenge." This statement is unclear. "Study novel structures to address durability." It would be helpful to supply an example of a novel structure and an explanation of why the structure would improve durability. The proposed future work for the HFTO R2R activity includes the following statement: "Complete key deliverable projects and transfer to industry partners." It is unclear what the key deliverables are. "Pursue continued funding with HFTO." It is unclear what that funding would be for. It is unclear whether pursuit of funding is a project or a need.
- The major focus of the proposed future work is seeking "continued funding" (both with AMO and HFTO). There is not much here with respect to specific goals. What is obviously lacking is to focus on making five- and seven-layer MEAs.

Project strengths:

- The team is strong. The management plan and execution appear to be first-rate. The project created a credible technology base, which needs to be the basis of a successful commercialization.
- Strengths include the laboratory capabilities, from characterization to pilot-scale manufacturing of MEAs and gas diffusion electrodes, as well as strengthened relationships with key industrial partners.
- The project has a very strong team of researchers. The project is leading in manufacturing R2R understanding for industry quality control.
- The project is using the experience of all team members.
- The project has five national laboratories with many capabilities.

Project weaknesses:

- In general, not much weakness is evident. There is absolutely no mention about competition, and what the competition is doing, e.g., Toyota. There is a global activity for different electrochemical systems, such as lead acid. That technology has a very admirable recycling arrangement, and much of the Pb in the global lead acid batteries is recycled, not mined. This is a good example to build in.
- No major weaknesses were noted.
- The R2R processing developed to date is too limited in that limited numbers of layers do not translate into a commercial fuel cell. Only the seven-layer reel-to-reel synthesis gives a fuel cell process useful for practical manufacturing.
- There is poor engagement with industry, both with respect to understanding what manufacturers actually want and to obtaining R2R knowledge that exists in industry.

Recommendations for additions/deletions to project scope:

- There are many established capabilities in industry that NREL could leverage here, which include R2R coatings of polymers for non-fuel-cell components as well as CCM processes developed by W.L. Gore and 3M (who, having now exited the CCM business, may now be more willing to share some know-how). It is not clear whether NREL has tried to engage and learn from the R2R experts in industry. There is no evidence of that here. If there is interest in integrating CCMs and GDLs, the project should consider starting with making UEAs for redox flow batteries (RFBs), which consist simply of bare membranes and C papers (without polytetrafluoroethylene). Ideally, these should include some polymer picture frame on the perimeter, which is desirable for all types of cells for sealing purposes. Researchers could work on this in parallel with making CCMs that are acceptable since CCMs are not required in RFBs.
- The project needs to focus on a way to make a seven-layer membrane, anode layer, cathode layer, anode GDL, and cathode GDL, which is most relevant to manufacturers. The team should consider novel ways to deposit good, complete seven-layer structures using reel-to-reel methods.
- The project should accelerate the R2R effort and quality control effort and bring in additional industrial partners.
- The project is close, in this phase, to completion.

Project #TA-009: Maritime (Pierside Power) Fuel Cell Generator Project

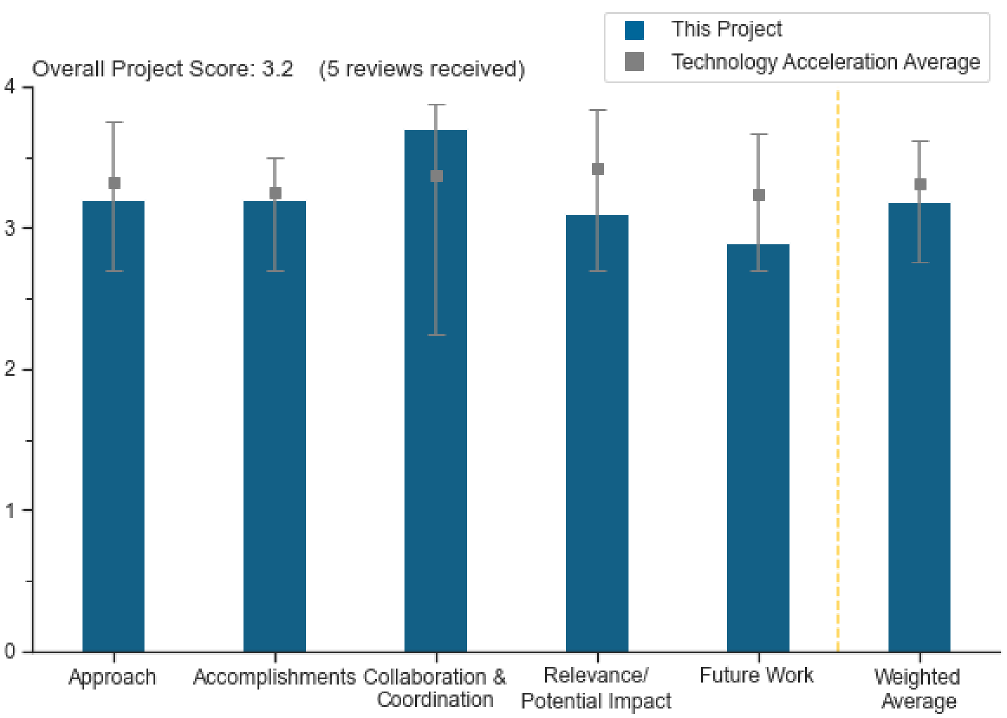
Lennie Klebanoff, Sandia National Laboratories

DOE Contract #	WBS 9.2.0.2
Start and End Dates	7/1/2016
Partners/Collaborators	Scripps Institution of Oceanography, Hydrogenics
Barriers Addressed	• Inadequate standards • Financing mechanisms • Inadequate user experience

Project Goal and Brief Summary

The overall objectives of this project are to (1) lower the technology risk of future maritime fuel cell deployments by providing performance data on hydrogen polymer electrolyte membrane fuel cell technology in this environment, (2) lower the investment risk by providing a validated business case assessment for this and future potential projects, (3) enable easier permitting and acceptance of hydrogen fuel cell technology in maritime applications by assisting the U.S. Coast Guard (USCG) and the American Bureau of Shipping (ABS) with developing hydrogen and fuel cell codes and standards, (4) act as a stepping stone for more widespread shipboard fuel cell auxiliary power unit deployments, and (5) reduce port emissions with this and future deployments.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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 project concept is concise, with clear objectives and goals and a path to complete the required work to meet the goals. The partnerships leveraged the necessary skillsets by letting the partner with the most experience complete the work. This ranges from sourcing the hydrogen for the quayside power system to servicing the power system after the pandemic isolation subsided.
- One of the goals of the U.S. Department of Energy (DOE) Hydrogen Program is to enable market introduction of fuel cell technology. This project is relevant to that effort and could help to reduce barriers to further deployment of fuel cells.
- The project demonstrates that a stationary fuel cell system can operate in the demanding maritime environment and demonstrates that fuel cells and hydrogen can meet performance challenges. The project also provides experience with fuel cells, visibility to fuel cells and hydrogen, and use of hydrogen in a new market that could potentially help increase demand and market pull. The project has addressed issues with standards and siting. The original involvement of ABS and USCG has promoted the development of hydrogen and fuel cell codes and standards within these organizations. The gathering of performance data will further promote the development of standards based on real-world experience. The use of renewable/green hydrogen shows the potential of green hydrogen for distributed power production. The project could be improved by tying more closely to technoeconomic analysis studies, looking at the cost to provide clean electricity with this system and projected future systems and comparing these costs to those of other dispatchable options (potentially swapping truckloads or shipping containers full of batteries, or diesel generators with biodiesel, or standard diesel and a carbon tax). It is not enough that hydrogen and fuel cells can do the job; they have to be able to do it while being economically competitive with alternatives or providing significant other advantages. At the cost of hydrogen for this project (>$45/kg), it makes it look like the hydrogen fuel cell solution cannot be competitive, as a rough estimate suggests the resulting cost for electricity would be over $2/kWhe. However, this hydrogen cost seems excessive, and a projected cost of electricity at more reasonable hydrogen costs and at hydrogen costs that meet DOE targets would be helpful.
- The general goals of the project are sound, and the team and project have shown considerable flexibility with recovering from the various issues along the way (permitting at various sites, COVID-19, power quality, etc.). From a clean energy perspective, some element of shipboard use for powering reefer containers would have been nice to see.
- The project objectives of building and deploying a containerized hydrogen fuel cell generator for portable power in land or sea applications for replacing diesel generators, aimed at reducing fuel costs and greenhouse gas (GHG) emissions, are clearly articulated. Major barriers being addressed are clearly identified.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- COVID-19 restrictions have essentially put the project on hold for the past year. The principal investigator has made as much progress under those circumstances as could be expected. The unexpected long shutdown, while unfortunate, has provided a useful test and demonstrated that the system can be shut down for extended periods and apparently suffer no ill consequences. This also suggests the system would have a reasonable shelf life.
- The project was hindered by and benefited from the pandemic in that the site realities changed during the pause and provided the opportunity to demonstrate the portability and flexibility of the technology concept. Working with actual customer loads and discovering issues, such as the electrical grounding issue, that will not appear during laboratory testing reveal the value of demonstrations for maturing technology. The electrical grounding issue should still be monitored closely, as this can be a non-trivial issue plaguing electrical systems.

- The project seems to be doing a reasonably good job of demonstrating that fuel cells can be used for power on land and at sea at ports. There was little progress in the last year because of COVID-19. The team seems to be making progress toward getting the fuel cell system running again after the prolonged shutdown.
- The project was delayed because of COVID-19 pandemic restrictions. Team members kept in contact with periodic phone calls to keep the team together. Equipment was confirmed operational despite the long, unanticipated shutdown. The project began using renewable hydrogen in July 2020 to further reduce lifecycle GHG emissions. Deployment of the Scripps Institution of Oceanography (Scripps) vessel has been delayed until June 15, 2021.
- It is unclear whether enough hours have been run to validate any model of the economics. It is to be hoped that this will improve during the remaining six months in the project. Also, it would be helpful to see a little more data on the hydrogen usage and duration between refuelings.

Question 3: Collaboration and coordination

This project was rated **3.7** for its engagement with and coordination of project partners and interaction with other entities.

- Partners cover all critical aspects of the project, from Cummins (Hydrogenics), which manufactures the fuel cell system, to IGX Group Inc. (IGX), which manufactures equipment for and supports hydrogen fueling, to Scripps, which will deploy the technology, to Sandia National Laboratories (SNL), which covers project safety in addition to leading the project. There appears to be excellent collaboration between all team members. Funding provided by the U.S. Department of Transportation's Maritime Administration from fiscal year (FY) 2017 through FY 2020 shows that the federal Maritime Administration is interested in and supports the potential of this DOE technology for addressing GHG emissions in the industry. The project demonstrates cooperation and collaboration between two different federal agencies.
- This project incorporates the full spectrum of participants in the energy chain, from supplier to end user. The California State University, Los Angeles, solar (photovoltaic) supplier feeds IGX water electrolyzers for converting sunlight into hydrogen gas. Cummins (Hydrogenics) converts that hydrogen into electrical power for a research vessel at Scripps. SNL orchestrates the music and dancers.
- Collaborations with Scripps, IGX, and Cummins appear to be effective, and earlier collaborations with USCG have been beneficial for the maritime and fuel cell communities.
- There is excellent collaboration between SNL, Cummins, and Scripps.
- Obviously, there were initial struggles in the project with attempting to support reefer containers; these issues occurred because of a disconnect on permitting. That may not have been a collaboration issue, per se, but it seems like there may have been a disconnect in planning that caused some of those problems. Technically, it seems like the project has proceeded well, with the partners working together successfully since the shore power model was put in place.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project began in 2013. The unit has been demonstrated on land and over the ocean in Hawaii for a portside refrigeration demonstration. The unit has since been upgraded to provide shore power for a Scripps vessel. The two demonstrations should provide cost data and performance data to help define standards, and they provide users with experience in using fuel cell power systems. The project addresses the DOE Hydrogen Program goal of developing hydrogen/fuel cell technologies for replacing diesel generators to reduce GHG emissions, as well as conducting a demonstration of the technology. Reducing high hydrogen infrastructure cost was identified as a DOE target. The cost of renewable hydrogen is high. Addressing the high cost of renewable hydrogen or the hydrogen infrastructure as a technical target seems beyond the scope of this project. Demonstration activities provide the performance and user experience to address the identified market transformation barriers of inadequate standards, market uncertainty, and inadequate user experience.
- The project is helping to demonstrate the relevance of fuel cells for power in ports and other stationary/portable applications. There is a need for more analysis demonstrating that fuel cells are competitive or evaluating what improvements are needed to make them competitive.

- As outlined in the feasibility report, this demonstration could be the energy storage portion of the hybrid power and propulsion system of maritime vessels. It also could provide shore power to piers in remote or compromised marinas.
- The experience gained from demonstrating the technology with potential customers is very valuable and essential to getting a successful product to market. The potential impact will be tied to the economics and to how this product compares with the competition. This project does not address the economics or how hydrogen and fuel cells compare with the competition.
- The technical demonstration is generally satisfactory, including capability, robustness (during the COVID-19 delay), and portability. The quoted price of hydrogen ($45/kg) is concerning. The reasons behind that were not well-explained, and it seems that the economics are not going to work at that level. It is unclear whether the team has explored any other alternatives for hydrogen supply at a lower price.

Question 5: Proposed future work

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

- The future work focuses on upgrading and modifying the unit for a third demonstration: providing power on the hydrogen barge at the San Francisco waterfront. Demonstrating the unit in a number of different maritime applications provides a range of performance and cost data that enable one to better evaluate whether the technology can compete with incumbent diesel technology in these applications.
- The project is drawing to a close with a clearly identified series of tests to complete. The electrical grounding issue is appropriately at the forefront of the discussion, as it could be a non-trivial complication. It will be interesting to see what the processed data and testing reveal for utilizing hydrogen as an energy storage medium in this application.
- Given the remaining life of the project (six months, until December 31, 2021), it makes sense that the team is focused on running as much as possible and getting as many operational and economic data as possible. This project has the opportunity to inform a broader array of stationary power applications for fuel cells, so the team is encouraged to consider other applications in reporting the experience and data.
- The project is nearing its end, and the proposed remaining work for the dockside deployment for Scripps and data collection should provide useful information. Plans for an additional deployment in San Francisco could be beneficial, but more information is needed regarding that deployment and, in particular, what the fuel cell unit would power.
- The future work is vague. More information should be provided about what upgrades are planned, what work is required, and what benefits are expected from the new deployment on the hydrogen barge.

Project strengths:

- Multiple demonstrations for different applications provide a wide range of performance and cost data to inform portside operators of the potential benefits of hydrogen/fuel cell technology. The ability to modify and upgrade the unit for the various applications is a major benefit.
- Clearly, the leading strength to this project is the collaboration partners. The correct partners are collaborating with the appropriate equipment at the precisely controlled venue to illustrate the feasibility of the stated project objective.
- The team has shown much perseverance and flexibility over the whole (eight-year) life of the project.
- The project is helping to demonstrate that fuel cells can be used for land and sea power in ports.
- The project provides hands-on experience with hydrogen and fuel cells for people in the maritime arena and provides fuel cell developers with experience in the marine environment.

Project weaknesses:

- There are no major weaknesses. The cost of hydrogen for demonstration projects such as this will be high, even unreasonably high, especially if the goal is to use completely “green” hydrogen. The expectation is that the cost of “green” hydrogen will come down as demand increases. The project needs to understand that using “green” hydrogen at $45/kg could strain the budget.
- This project is still recovering from pandemic complications. Reality ties it to a singular, specific vessel. The project technical data are moderately challenging to find, as the listed website contains reports from 2017.

- The use case has ended up being quite narrow, and the extremely high cost of the hydrogen ($45/kg reported) undermines the usefulness of any economic data that come out of the project.
- The project does not sufficiently address the economics or competitiveness.
- There is little science or analysis in this project. There is no indication that the fuel cell is providing a significant value proposition.

Recommendations for additions/deletions to project scope:

- If feasible, it would be beneficial to illustrate the capability to power a remote marina or a primary shore-power bus for multiple smaller vessels. This would illustrate the capability of not only addressing the shore-power needs of a major vessel but also addressing shore-power needs of smaller venues. The second recommendation would be to demonstrate the maritime fuel cell system powering the *R/V Robert Gordon Sproul* electrical loads while the research vessel is at anchor away from the pier. This would demonstrate both the versatility of the power source and its minimal environmental signature as to not impede ongoing research activities.
- Technoeconomic analysis and comparisons to alternative green power sources should be a part of future demonstrations related to this project.
- As noted in the presentation, it is important to make sure that all data are available to the public. It was mentioned that the unit's initial location was at a dock that was close to a private home and that noise coming from the unit could be an issue. It would be good to know much noise was coming from the unit and whether the noise can be further reduced.
- It is likely too late for much change at this point in the project, but it is recommended that the team take a look at alternative means of hydrogen delivery/on-site storage to get the cost down. It would be helpful in the final analysis to determine what cost level for the hydrogen fuel would be required to make the unit competitive with other stationary power alternatives.
- Analysis is needed that would support the relevance and applicability of fuel cells in port applications, and that would assess the competitiveness with alternative technologies.

Project #TA-016: Fuel Cell Hybrid Electric Delivery Van

Jason Hanlin, Center for Transportation and the Environment

DOE Contract #	DE-EE0006523
Start and End Dates	7/15/2014 to 7/31/2022
Partners/Collaborators	California Air Resources Board, South Coast Air Quality Management District, California Energy Commission, United Parcel Service, Center for Transportation and the Environment, Hydrogenics, Unique Electric Solutions, Center for Electromechanics – University of Texas at Austin
Barriers Addressed	• Lack of fuel cell electric vehicle performance and durability data • Market uncertainty around the need for hydrogen infrastructure versus timeframe and volume of commercial fuel cell applications • Inadequate user experience for many hydrogen and fuel cell applications

Project Goal and Brief Summary

This project aims to increase substantially the zero-emissions driving range and commercial viability of electric-drive medium-duty (MD) trucks by integrating a hydrogen fuel cell into the powertrain. Investigators will develop and validate a demonstration vehicle to prove its viability and then build and deploy up to 16 vehicles, which will perform at least 5,000 hours of in-service operation. The project will also develop an economic and market opportunity assessment of MD fuel cell hybrid electric trucks.

Project Scoring

The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The Center for Transportation and the Environment (CTE) showed a good approach to the work for demonstrating fuel cell hybrid delivery vans. The team is flexible in adjusting the scope as needed, such as choosing to stay with 350 bar tanks instead of going to 700 bar tanks. In large fleet applications, this lower pressure can save significant money on the cost of fuel delivery and the capital cost of building out a new fueling depot. The project also had to work around long delays in infrastructure availability and station reliability outside of the researchers' control. It is amazing they will complete the project after 10 years; most partners would have stopped by now. Phase II is a big step forward in going from one vehicle validation to 15 new vehicles.
- It seems much progress has been made since the last Hydrogen Program Annual Merit Review. It is great to see the fuel cell van well received by United Parcel Service (UPS) drivers. Most issues have been addressed, except for the life/durability issues, which will require extended study and testing to evaluate to end-of-life conditions.
- Development of a vehicle to which the operator is accustomed and that works for the operator is a good plan. The choice of a progressive and large partner in delivery is also good. The location is suitable. It is wise to start with one vehicle and then build the fleet with any lessons learned in hand.
- The project approach is greatly aligned with technical barriers, and the scope is clear on how each will be addressed. The economic and market opportunity work are well-suited to addressing the market uncertainty challenge.
- The project demonstrates a sound approach to accomplishing tasks. The project objectives are clearly identified, and the project addresses barriers in hydrogen fuel cell MD vehicle commercialization.
- The project used a large commercial van fleet user, UPS, to collect feedback, as delivery services will be the ultimate users of this vehicle. The project used a reputable fuel cell supplier, Hydrogenics, to source the system, and well-known integrators.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Good progress has been made toward DOE goals. It is unfortunate that the project experienced early delays from 2014 in component integration (inverter). Then, as soon as the researchers started meeting build deadlines in 2019, there were issues with infrastructure, and then there was the COVID-19 delay. That being said, the project is making good progress with UPS to demonstrate the availability and long range of a fuel cell delivery van for zero emissions. The team went above and beyond by nearly doubling the demonstrated time from 6 months to 11 months in total. The project has also hit major cost hurdles by completing the UPS Ontario maintenance bay hydrogen safety audit. The online dashboard will be critical to optimizing the driver experience and showcasing economics of the hydrogen delivery vans. This will allow DOE to better track fleet performance and give UPS confidence to deploy additional vehicles after this pilot Phase II is complete. Procurement of all parts required for the 15 Phase II vehicles shows the researchers are good at planning and are making good progress on high-level goals, i.e., deploying multiple zero-emissions delivery vans to lower greenhouse gas (GHG) emissions and creating learnings for hydrogen infrastructure choices to enable broad deployments. This project should be critical in supporting DOE's economic and market opportunity assessment. The 169-mile range validation is the most impressive metric in proving overall project success.
- The project has accomplished much during the preceding 12+ months (especially during the COVID-19 timeframe). Extending the duration of the demonstration enabled the team to gain more data, as well as gain understanding of how well certain design changes will perform in the new phase of vehicle builds. The team has active project participation and has solved fueling issues along the way. The project began the rollout of the Phase II vehicles, which will provide more data from more vehicles over time.
- Over the last year in a build phase, one vehicle was completed and is in extended service. The project demonstrated a range suited to the application so refill would not be needed during the day very often. There is much better progress than indicated in the slides, as five more vehicles are finished and five more

nearly so. The project has achieved much improved idle fuel consumption and a 170-mile range, which covers virtually all delivery routes for a day (so no refuel is needed en route). The project also found some "soft" selling points. Drivers liked showing off a socially responsible vehicle. The fact that UPS went for double the time to which the company originally agreed indicates UPS liked the project.

- The project completed multiple phases, and managing a small fleet of 10+ vehicles in multiple locations is a substantial effort.
- This project is very well-aligned with DOE goals of demonstrating fuel cell MD trucks in the real world.
- The project demonstrates good progress towards meeting overall project and DOE goals. While total cost of ownership (TCO) is one of the project's end goals, it would be nice to see some initial costing information (e.g., available from Phase I of the project) to get the interim performance indicators.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- CTE has done an outstanding job of coordinating all the partners. There is significant unseen overhead when managing multiple sponsors and ensuring all funding organization needs are met. This is even before the difficult coordination of integrating non-commercial technologies across UPS operations, which must not disrupt the company's revenue service. It is difficult to interface between service needs and technical specifications with the multiple component integrators and suppliers: the Center for Electromechanics at the University of Texas at Austin, Unique Electric Solutions, and Hydrogenics. The fact the project met the long range, exceeding fleet requirements, with only 9 kg, and met 15 mi/kg efficiency is very impressive proof of the excellent coordination. Other organizations such as the Hydrogen Safety Panel and the National Renewable Energy Laboratory can both detract from and add to a pilot project such as this. Data collection can add additional hurdles in formatting and user fatigue. The second review of safety may result in constructive support but brings additional project risk and possible cost.
- Collaborating with UPS is about as good as it gets as far as end customers for these types of vehicles. It would be interesting to see how smaller fleet owners would respond to a fuel cell electric vehicle (FCEV) van, given the difficulties with infrastructure (UPS can probably afford to install infrastructure). The majority of van fleets are smaller (<20) vehicle fleets; infrastructure affordability will be an issue.
- The project has extensive partners and participation from the appropriate members. The members give this project a best chance at success.
- There is a good choice of partners; they can place orders at large scale if the pilot succeeds. It looks like there are appropriate levels of coordination.
- The project demonstrates satisfactory collaboration and coordination with project partners. To capture the most honest feedback, the team should gather feedback from the operator/user/maintenance crew through a formal, anonymous survey instead of just informal conversation.
- The collaboration between all the partners seems good. Clearly, the project has been delayed somewhat, and it is unclear whether there were collaboration issues in the past, but based on the presentation, all parties are currently involved and contributing to the success of the project.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This is a perfect project to showcase the pivot from passenger cars to medium- and heavy-duty vehicles. The on-road results are critical to proving the technical capability of the fuel cells and hydrogen storage, while helping to highlight hurdles of hydrogen cost and infrastructure deployments. The fact that the target range was exceeded with 350 bar onboard storage rather than with 700 bar is an important signal for where cost reductions should be focused across the DOE Hydrogen and Fuel Cell Technologies Office. The detailed route maps, fuel consumption modeling, and real-world driving results are invaluable to showing Hydrogen Program progress.
- This project captures what needs to be done, especially as it moves into Phase II. Starting with one vehicle and learning about its use and performance, then building many more vehicles, is a great plan and is providing essential information to the technology community, as well as the municipal

community. Assuming a successful conclusion, the impact could be huge for delivery providers in terms of reducing carbon emissions and maintenance.

- Understanding reliability and maintenance in MD FCEVs is important, especially as a partner has the ability to have great impact on the penetration of the technology. The project aligns well with reducing criteria pollutants and GHG emissions. There could also be a broader supply chain impact if the project does induce early adoption of this technology in delivery vans.
- Collecting strong customer fleet feedback on these range-extended electric vehicle vans is crucial to understanding powertrain sizing and customer needs.
- The project aligns well 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.
- A technoeconomic analysis (TEA) should be done at the end of the project to see how close the technology is to meeting Hydrogen Program goals and targets. No indication was provided in this presentation regarding the hydrogen targets.

Question 5: Proposed future work

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

- The project has a strong future work proposal that will continue to answer questions about the challenges associated with fuel cell mass adoption. Market opportunity assessment is one of those essential pieces of work that needs to be completed along with the data collection on the additional vehicle fleet.
- The project demonstrates a sound approach to the future work plan. It sounds like vehicle certification remains a challenge in certain states. Recommendations on how to address this barrier need to be addressed.
- It was good that CTE and UPS were able to use public infrastructure as a stopgap, but it clearly shows how difficult it is when the infrastructure is unreliable, and the fuel is very costly. Because of the ongoing delays in infrastructure build-out and the multiple delays in delivering fuel to California over the last three years, low-cost, reliable delivery of fuel will likely be the biggest hurdle for a positive Phase II test and evaluation. Extra care should be taken with ongoing coordination regarding the Shell hydrogen station.
- It will be very interesting to see all the trucks on the road.
- The project will finish the creation of vehicles and gather operation data. Maintenance is part of the future work, but there are no data now.
- The project is nearing completion.

Project strengths:

- It is good to see a fleet of 15 trucks built and demonstrated. This will provide the industry with performance, reliability, and cost metrics that will be the basis of future hydrogen-focused projects. It was great to see Phase I completed successfully after all the initial hurdles. This project seemed to uncover some shortcomings in the hydrogen distribution network.
- The project uses a vehicle body with which the customer is familiar and that the customer values. The project aims for a range that will minimize fueling issues so long as hydrogen is available at the base of operations. The project has a nearly perfect customer partner and test area.
- For CTE and the project partners, the biggest strength is perseverance, which is required to see this project through from start to finish. This strength is followed closely by execution and coordination required to reach the outstanding technical results of range, fuel economy, and meeting all routes requested from UPS.
- The project has a strong plan to gather real-world usage data on a fleet of fuel cell delivery vehicles. The phased approach with a go/no-go decision is excellent. The project has a great, experienced team.
- This demonstration project addresses barriers in fuel cell MD vehicle commercialization. There is effective engagement and coordination with UPS and local hydrogen station operations.
- The project has deployed real-world demonstration vehicles with a large fleet customer.

Project weaknesses:

- It would be good to know what the “fueling station issues” were and how they were addressed. This can help the industry improve infrastructure for future easier adoption.

- Retrofitting the old chassis vehicles may be an impediment because of certification issues and not being able to take advantage of the latest developments in safety, functionality, weight savings, connectivity, etc.
- There is no formal feedback (e.g., survey) nor initial TCO data presented from Phase I to determine interim cost outlook. Some barriers in vehicle certifications have yet to be addressed.
- There is no ability to scale up production nor to develop a certified vehicle where sales could be scaled to any level desired.
- The most significant weaknesses were likely past failures from component suppliers for smooth integration and the uncertainty of hydrogen infrastructure due to the unreliable California hydrogen market delivery performance to date.

Recommendations for additions/deletions to project scope:

- As it stands, this project will show this conversion can be done and give some data on how well it works. That might catch the eye of someone who could take it further, but the odds are it will not. To have real value to the country and to the company, this work needs to scale up in a very large way, and since the researchers cannot do that, they need to be very actively courting people who can. Certification is a problem, so lining up a partner who can build the hybrid vans from scratch at appropriate scale is critically needed. The project should consider looking for a large partner that could do the extensive engineering and validation/test work needed for vehicle certification by the government and that could accomplish production on any scale.
- The project should prioritize Task 8 to ensure hydrogen fuel is available as the new vehicle batches are commissioned and delivered in Task 5. Task 6 will also be critical in operations training relating to driver acceptance and a smooth integration for UPS. Given the previous project experience, it is important to highlight the importance of a reliable fuel supply. If possible, priority should be increased for coordinating logistics and fuel delivery in the event of unexpected outages from Ontario regarding the supply of hydrogen, as well as the potential for such outages. It may be helpful to consider a contingency plan if the station goes down without notice and a backup supply of hydrogen is needed on short notice.
- It would be good to add a TEA task to determine all the costs associated with the trucks, maintenance, and fueling. This can form a baseline to see how much costs need to improve if FCEV trucks are to be successfully adopted.
- The project could perhaps conduct a small demonstration with smaller fleet owners to get a different perspective on willingness to use hydrogen as a fuel.

Project #TA-017: Innovative Advanced Hydrogen Mobile Fueler

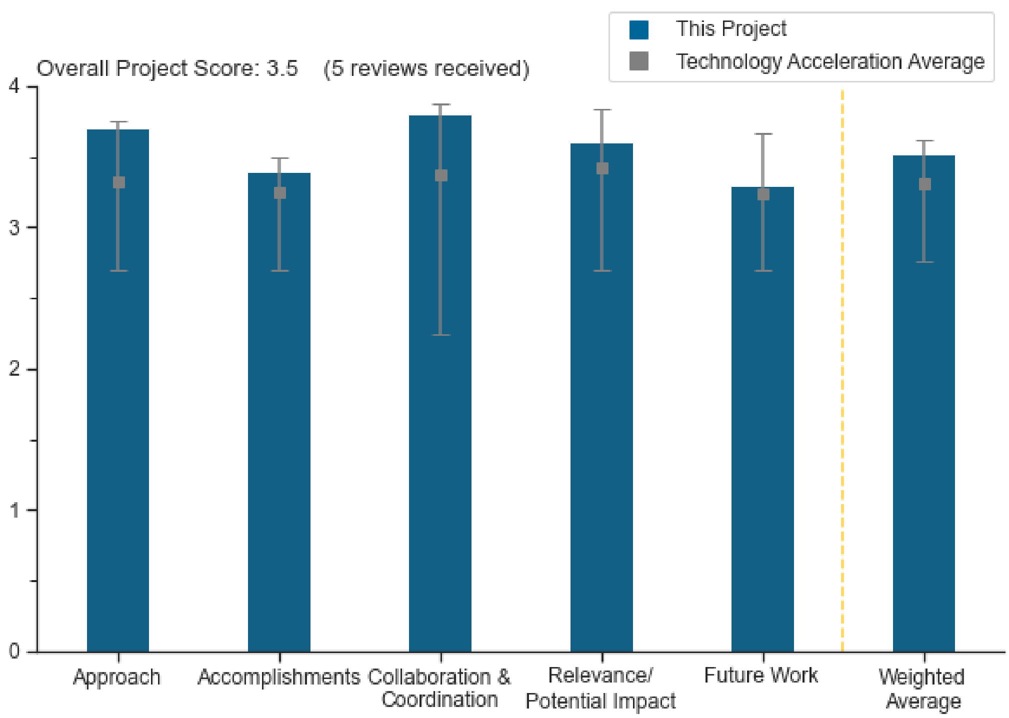
Sara Odom, Electricore Inc.

DOE Contract #	DE-EE0007275
Start and End Dates	7/1/2016 to 6/30/2021
Partners/Collaborators	Air Liquide, HTEC, QAI Laboratories, Manta Consulting
Barriers Addressed	• Hydrogen codes and standards • Hydrogen storage • Lack of hydrogen refueling infrastructure performance and availability data

Project Goal and Brief Summary

The objective of this project is to design and build an advanced hydrogen mobile fueler (AHMF). The developed mobile fueler will be deployed to support a network of hydrogen stations and vehicles; fueling data will be gathered for analysis by the National Renewable Energy Laboratory's Technology Validation Team. To reduce risk, the mobile fueler is based on an existing conventional station design, and project efforts are coordinated with station providers and automotive manufacturers.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project has a strong approach to meeting the challenges specified. The design and demonstration of the mobile refueling station that is able to accomplish point-of-sale hydrogen sales will provide excellent usage

and performance data to follow-on efforts. Demonstration at three sites provides a more robust use case with more varying data for any design improvements.
- This project has been under way for several years now, and the most challenging objectives and barriers have been identified (Tasks 4 and 5) and addressed. It appears previous input from reviewers and project stakeholders has been considered and included where there are needed improvements to the project.
- The staged approach with design and development, followed by demonstration and validation, was good. It is nice to see concept-to-hardware all the way through. It is good that the performer received a special waiver to carry 950 bar and that this can be used in other projects. This is a small thing, but bar seems to be the standard unit for hydrogen, so it would make sense to report as bar *vice* MPa.
- The approach is sound and reasonable. The compact design is applicable to most potential sites and expected to be user-friendly.
- The connection to U.S. Department of Energy goals and the benefits to the industry are clear.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made great progress toward its goals. The liquid nitrogen (LN2) cooling validation was a big step and important to validating the station performance and the ability to meet commercial filling requirements. Site selection was also an important accomplishment toward getting the project completed.
- Carrying 95 MPa, without purging for system transportation, requires a special permit—a valuable achievement for the overall industry. LN2 appears to work as anticipated (to be fully proven through Hydrogen Station Equipment Performance [HyStEP] device testing). It has been system-integrated, and it passed quality testing. The self-contained system for H70 fueling from the mobile fueler is a very positive achievement and sets the bar for the United States for future mobile fueling solutions with similar fueling capacity. The anticipated first demonstration site has been selected.
- This project is on track to demonstrate the mobile fueler, although timing was delayed. The delays are understandable, considering the issues during the pandemic.
- Progress has been made. It is understood that COVID-19 and permitting processes tend to take a toll on the schedule. Perhaps selecting a location with permitting under industrial or commercial zoning would help, at least for initial qualification refueling, in order to begin demonstration use as light-duty-relevant locations are permitted.
- It would have been preferable to see more actual hardware by now, but the design looks good.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- The project appears to be successful in collaboration with partners and with initial demonstration site providers. The city of Ontario is expected to come through with a temporary permit after the paperwork is submitted, in part because of previous experiences in that region.
- This project is well-connected with major hydrogen suppliers, as well as DOE national laboratories and other partners. It appears to be a well-balanced and strong team.
- The team looks like a good mix of industrial experts. Teaming with the national laboratories for economic analysis seems like a good approach.
- This is a well-coordinated project, with multiple specialist partners that span industry and government.
- There is excellent collaboration between all project partners.

Question 4: Relevance/potential impact

This project was rated **3.6** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The information from projects like this will help municipal governments expand hydrogen filling access as new stations get planned. If usage is below or above the planned use case, that could help save funding in the long run. The U.S. Department of Transportation's (DOT's) approving 95 MPa hydrogen tanks is huge

for the industry and has already been trickling down to other projects and efforts. This effort is also helping with the permitting work, which can be a huge obstacle in many places. This also has a huge potential impact.
- The project is highly relevant to DOE goals because it will facilitate build-out of hydrogen infrastructure. The mobility and quick set-up are important. This type of system could be used to fill in the gaps of a network or to help test out locations for permanent future stations. The lessons learned during this project could be used to help improve other stations and potentially lower station footprint, which is a challenge for some sites. Approvals from DOT could aid other mobile fueler development.
- Mobile refuelers that are more than just a cascade fill are going to be critical in building demand and consumer confidence in new markets. Building fixed infrastructure has too long of a lead time and cost for early, low-demand markets.
- This is the first project under DOE funding to achieve a fully self-contained H70 mobile fueler at this fuel pressure and with this capacity.
- Mobile refuelers are a nice demonstration project to help achieve hydrogen at scale because they can be moved to various demonstration sites.

Question 5: Proposed future work

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

- The future work planned is in line with the needs and objectives. The project is working on an extension to allow full time for demonstration and data collection, and it is very important to analyze these data and eventually share results.
- Future work falls in line with completing the efforts as proposed: finishing the demonstration sites and getting the required data to mark the project as a success and contribute to progress on the DOE barriers.
- Some contingency planning concerning alternate siting or siting philosophies, in case permitting continues to be drawn out, could help.
- There is a high degree of effective planning, even through delays. Successful continuation of the project based on the proposed future work is anticipated.
- It is good to see that Air Liquide plans to use the AHMF beyond 2022.

Project strengths:

- This project has a strong approach in developing and demonstrating a mobile filling solution that can help bring down hydrogen filling barriers. There is a strong team working together to learn as much as possible about the system to help enable future iterations for specific needs.
- AHMF is a first in the United States, and it has strong potential for replication to accelerate the rollout of infrastructure and provide infrastructure where needed (because of a new market, delayed planned infrastructure, temporary infrastructure where existing infrastructure is down, or emergency fueling infrastructure). Another strength is the 95 MPa special permit and the simultaneous education of DOT. There is potential for the use of lessons learned from the “station equipment footprint reduction” exercise to fit on the semi-trailer for future new approaches toward footprint reduction of permanent hydrogen stations.
- The compact mobile design is easily set up and user-friendly. The mobile fueler could be used to test out viability of sites for future permanent stations and also to fill in gaps in the overall hydrogen station network. The lessons learned can aid other DOE projects and mobile fueler development.
- This project provides a well-thought-out design for a mobile refueler, with a demonstration plan and validation. The innovative LN2 cooling technology will be interesting to compare side by side with the incumbent cooling technology from other projects.
- This is a well-engineered system from a team with the right strengths.

Project weaknesses:

- LN2 as a consumable is a little concerning. Maybe it would be good to include some economic analysis showing the low cost of LN2 relative to the cost of other cooling technologies.
- It is strongly suggested that the project look at high-density fuel cell power packs (bus powerplants, perhaps) instead of a diesel genset.

- The cost reduction potential and outcomes of the economic modeling are unclear. The timeline of execution is also a weakness.

Recommendations for additions/deletions to project scope:

- It is recommended that the project conduct a follow-up project to build two to five additional units. The team should apply the lessons learned to a future version that can be used for fueling medium-duty and heavy-duty vehicles. Removal of the fueling data collection requirement should be considered, as the majority of equipment components exist elsewhere or apply significantly to only specific components of the system.
- The project needs an analysis of the LN2 cost as a consumable, along with user feedback on it.
- The project is well-planned, and no additions or deletions are suggested.

Project #TA-018: High-Temperature Electrolysis Test Stand

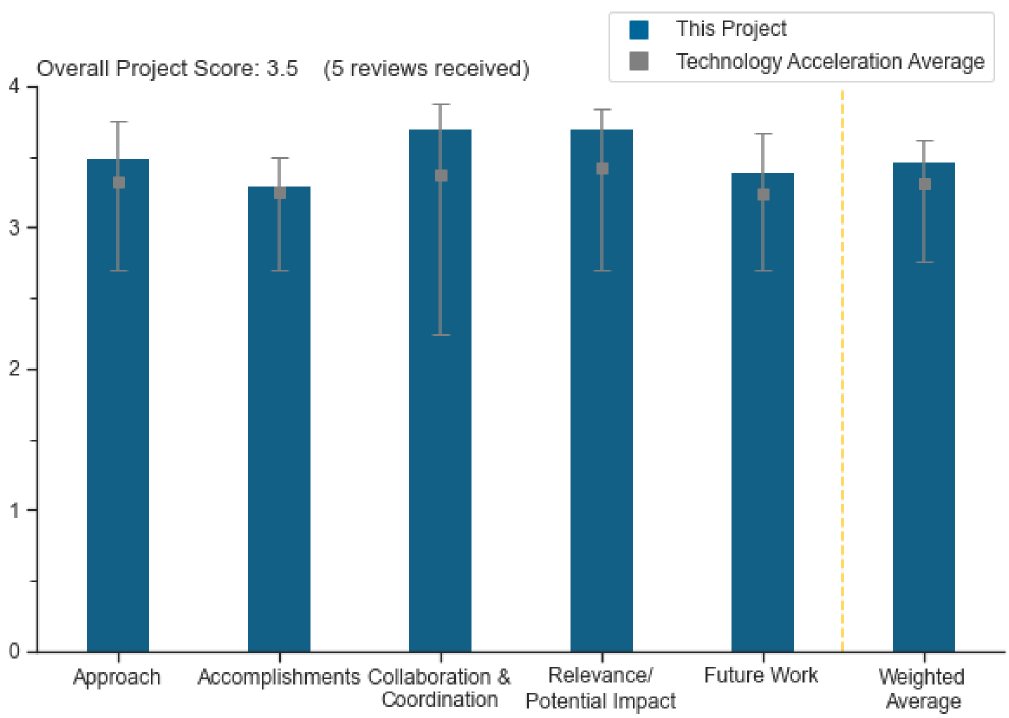
Micah Casteel, Idaho National Laboratory

DOE Contract #	WBS 7.2.9.1
Start and End Dates	9/30/2020
Partners/Collaborators	Idaho National Laboratory, Strategic Analysis, Inc., Bloom Energy, FuelCell Energy, Nexceris, Energy, Xcel Energy, OxEon
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Controls and safety

Project Goal and Brief Summary

The project objective is to advance the state of the art of high-temperature electrolysis (HTE) technology by discovering, developing, improving, and testing thermal–electrical–control interfaces for highly responsive operations. The project will (1) develop an infrastructure to integrate support systems for 25–250 kW HTE testing units, (2) support HTE research and system integration studies, (3) measure cell stacks, performance, and materials health under transient and reversible operation, (4) characterize dynamic system behavior to validate transient process control models, (5) demonstrate integrated operation with co-located dynamic thermal energy distribution/storage systems, and (6) operate the system with co-located digital real-time simulators for dynamic performance evaluation and hardware-in-the-loop simulations.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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.

- This is an outstanding project. Idaho National Laboratory (INL) is supporting several solid oxide electrolysis stack developers with performance and durability testing while providing the U.S. Department of Energy with data to assess the status of solid oxide electrolysis cell (SOEC) stack technology. As the project goes forward, INL will develop the capability to test larger stacks (and multiples of larger stacks). This capability will enable system-level assessments of SOEC technology.
- The approach to evaluate stacks from multiple customers to further compare the technologies and to further advance stack/system technologies (in terms of technology readiness level [TRL]) is highly valuable. The major solid oxide cell (SOC) players will be participating in the project, which will encourage collaboration toward a mutual goal of reduced hydrogen production cost. The attempt to provide open-access benchmark information on various tests for different customers, along with their supply chain options and costs, may be easier said than done, and what information is shared will depend greatly on the willingness of the customers. Another potential challenge is that the operating conditions for different customers may be different. This will create a challenge in data comparison if, for example, all stacks are operated at different current density.
- It is very important to provide an independent testing platform for manufacturers that also functions as external validation for end customers and applications that require a high degree of reliability. The list of companies that collaborate in this project is impressive.
- Objectives are clearly defined, but additional detail would be helpful. Barriers are listed as capital cost, system efficiency/electricity cost, and controls/safety. Controls and safety seem to have been addressed in the slides and talk, with perhaps some information on system efficiency and electricity cost, but it would be better if there were more discussion on how capital cost, system efficiency, and electricity cost are being addressed. The project approach in general seems sound; however, when a stack test stand is used to evaluate multiple technologies, it is advised that caution be taken since certain aspects of the test stand may yield bias toward one stack technology versus another and skew interpretation of results. As long as analysis of data and reporting of results take this into account, the bias can likely be minimized. It was mentioned that input to the cost modeling would come from participating companies. However, past cost studies sponsored by the U.S. Department of Energy have not always done as good a job as they could clearly describing the limitations in their assumptions and the impact that uncertainties may have on the results. Sensitivity analyses are not always going to uncover the impact of unknowns if the unknowns are greater in scope than assumed. It is advised that the approach to the cost study probe the participating companies to acknowledge whether they are omitting certain sensitive information, which can then be acknowledged in cost study reports and addressed as a potential risk.
- The project approach is excellent in setting up a test station appropriate for evaluation of multicell stacks provided by various manufacturers. However, the team should identify, discuss, and document issues, if any, in operating such a system.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The new larger test stand is a primary focus of this project, but that progress has been impeded by procurement delays resulting from the COVID-19 pandemic. Given that, the performer has wisely shifted to using its smaller test to test additional stacks and get data on smaller-scale stacks, which can be useful in comparison to the larger-size stacks that will be tested eventually, once the larger test stand build is completed. The performer has added many more companies to the list of those who will provide stacks for testing, which will increase the available data for comparison to achieve DOE goals and project objectives. The performer acknowledges that the increased number of companies that will be involved presents a challenge, especially since assembly of the larger test stand has been delayed. It is advised that the performer think about prioritization of stacks to test that will provide more useful data sooner, considering the delays and limitations in the number of simultaneous tests that may proceed for long periods of time.

- The project has made excellent progress in setting up the test station and demonstrating operation and performance of stacks provided by several manufacturers.
- INL has established a state-of-the-art SOEC stack testing capability and is working toward extending this capability to larger stack sizes and power levels. Testing results will provide inputs to a number of SOEC-stack-related system design decisions, such as optimum stack sizing, current density, and thermal management.
- The INL team has already demonstrated a flexible electrolysis stack test platform with multiple stacks from different vendors. Promising durability and degradation of ~0.5%/1 kh have been achieved with some stacks, meeting the go/no-go decision. What is not clear is the current density at which these tests are conducted (on a stack) or how operation at different current density affects durability and lifetime. Because of COVID-19, significant delays have been experienced on the equipment side, which will make completion of system validation challenging. However, the team is doing everything it can to catch up.
- This project has clearly shown progress with external manufacturers, but the boundary between troubleshooting testing hardware and customizing for stack/hotbox integration is vague. Typically, it is not acceptable for a test station to suffer from steam instabilities or blackouts if the aim of the testing is to show trouble-free operation for 3,000 hours. Therefore, the system maturity should increase with the next partners coming to test.

Question 3: Collaboration and coordination

This project was rated **3.7** for its engagement with and coordination of project partners and interaction with other entities.

- The performer appears to have recruited a great number of organizations with whom the project team will collaborate through testing of those organizations' stacks. This has the potential to increase the usefulness of the project but presents a coordination challenge, as acknowledged by the performer.
- The project structure requires excellent communication and collaboration with customers, vendors, national laboratories, and academia. The team has strong relationships with partners.
- INL is working with and has established testing agreements with all of the major HTE stack developers in the United States.
- Collaboration is clearly industry-focused, one-on-one and sequential testing, but it would be good to see that the test results also feed back to a wider consortium directly (not just a paper) so that the entire SOEC community can be engaged to increase TRL levels collectively and bring closer nuclear applications.
- The project has collaboration with many major manufacturers of high-temperature electrolyzers.

Question 4: Relevance/potential impact

This project was rated **3.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project has potential to accelerate HTE stack development work by collaborating with HTE stack developers, both by providing independent testing results and by testing HTE stacks for longer durations than feasible for some HTE stack developers. This provides valuable data that HTE stack developer needs to prioritize improvements in performance and durability. The HTE stack testing and system design capabilities being established will make INL an excellent partner as HTE systems are developed and implemented.
- Demonstrating the reliability and efficiency potential by an independent party on a trusted test system is needed to increase the trust in and maturity of SOECs.
- This project provides one way to benchmark current stack TRLs and evaluate the amount of research that DOE should provide (and in what areas of focus) to achieve DOE Hydrogen Program (Program) goals of $2/kg (and now $1/kg with the Hydrogen Shot initiative). Given the potential for bias, as outlined in Question 2, additional testing by stack developers and other independent testing organizations is advised.
- Data validation (stack, system testing) at INL provides significant value to customers and DOE. This project will strengthen relationships with industry and national laboratories to accelerate technology advancement and achieve the overall Program objectives.
- The test station provides a common platform for evaluating high-temperature electrolyzers from different manufacturers.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The proposed future work is reasonable and will include testing of various stacks and completion of an HTE system.
- INL plans to expand the scope and size of HTE stack tests, expanding the lab's solid collaborations with industry.
- The proposed future work is consistent with its work scope and timeline.
- The plan forward is clear, but it would be good to see the test station improvements being quantified in the roadmap, not just when new stacks will be tested. This project should provide a quality standard for third-party testing, in which the quantity of stacks tested is not a key performance indicator unless they meet target performance expectations (test station and stacks are all technically sound and qualified for application).
- Plans for dealing with delays and possible unknowns when the missing equipment is received could benefit from additional details. The project plans to build a second HTE system, which will address the increased number of participants, but it is unclear what delays will exist in building the second system.

Project strengths:

- The approach to evaluate stacks from multiple customers to further compare the technologies and to further advance stack/system technologies (in terms of TRL) is highly valuable. The major SOC players will be participating in the project, which will encourage collaboration toward a mutual goal of reduced hydrogen production cost.
- There is key expertise, as well as high-end facilities, and these capabilities are key for manufacturers to bring their products to market (nuclear). The technical skills presented are impressive.
- The project seems well-thought-out, and the approach for widespread participation will generally help provide more data that can be useful in the pursuit of DOE's hydrogen production goals.
- The main strength of the project is the development and demonstration of a common platform for evaluating high-temperature electrolyzers from various manufacturers.
- State-of-the-art HTE stack testing capabilities have been established. Collaboration with industry is the strongest attribute of this project.

Project weaknesses:

- A good deal of time and many resources could be needed to adjust to each manufacturer, as there is no standardization and there are probably many proprietary system solutions (hotbox) that would not allow mutual comparison of test results. Therefore, it seems questionable whether the objective of the test to demonstrate TRL 7 from manufacturers can actually be validated on a common denominator if the stacks are all different in nature. It feels like the testing service provided aids individual product development rather than being a stage gate for proving technical maturity.
- The information shared from an open-access system will depend greatly on the willingness of the customers. Also, the operating conditions for different customers may be different. This will create a challenge in data comparison if, for example, all stacks are operated at different current density.
- The project seems focused on large-scale implementations (likely because of Programmatic focus) but would eventually benefit from investigating smaller-scale, distributed generation applications.
- The project needs to put some work into collecting and documenting "lessons learned" in operating the test station with different stacks (having different materials and architectures) from different manufacturers.
- INL will probably want to improve uniformity of steam delivery to their test stands.

Recommendations for additions/deletions to project scope:

- Rather than check TRL 7, a wider range of customer-specific development support could be offered to reach the overarching goal faster, such as application of SOECs with nuclear. Shorter test timeframes or specific accumulated accelerated stress test protocols could prove very valuable, bringing experience from other partner test experiences to fruition.

- The project should seek to establish a meaningful matrix in which stacks from different vendors can be quantitatively compared at the same level (similar conditions) and to identify which stacks (technologies) have the best potential for scaling and for hitting the cost metrics. For instance, durability at 0.1 A/cm^2 is rather different from at 1.0 A/cm^2, which is a minimal DOE target to get anywhere near the target hydrogen costs.
- There are no recommendations for additions or deletions to project scope.

Project #TA-024: Analysis of Fuel Cells for Trucks: Real-World Benefits

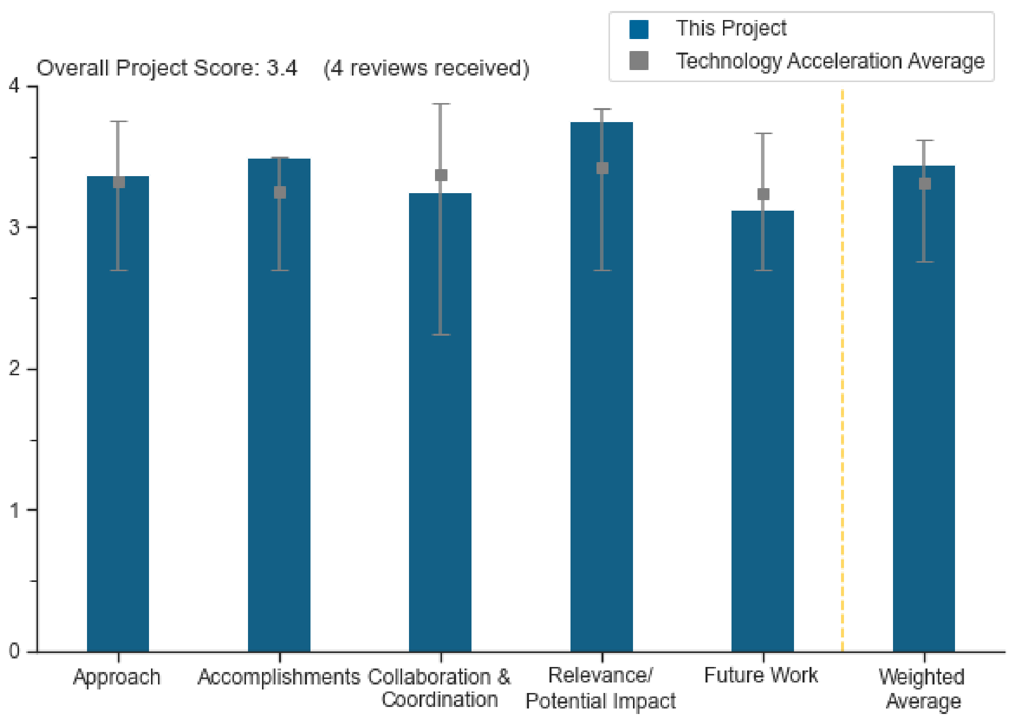
Ram Vijayagopal, Argonne National Laboratory

DOE Contract #	WBS 7.3.8.1
Start and End Dates	9/1/2020
Partners/Collaborators	National Renewable Energy Laboratory, 21st Century Truck Partnership (21CTP)
Barriers Addressed	• Future market behavior • Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools

Project Goal and Brief Summary

The primary objective of this project is to reduce the ownership cost of a fuel-cell-powered truck by finding optimal component sizes for the onboard hydrogen tank and battery pack energy storage system. The Argonne National Laboratory Fuel Cell Team will support the U.S. Department of Energy by creating a design solution that will meet or exceed the baseline performance and cargo capacity of a conventional vehicle.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project has a good approach, and Autonomie is a respected tool for this sort of work. The baseline chosen makes good sense, and as the two test cases bracket vehicle duty cycles likely to be seen on the road, the test plan also makes sense. As maintenance expenses will differ from those associated with conventional vehicles, maintenance should be included in a simple cost of ownership (SCO) estimate (rather than just fuel and purchase costs), even though maintenance does have a smaller influence on total cost of ownership (TCO). Leaving out insurance and wages is a good plan.

- The approach is sound and provides comparisons to multiple conventional architectures.
- The project has a clear description of the methodology, with focus on a couple key vehicle types.
- The vehicle powertrain sizing approach is practical and based on worst-case gradeability scenarios of Davis Dam.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- This is good progress. Fuel cell hybrid electric vehicles (FCHEVs) using battery energy and reducing fuel cell usage save up to $15,000. The fuel cell allows the battery to run at a maximum charge rate, so the researchers went with energy. They size the battery by ensuring proper speed for 11 miles at 6% grade. The project should use DOE Vehicle Technologies Office cost targets for battery cost. The project predicts 50% energy savings using hydrogen priced at $6.00 to $7.00 per kilogram and $2.60 per gallon for diesel, but the prediction is relative to conventional trucks, not a hybrid with an advanced engine. The idea that the slope of the SCO plot shows the justifiable cost increase for improved fuel cell efficiency is a valuable biproduct of this study.
- Many good insights can be drawn from this work, and the accomplishments, to date, should be appreciated. The following are a few suggested improvements:
    - For meeting baseline performance, more context for the vehicle's design would be appreciated (i.e., whether the vehicle is designed for the average representative cycle or the most difficult cycle). Also, it would be interesting to know whether the powertrain can achieve a one-to-one replacement of the difficult duty cycles or whether there are challenges to consider other than costs.
    - With the addition of battery electric vehicles (BEVs), insight could be greatly improved with a BEV comparison to understand both performance differences and cost differences.
    - Helping to set technology targets does not appear to be a prime part of the scope, but this was mentioned a few times. More clarity about whether target-setting is an end goal would be appreciated—as would information as to whether the focus will be on Class 4 and Class 6 delivery trucks only.
- The project has made excellent progress and accomplishments on defining the baseline sizing and TCO; many extra use cases and scenarios can be built off these results.
- The project is on track with the team's plans. The completed simulations predict cost curves and estimate the timeline of cost parity with conventional vehicles.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- There is an appropriate mix of industry through the 21st Century Truck Project (21CTP) and government organizations. Until recently, 21CTP was not well-represented with original equipment manufacturers (OEMs) in the lower weight classes. It is to be hoped that in the coming years, coordination and data in these lower weight classes will continue to improve.
- The project has great collaboration with industry and other laboratory partners. Participation in 21CTP enables input from OEMs and other technical teams for specific parameters.
- The project obtained information from OEMs on technical specifications and information from the National Renewable Energy Laboratory on drive cycles. This is a good choice of partners.
- Both internal and external collaborations are good, as the team leverages other projects within DOE and obtains industry input. The project could benefit from more input on a "representative" cycle that would actually meet the needs of most customers. There is also an opportunity for more collaboration related to TCO. The addition of a simple TCO is actually a bit confusing when there is another referenced DOE

project that dives deeper into TCO; perhaps better coordination is more appropriate than trying to make a simplified and separate calculation.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- These projects are needed to establish reasonable baselines on vehicle sizing and duty cycles from which infrastructure, cost of ownership, and other considerations can be deduced.
- It is important to estimate, in a rigorous way, the cost of ownership for medium-duty (MD) fuel cell electric vehicles and to explore methods to reduce that cost in simulations rather than much more expensive hardware. This points out where research is needed and eventually acts to give early adopters confidence that they understand the costs they will incur.
- The project aligns well with DOE objectives and contributes to target-setting for Class 4 and Class 6 trucks. Typical use for these truck classes is significantly different from long-haul trucking, which necessitates targets specific to this use.
- This is a very valuable project. There is room for further value add and more clarity in informing DOE.

Question 5: Proposed future work

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

- The mention of both near-term expansion and future ideas is welcome. It is recommended that the project include a focus on near-term opportunities, such as other priority vehicle classes/vocations (Class 8 trucks, transit, MD vans, etc.) and a refinement representative cycle. Access to synthetic drive cycle data would certainly provide more opportunities to explore.
- Including system cooling capacity in the analysis would be valuable. Difficulties in this area for Class 4 pickup trucks and max trailer tow gross combined vehicle weight (GCVW) ratings are seen in other analyses. The analysis should include additional vehicle-to-load function (V2L) loads up to 20 kW, as this is an increasingly important feature in the truck space. It would also be good to add grid service balancing and fueling time versus fleet hourly shift requirements.
- The project's plan to study potential future traffic situations and systems is useful work, but it is somewhat more speculative in nature.
- Proposed future work presents the next logical step to current work.

Project strengths:

- This project has a strong focus on fuel cell vehicle design that will meet the needs of operators. This is then coupled with real driving data to understand how the vehicles are used. This combination is a powerful tool.
- There is a highly validated tool chain. This is a good simulation team with good data sources. The author's call for MD standards is correct; heavy-duty standards are likely to be too easy or too hard for the MD case.
- The project has an excellent methodical approach to vehicle sizing and ownership costs. Logical assumptions are made in most cases.
- This project provides valuable insight into estimated timing for cost parity with current technology.

Project weaknesses:

- The project is well-done overall. The smallest gripe is that OEMs typically like to size for Davis Dam at 65 mph, not 40 mph. This will increase the total powertrain sizing and energy demand.
- Using real-world data to validate the model results (once fuel cell electric trucks get into service) is recommended.
- It is not clear the project is looking at similar levels of progress in batteries or gasoline engine–battery hybrids, or expected levels of progress in the diesel hybrids.
- It is a bit unclear whether the final goal and output are target-setting, TCO, or performance comparisons. It is hoped that all three will be expanded on, but they are currently only partially addressed.

Recommendations for additions/deletions to project scope:

- The project team should consider the following:
    - Including system cooling capacity in the analysis would be valuable.
    - The project should focus on designing to the most difficult duty cycle since the trucks must be capable of that.
    - The project team should collaborate for TCO insight rather than create a simplified version.
    - The project should expand to other vehicles, such as Class 8 trucks, transit, and vans.
    - The project team should recommend new targets if appropriate.

  The principal investigator and team have done a great job.
- Including a system cooling capacity analysis is recommended, as difficulties in this area for Class 4 pickup trucks and max trailer tow GCVW ratings are seen in other analyses. Additional V2L loads up to 20 kW are also recommended for inclusion in the analysis, as this is an increasingly important feature in the truck space. The project might also add grid service balancing and fueling time versus fleet hourly shift requirements.
- The project should search for a non-fuel-cell case that would exceed the performance the team calculates for the fuel cell or FCHEV to identify whether there is any true competition in future years.

Project #TA-025: Laser Three-Dimensional Printing of Highly Compacted Protonic Ceramic Electrolyzer Stack

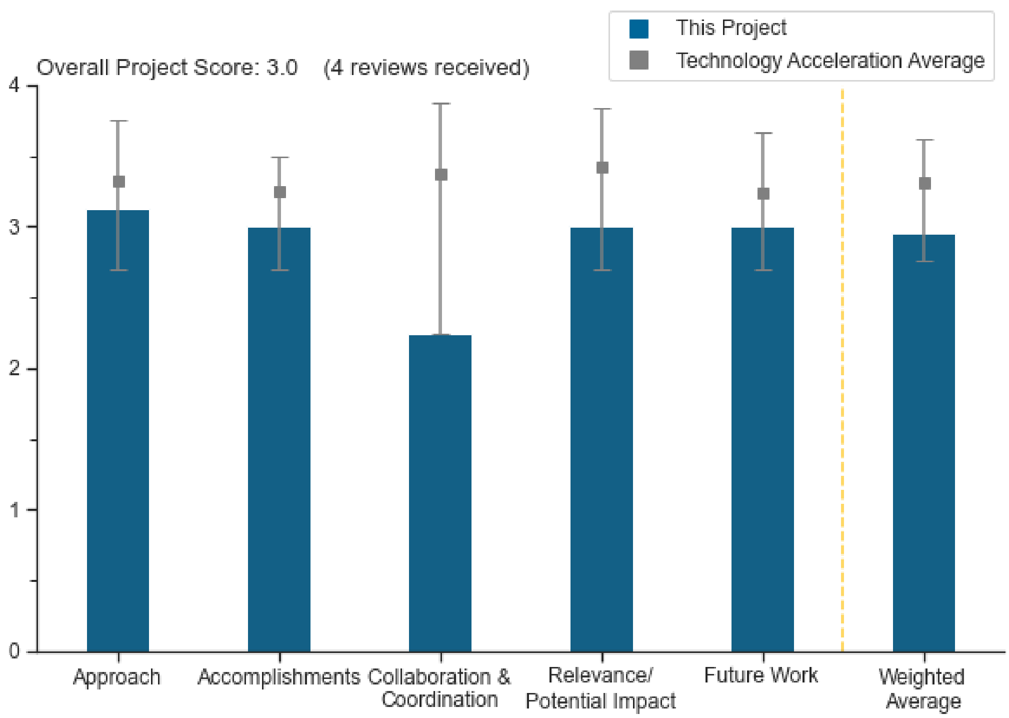
Jianhua Tong, Clemson University

DOE Contract #	DE-EE0008428
Start and End Dates	11/6/2018 to 4/30/2022
Partners/Collaborators	N/A
Barriers Addressed	• Capital cost: Capital cost of water electrolysis system is prohibitive to widespread adoption • System efficiency and electricity cost: Low-cost cell stacks addressing efficiency are needed • Manufacturing: Electrolysis units are produced in low volume; fabrication technology is capital-intensive

Project Goal and Brief Summary

This project aims to reduce the cost of manufacturing state-of-the-art electrolyzers by designing, developing, and demonstrating a laser three-dimensional (3D) printing technology. This innovation will enable cost-effective, rapid, and flexible manufacturing of high-performance, intermediate-temperature protonic ceramic electrolyzer stacks (PCESs) for hydrogen production at various scales. The target PCES will have a total effective area of over 100 cm^2, a current density of over 1.0 A/cm^2, and a stable operation time of over 1,000 hours at 600°C.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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 application of 3D layer construction and reactive laser sintering opens up a wealth of possibilities in design and implementation.
- The approach lays out a logical path toward the exploration of laser 3D printing as a laboratory-scale fabrication pathway for solid oxide electrolyzer cells (SOECs) and stacks. Different aspects of deposition and sintering are evaluated, and different material compositions are of interest. Testing of fabricated cells and stacks is necessary and is being pursued. An economic assessment is certainly needed and is being pursued as well. This being said, the potential outcomes of the project do not seem to be a good match to the perceived scope of a Technology Acceleration project. In particular, the fabrication technologies under study do not seem to be relevant to addressing near-term manufacturing goals or targets or, thus, to addressing cost targets.
- This project is a novel laser processing of ceramics into water electrolyzers.
- Generally, the description of objectives and barriers is fairly clear. However, it is difficult to understand the extent to which the project will be able to assess the impact of developments on manufacturing costs. The project would benefit greatly if Clemson University (Clemson) worked with, or at least spoke with, other organizations with manufacturing experience. The project would also likely benefit if Clemson spoke with, for instance, an appropriate national laboratory to truly understand how the process being developed will compare with standard processes.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The technical accomplishments demonstrated, from a materials and structures perspective, are good, and the effort appears to be on track relative to project milestones. The materials, fabrication, and cell testing work are of value for an exploratory effort. The progress toward achieving conductivity and performance targets is good, though it would be useful to have comparison data for cells fabricated via standard/typical fabrication techniques, e.g., tape casting and firing. Appropriate characterization methods appear to be in use. The use of the cylindrical lens with the laser sintering appears to have been a success, with target morphologies achieved. It is stated that laser scanning could significantly decrease manufacturing energy consumption, assumedly in comparison to high-temperature air sintering. On an instantaneous basis, this would seem to be the case; however, a rate needs to be assessed to validate this on a cell-area-per-time-unit basis. While sintering ovens can use a lot of energy, per-unit energy usage can be offset by the high throughput of material (in a batch oven) or the use of continuous sintering kilns.
- The presentation shows clear interactions toward scaling up the active area, while dealing with identified issues along the way. The technical solutions seem effective.
- The project demonstrated a 5 x 5 cm water electrolyzer with good performance (1 A/cm^2 and 1.3 V) at 600°C with non-platinum catalysts.
- The project seems to have yielded good results so far. Additional detail and clarity around certain aspects of the project would be useful (e.g., given all the various configurations, laser types, etc. that have been explored). The team should either describe each in very clear detail and/or do the same for the one that has the greatest potential for achieving the most project goals. Also, that best combination structure and process should be clearly compared to standard ceramics manufacturing processes in large-scale production, such as pusher kilns. There are clear energy efficiency and flexibility advantages that may potentially win over standard processes, but the Clemson team seems not to fully understand that in large-scale manufacturing, pusher kilns can lead to relatively large batches of parts being made relatively quickly once the process has been started (e.g., one batch every minute, or even hour, can lead to an effective rate of more than one part per minute). Being clear about the comparison of the laser sintering approach to conventional approaches will help in the evaluation of cost and implementation of the technique in large-scale manufacturing.

Question 3: Collaboration and coordination

This project was rated **2.3** for its engagement with and coordination of project partners and interaction with other entities.

- Currently, it does not appear that Clemson is collaborating with other organizations. However, Clemson has indicated interest in collaboration with national laboratories and industry.
- All work is done at Clemson, but the team is looking for national laboratory partners.
- Clearly, little collaboration outside of Clemson has been established to date. The principal investigator indicates that national laboratory collaborators are sought, but he did not provide much about what the objective or intent of the collaboration would be. He also indicates that industry collaborators are being sought but does not indicate which companies. It may be that non-disclosure prohibits this, but some indication of industrial interest would be of value to DOE, especially for a Technology Acceleration project.
- The project's wish to collaborate was expressed, but no evidence of concrete implementation was presented.

Question 4: Relevance/potential impact

This project was rated **3.0** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Electrolyzers are a good way to store renewable energy, and this electrolyzer had fairly good performance and low materials cost.
- The technology readiness level of this project is still low, and the level of control of the final outcome and performance is in question. The number of creative options available compensates for these concerns.
- The project could technically reduce the cost of manufacturing, but it is unclear how this will scale. The flexibility to do small and potentially large quantities is attractive, but it is unknown exactly how this approach competes with conventional high-volume sintering methods. Furthermore, it is unclear how well this technique will transfer to larger-size cells and whether the stresses experienced in the cell during rastering of the sintering laser will be exacerbated at the larger cell size. While the project has merit, Clemson would benefit greatly from discussing such matters with national laboratories and industry to gauge the types of issues that may arise in attempting to transition the methods being developed to a scaled-up implementation.
- SOEC, as a high-efficiency hydrogen production technology, is definitely highly relevant and is of high value that merits DOE support of its development. However, it is not at all clear how the fabrication methodologies currently under study, from a throughput perspective, will really contribute to reducing hydrogen production costs via reducing manufacturing costs. In particular, the rates shown in the accomplishments are extremely slow. It is very hard to understand how these technologies, unless future improvements can provide very large rate increases, could reduce manufacturing costs compared to current methods that are known to be relevant for high-volume production. This is an open question that, relative to the goals in the Technology Acceleration subprogram area, should be addressed by the project, at least from a cost analysis perspective. Relevant industry input should be used to validate any cost model.

Question 5: Proposed future work

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

- The proposed future work appears to show a logical progression forward. Industry participation seems critical, particularly input to a validated cost analysis. Some level of comparison to cells made from standard methods would be of value to the project.
- The need to demonstrate the capability at larger scale is understood, and the plans continue on the current path. There are some doubts as to whether inherent material properties, such as thermal expansion, will inherently limit the production size with the current design.
- Additional detail would be desirable to clarify what the remaining focus of the project is intended to be and why. While a focus on estimating the manufacturing cost is important, Clemson would benefit greatly from talking with the appropriate parties at national laboratories and/or industry to ensure inputs to the cost model are valid. A better comparison is needed between the laser sintering approach and conventional

(continuous process) sintering at scale. Ideally, such an analysis will also lead to a clearer vision of how the laser sintering approach will realistically scale for high-throughput manufacturing.
- The project needs to expand its area and possibly raise the current density at 1.3 V.

Project strengths:

- The team is in command of a novel new process for improved ceramic electrolyzers. It has a straightforward approach, good characterization, and low materials costs. Thin films are being made, which are more robust than thicker films. Stacking is demonstrated using this fabrication method.
- Clemson has a strong knowledge of protonic ceramic electrolyzers. The team has made good progress in developing the laser sintering method for small-scale cells.
- The team has strong capabilities and facilities related to laser-based fabrication. There is a good team at Clemson to accomplish most of the stated goals of the project.
- A clear expertise has been demonstrated, and there is awareness of the resulting composition (gradients), ultimately translating to performance results.

Project weaknesses:

- More attention should be placed on how the laser sintering method is scaled to larger-area cells in a way that keeps it competitive with conventional sintering methods. As in conventional sintering, the larger the cell size, the harder it is to sinter the cells using the laser sintering approach. More attention needs to be placed on a clear comparison of the laser sintering method with conventional sintering in larger-scale manufacturing (e.g., continuous pusher kilns). Clemson should make sure to determine how the laser sintering method will scale and compete versus the conventional methods.
- There is no industrial participation, specifically as related to the relevance of manufacturing methods and cost analysis—this should be a focus in the next year. The team may want to reach out to the high-temperature electrolysis part of the new Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium, led by Idaho National Laboratory, to discuss cost analyses and how H2NEW is going to evaluate manufacturing costs. Ideally, the team’s cost analysis would be comparable with and/or using the same methodology as is used in H2NEW. Quite frankly, it seems that this would be a much better HydroGEN project than a Technology Acceleration subprogram project.
- It appears that this project is not grasping the true 3D nature of laser sintering and tries to mimic traditional coating/annealing technology. Considering the background of 3D printing, more design solutions to interweave weak interfaces and counterbalance thermal tensions would be expected.
- The processing costs are not clear. The path to improved scalability to larger-area cells is not clear. This is a very interesting project, but it may be a “flash in the pan,” dead-ended project if these scaling and process cost issues are not successfully addressed to help get past possible limitations.

Recommendations for additions/deletions to project scope:

- This project should consider alternative options to achieve larger active surface area by designing cells in parallel, as well as in series; this way, the uniformity of a single 1 cm^2 cell can be guaranteed, and a complete pack of cells can be designed to best practices. This stays within the strengths of a small beam and a controlled outcome.
- The project should work on increasing its cell area. Nickle metal support may help prevent failure from mechanical shock. The project also needs to work on steel interconnect to minimize failure due to thermal shock. The team should address reliability when cycling (turn-on and turn-off cycles) this high-temperature device.
- Clemson should work with a national laboratory and/or industry organization to help think through the realistic barriers that will be faced in trying to scale the laser sintering approach to large-scale manufacturing. This is best done by comparison with a conventional sintering process, and such an analysis will also benefit the technoeconomic analysis work that is planned.
- No additions or deletions are suggested for this project, but one point should be reinforced: a validated cost analysis (with industry input and review), showing how these fabrication techniques can reduce manufacturing cost relative to standard methods, should be a strong focus. Observing the H2NEW cost analysis would be beneficial.

Project #TA-026: Low-Cost, High-Performance Catalyst-Coated Membranes for Polymer Electrolyte Membrane Water Electrolyzers

Andrew Steinbach, 3M Company

DOE Contract #	DE-EE0008425
Start and End Dates	10/1/2018 to 3/30/2021
Partners/Collaborators	National Renewable Energy Laboratory, Giner, Inc.
Barriers Addressed	• Capital cost • Manufacturing

Project Goal and Brief Summary

This project aims to reduce the manufacturing cost of polymer electrolyte membrane (PEM) water electrolysis catalyst-coated membranes by developing scalable roll-to-roll fabrication processes capable of producing reproducible and uniform state-of-the-art PEM water electrolysis components. These advanced processes will convert input raw materials into high-performance, roll-good components while reducing process time six-fold. If successful, this project will enable cost-effective, high-volume production processes that can meet the needs of gigawatt-scale electrolysis infrastructure.

Project Scoring

The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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.

- It seems like the participants are well-drilled in moving toward targets. The goals are clear. Sensible tasks are under way. The activities are appropriate and correct.

- With the wide range of potential parameters and objectives, the project clearly identified concise objectives and a clear plan to achieve them. These approaches were successful in that the project exceeded most of these objectives, with identified paths forward for the two metrics not met, had the project continued.
- The project provides a Gantt chart for the approach. That is good for those active in the project, but for a reviewer from outside, a discussion would have been helpful.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There is a very impressive list of successes given in chart 6. Subsequent charts are very helpful in understanding how these successes were achieved, and there is a good explanation of what the next steps should be. Roll-to-roll optical inspection is very successful. Process development of the catalyst powder rate improvement is reported, but how it was achieved was not explained. Scaling of the production process is impressive. Successful catalyst-coated membranes yield high and uniform performance—another success. NREL development of direct electrode dispersion coating appears to be moving the manufacturing process for fuel cell stack components forward, and, combined with 3M's approach, it may be time to cost the processes again. Giner, Inc., test results suggest these concepts are solving many of the problems of the industry. Cost may be an issue.
- The project exceeded four of the six project objectives and arguably met a fifth. The sixth objective was not met likely as a result of overly succeeding on the platinum group metal (PGM) loading. The results of this project will have impacts on not only the stated partners but also any of the customers of this membrane electrode assembly (MEA) supplier.
- PEM electrolyzers are on DOE's plate. There is ongoing foreign competition, both in the European Union and in Asia. It is good to have America's best on the trail as well. It is hard to understand the status of the global competition. There is positive progress evident. Making hydrogen is a DOE goal.

Question 3: Collaboration and coordination

This project was rated **3.7** for its engagement with and coordination of project partners and interaction with other entities.

- This activity included a supplier, an end user, and an independent evaluator, which captured representatives of the key commercial entities for this product. Over the course of this project, each organization completed its assignments to deliver on the contract requirements.
- It is hard to understand who does what. It seems like those participants in this activity are well-focused and supportive. Collaboration with participants seems appropriate and good.
- There is a great combination of industry and national laboratory collaboration.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Clearly, electrolyzers are a hot item right now. The age-old debate of acid/alkaline rages on. It seems like with electricity "too cheap to meter," the emphasis on efficiency (voltage) is less critical. Probably, the competition will depend more on endurance and cost. Very similar to photovoltaics, when electricity gets cheaper and cheaper, say, a few U.S. cents/kWh, many things change. Cheap electricity results in cheap hydrogen. The engineering constraints change.
- With the large range of customers for this electrolyzer MEA supplier, this activity has the potential for significant impacts on multiple customers across a range of applications, achieved by reducing both the capital and operating costs of generating hydrogen on a per-unit basis.
- The project addresses needs for high-volume production processes for PEM electrolysis at scale. This is a needed project.

Question 5: Proposed future work

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

- Future work is not clear. In the present global push, new players seem likely, so even if this project had achieved outstanding performance, such an accomplishment will have others with similar success. The project needs to team with people who have a compelling need for hydrogen, perhaps a fuel cell auto manufacturer. 3M certainly knows the “get to market” drill. There needs to be some discussion about “which market.” Certainly, should anyone be thinking about infiltration into urban environments, there need to be amendments in codes and standards. It would make sense that the regulatory regimen is documented before products hit the marketplace. A device with a 50-year lifetime needs to get it “right” quickly.
- The project discusses remaining challenges and gives potential solutions. This is very good; not many projects do this. The project is complete.
- Proposed future work is not applicable. This activity concluded on March 30, 2021.

Project strengths:

- This activity delivers an improved industrial-scale manufacturing process using very low-PGM catalyst loading, demonstrating equivalent or superior performance to the current state of the art.
- The project has good people, good organization, and supportive federal aid. The project has just who is needed for success.
- The team working on this project is exceptionally strong, as demonstrated by the success of the effort.

Project weaknesses:

- This report is rather positive. If there is weakness, it is well-hidden. The electrolyzer technology is moving rapidly. Some review of who is doing what, and how well, would have been welcome. It is hard to grade a company when this involves an analysis of its performance contrasted to others. The document provided is sort of cocky, in a good way. It shows good people doing their thing.
- Testing protocols are not as consistent as would be appropriate for this sort of activity. In particular, the location of the thermal measurement can significantly influence the accuracy and precision of the likely MEA surface temperature.

Recommendations for additions/deletions to project scope:

- It seems like the project has been successful (almost, but the targets are all arbitrary). The project needs to get a fleet of electrolyzers machining hydrogen and see just how long they last and what sort of technical problems show up. With electrochemical stuff, “accelerated” testing can never be useful, because it takes just one “hot spot,” if testing conditions are not controlled well enough, to wreck the device. Ten years of evaluation needs to take ten years.
- DOE should meet with the researchers and ask them what the next steps should be to move the manufacturing technology forward.
- This question is not applicable, as the project has concluded.

Project #TA-027: Catalyst Layer Design, Manufacturing, and In-Line Quality Control

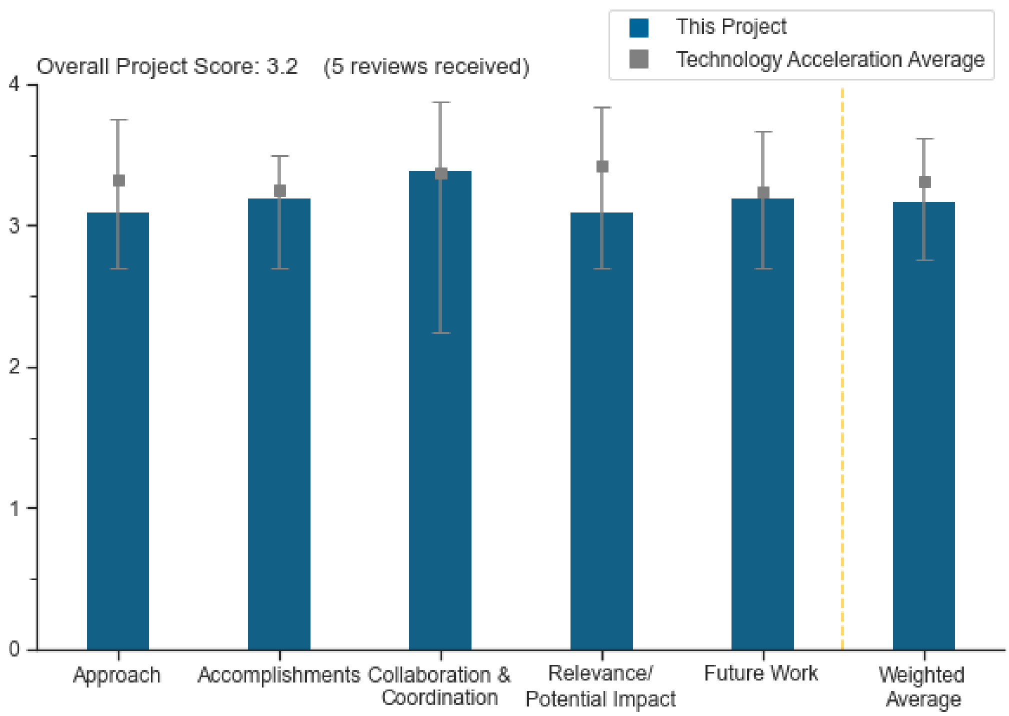
Radenka Maric, University of Connecticut

DOE Contract #	DE-EE0008427
Start and End Dates	10/1/2018 to 11/30/2021
Partners/Collaborators	Nel Hydrogen, Mainstream Engineering
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Manufacturing

Project Goal and Brief Summary

This project will demonstrate the capabilities of reactive spray deposition technology (RSDT)for direct catalyst deposition and fabrication of large-scale membrane electrode assemblies (MEAs). The project aims to produce MEAs with 10% of the catalyst loading of commercially available MEAs and stability for over 1,000 hours of use, greatly reducing the cost of hydrogen electrolysis.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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 approach appears to lay out a logical plan toward validation of a novel fabrication technique for catalyst-coated membranes. Scaling the technique from active areas of less than a hundred to hundreds of square centimeters is an important aspect for the Technology Acceleration subprogram area. Also, exploration of using the technique to fabricate a recombination layer is important, as this is an open question for electrolysis MEAs. Including a commercial polymer electrolyte membrane (PEM) water electrolysis supplier enables strong inputs as to the technique's viability, and including quality inspection is appropriate to help ensure high yield, should the technology be adopted by industry. Overall, the work is appropriate for a laboratory fabrication technique that may have some MEA formation advantages. The technique's viability as a true high-volume production technique is a large question, and it should be addressed in the future to truly assess the usefulness of the method. The principal investigator stated that unit fabrication time was on the order of two hours, potentially reducing to 15 minutes with higher jet speeds. Depending on the other potential benefits of the technique to create a high-performing cell, this may not be enough benefit for the cost. The industry participant can presumably give guidance on the needed rates for high-volume production.

- The reactive spray method is meant to enable achieving the target loadings and meeting durability targets, but it is hard to see how this method ever leads to a manufactured product or meets overall manufacturing cost targets, as the reactive spray deposition process is slow compared to continuous roll-to-roll (R2R) coating methods. In terms of developing an MEA manufacturing process that could translate to industrial production, this project misses the mark, and it is not clear how a stack produced with reactive spray deposition would be able to produce $2/kg hydrogen. It is a shame that so much emphasis and so many milestones focus on developing the spray deposition process for large-scale coatings, as this does not seem to leverage the capabilities of reactive spray deposition. Overall, there are some good parts to this project in terms of catalyst materials development, but the focus on large-scale MEA production is misplaced and detracts from what is the most compelling aspect of the project, which is the ability of reactive spray deposition to tailor IrO_2 particle size. This should be more of a focus.
- Clearly, the task is challenging. The "game" has become more intense now that the well-documented federal goal is to create hydrogen at the price of $1/kg or less. The materials—perfluorosulfonic acids (PFSAs), platinum, and solubilized PFSAs fabricated by a flame spray process—are in no way novel. One would think the first task is to examine existing PEM electrolyzers, perform a global search, and understand what others have and how that hardware deals with technical issues. The technical approach might be designed well for a pioneering situation. There are other devices, and it would be appropriate, one would think, to learn their tricks. There is a general theme of discovery rather than a theme of understanding. One interesting issue is that there is no discussion about repeatability, i.e., whether all MEAs perform at the same level, and if not, why not. The flame spraying also seems difficult to control. It is unclear whether the spray is actually homogeneous.
- The project uses a straightforward approach. It is not clear as to what porous transport layers are being used in the electrolyzer. The approach toward optimizing the process, although Edisonian, is sufficient.
- The approach was a series of Gantt charts, which gave the project status but not much explanation. A discussion of why the approach is taken would be most helpful.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There is good progress toward objectives, given delays and laboratory restrictions associated with COVID-19. Stability of performance over time of the 86 cm^2 cells looks promising so far. Further exploration of causes of the observed degradation should be pursued, as the structural stability of the electrodes fabricated with the new technique must be understood. The ability to coat the thin Nafion™ layer is interesting, as this tends not to be easy to do with standard spray methods. From a performance perspective, the polarization data shown on slides 9 and 13 do not seem to be that great, though not all the details of the cell build and testing conditions are provided. Using the same test, the project should perform a comparison of the flame-sprayed electrode performance to that of a standard electrode (e.g., one fabricated by the industry partner's current methods, not just the large flame-sprayed electrode to the small flame-sprayed electrode). The progress on the optical loading quality diagnostic is good to see and is consistent with other electrode loading studies using the same method.
- The project goals are clearly stated. There is mention that project results will be compared with a "commercial" specimen. The goal of more than 1,000 hours is described. Importantly, the Pt loading is just 10% of something not stated. The DOE target recently redone is one of cost, not performance. As the cost

of electricity continues to plummet, the economics necessarily shift. There are certainly signs of progress, as the Period 1 milestones document. The performance data over 5,000 hours shows performance loss, and there is no indication that the rate of loss with time is decreasing. Fifty microvolts/hour seems rather "non-commercial." The precious metals, including Ir, tend to be moving around, which is not unexpected.

- Stable performance for 5,000 hours was outstanding. Polarization data are very impressive. It is unclear whether hydrogen crossover after 5,000 hours will be a problem. There is anode and cathode degradation in post-mortem, with particles in the membrane and cracks in the recombination layer. It seems like these are problems that may need resolution, but this was not discussed. Fabrication via RSDT looks very promising; perhaps it is ready for a detailed cost analysis by a third party. In situ Raman spectroscopy looks promising for quality control (QC). It would be good to know if RSDT can be used in R2R processing or if the batch is limited.
- The work is appropriate toward meeting the outlined milestones/goals of the project. However, the results do not make much progress toward DOE goals for technology acceleration because reactive spray deposition seems poorly suited to large-scale manufacturing. Results clearly demonstrate the ability to achieve target loadings of Ir and Pt with good uniformity. Stability targets have been achieved. It is hard to critically evaluate the MEA performance. Generally, the MEA performance seems low, but there are no higher-load baselines presented to make comparisons. Therefore, it cannot be determined whether these lower loadings actually lead to acceptable performance. Additionally, Alia et. al. (https://iopscience.iop.org/article/10.1149/2.0231915jes/meta) were able to achieve less than 1.9 V at 2 A/cm^2 with 0.1 $mgIr/cm^2$ loadings, whereas MEAs in this presentation on slide 13 are above 1.9 V at less than 1.5 A/cm^2. Given that there is an extra 25 µm of membrane due to the added N211 membrane, it would have been beneficial to show high-frequency-resistance-corrected polarization curves to make comparisons to other published results easier. At the next DOE Hydrogen Program Annual Merit Review, there should be polarization curves comparing the low-loaded MEAs prepared in this project and a higher-loaded baseline.
- There is good performance, stability, and scale-up, although not quite as high of performance as in some of the work coming from the Hydrogen from Next-generation Electrolyzers of Water (H2NEW) consortium and other techniques. The recombination layer is good for crossover, but it is unclear whether it is stable or whether it gets Pt migration or enhanced membrane degradation. It is unclear what causes the cracks in the recombination layer. The use of underlayers and mitigation shows promise. It is not clear how the porosity of the layers is controlled.

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.

- Teaming with industry is very appropriate for the Technology Acceleration subprogram, which is good to see. Inclusion of the PEM water electrolysis manufacturer is very important. However, the level of guidance that the electrolysis manufacturer is providing is not clear. This should be indicated in more detail in the next reporting period, especially regarding the veracity of the method for high-volume production, as well as acceptability of performance. Including the QC technology, the provider demonstrates that the team is looking ahead to implementation of the technique.
- Collaboration between UConn and Nel Hydrogen seems good, with materials generated at UConn being transferred to NEL Hydrogen for in situ testing. Mainstream Engineering seems similarly well-engaged. There have been numerous site visits.
- Industry and the university are working together for successful research and development.
- There is a good team and seemingly good communication between the partners.
- The management is hard to understand. It seems that most of the scientific work is done at UConn. Testing is done at Nel Hydrogen and Mainstream Engineering. Flame spraying is a commercial endeavor and has seen extensive use in other DOE projects. Most likely the management is just fine, but the presentation certainly was not convincing that was so.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Hydrogen production from electricity will be a major business globally. Any significant advance will be adopted in the marketplace. Yes, the goals are fully aligned with DOE research, development, and demonstration goals. There is potential here. However, the game is still just on, and “significant progress” may be difficult to achieve.
- This project addresses the key issues of capital cost (but needs third-party analysis), system efficiency, and manufacturing.
- The need for demonstration of scalable electrode fabrication methods for PEM water electrolysis MEAs is high, so the work certainly addresses strong DOE and industry needs. The applicability of the specific fabrication method to rates actually needed for high-volume production must be validated in some way. Also, the team should think about trying a thinner membrane, as the trend is certainly away from N117 toward 90–120 µm membranes (in the near term).
- Lower Ir and Pt loadings have been achieved. It is not clear that these lower loadings result in acceptable MEA performance, as they were not compared to the higher-load baseline. Results demonstrate a successful hydrogen crossover mitigation strategy to ensure safe electrolyzer operation. The MEA production speed of the reactive spray deposition process is too slow for high-volume production, so this technology might never be capable of meeting the economies of scale needed for low hydrogen production costs. If this project had been designed as a materials development project and scoped accordingly, it would have been rated it higher. It just seems poorly aligned with the objectives of the Technology Acceleration subprogram.
- The technique is interesting but needs to demonstrate it can go to lower loadings, as the state of the art is to move to much lower loadings. The project is not clear as to the throughput rate or cost of the process.

Question 5: Proposed future work

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

- There is emphasis on deposition of Nafion materials on the surface of the electrodes, and that is of interest. However, Nafion solubility has much to do with molecular weight and tends to move around. This technology is challenged by expectations of durability, perhaps unreasonable ones. The current status resulted in complex architecture, which is thought to be useful and stable. There need to be efforts to investigate polymers moving. It would be interesting to utilize segmented cells and check to see if the current density is uniform across the device surface. There needs to be some closure on the environmental implications of using Nafion polymers when those toxic compounds ooze into the environment. There needs to be some real care in knowing exactly where the Nafion is. The crossover issue is also a concern. There is a tradeoff with pressure (across the membrane) and hydrogen loss. Some modeling on crossover and operating pressure might be informative.
- The remaining challenges and barriers are clearly identified. Future work addresses most issues. The project should have a task that addresses formation of catalyst particles in membrane.
- Future work is fine, as the project is winding down, although seeing the feasibility of lower loadings would be interesting.
- Two tasks need to be performed: (1) comparison of the flame-sprayed electrodes to the industry partner’s standard electrodes under the same test in terms of polarization performance and (2) some kind of assessment of the fabrication technique’s viability for high volume, based on DOE’s, H2NEW’s, or an industry partner’s volume manufacturing analysis or estimates.
- How to rate and comment on the future work presents a conflict. Based on the milestones, the future work seems reasonable, given the design of the project, and is consistent with meeting upcoming milestones. However, as has been previously stated, there is not much value to the community for this project to focus on making 680 cm^2 MEAs, given the slow coating speeds. There should be more future work studying impacts of IrO_2 particle size on performance and durability. This seems like it would provide more value to the low-temperature electrolysis community and catalyst manufacturers.

Project strengths:

- The most compelling results of this project are the results related to IrO_2 particle size that were not presented in the slides but were discussed during the question-and-answer session. More studies related to decreasing particle size to increase electrochemically active surface area and catalyst utilization would be very beneficial to enabling reductions in precious metal loading in electrolyzers. More emphasis on this for the remainder of the project would be good to see. These studies could be very useful to the community in guiding improvements in catalyst design to enable high performance at low loadings.
- There is a certain optimism in the presentation. Good people are making progress working on, all things considered, necessary technology for the global community. There are good concepts. This is a work in progress.
- There are strong capabilities for flame spray development and advanced characterization at UConn. There is a good team, including important industry partners.
- The reactive spay technique is promising. The scale-up is being realized, and there is a good team.

Project weaknesses:

- This project is poorly categorized as Technology Acceleration, and the work is not focused on the strengths of this coating technology. The strength of this reactive spray is in materials development (catalyst particle size optimization, Ir/IrO_2 ratio, and MEA design), not manufacturing or technology acceleration. The presenter commented that reactive spray deposition could achieve one 680 cm^2 electrode in 15 minutes. That equates to about 45 cm^2/min. Continuous R2R coating methods are easily capable of square meters per minute and even square meters in a matter of seconds, in some cases. Some old work from 3M (http://www.nature.com/doifinder/10.1038/nature11115) indicated that production rates of tens of square meters per minute are needed for modest production of fuel cell vehicles, and presumably similar rates are needed for gigawatt-scale electrolyzer production. Therefore, it is not clear how this reactive spray method will ever be able to achieve the rates needed for mass production. This project should have focused on more closely exploring IrO_2 catalyst particle size and its effects on materials utilization, performance, and durability. This seems like very interesting work, and there would be much value here. Ultimately, this project suffers because it was funded as a Technology Acceleration project. It would have been a much better HydroGEN consortium seedling project focused on catalyst development. Had this been a materials development project, it would have been given higher ratings because the researchers are doing good work toward meeting their milestones.
- It seems like there is good progress, but perhaps there need to be some other experiments that will be useful for understanding.
- The project possibly needs to have a discussion with NREL about integrating RSDT into R2R processes.
- The team needs to compare the method under development to standard methods capable of high-volume production.
- The practicality for high throughput and lower loadings is not clear.

Recommendations for additions/deletions to project scope:

- The project should focus more on materials development and optimization. The presenter mentioned that the team is observing higher materials utilization at low loadings, thanks to the particle sizes, which are smaller than those in standard catalyst materials. It seems like, with reactive spray deposition, the UConn team could make MEAs with a variety of IrO_2 particle sizes without having to do a great deal of lengthy wet chemical IrO_2 particle synthesis to get catalysts of different sizes. If this work can show that a certain particle size is optimum for material utilization and durability, then this could be translated to mass-scale materials synthesis efforts and could be integrated into MEAs using higher throughput coating methodologies. This is where there could be some technology acceleration. This is where this project would provide much value. It is recommended that some MEAs containing these novel catalysts be tested by H2NEW to compare to that consortium's baseline MEAs. Alternatively, UConn should ensure that the project's control sample can match the performance of the H2NEW baseline, once that information is published. Because of the low coating speeds of the reactive spray deposition process, there is no value in making such large MEAs. Making one 680 cm^2 electrode in two hours does not add much value when screening different catalyst particle sizes. It seems like optimization of Ir particle size could be done at 25 cm^2 or below and not require such lengthy coating times.

- There are probably enough positive results to think of stacks at about the 25 kW sort of scale. Ten cells are sufficient. There is much literature about Ir anodes. The project should pay attention to the environmental issues and have answers ready when they are raised.
- The team should compare performance and potential throughput to standard methods shown to be able to fabricate PEM water electrolysis electrodes at high rates.

Project #TA-028: Demonstration of Electrolyzer Operation at a Nuclear Plant to Allow for Dynamic Participation in an Organized Electricity Market and In-House Hydrogen Supply

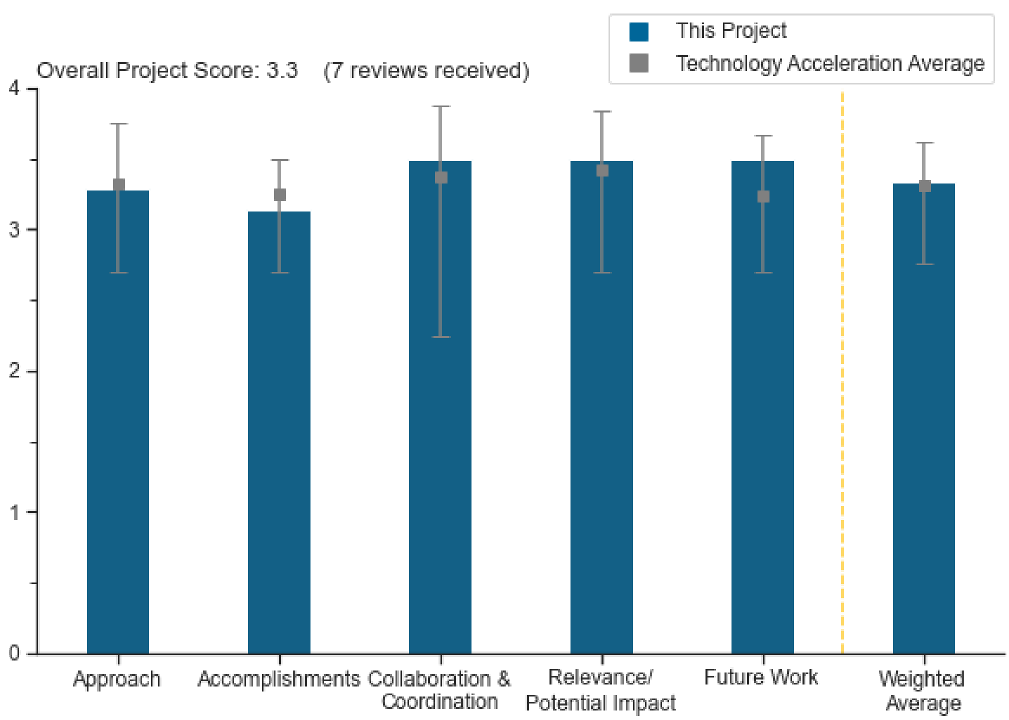
Uuganbayar Otgonbaatar, Exelon Corporation

DOE Contract #	DE-EE0008849
Start and End Dates	10/1/2019 to 4/1/2023
Partners/Collaborators	Idaho National Laboratory, National Renewable Energy Laboratory, Argonne National Laboratory, Nel Hydrogen
Barriers Addressed	• Site selection: What are the criteria for site selection? • Regulatory: What are the relevant regulations that affect nuclear hydrogen production? • Market-related: What is the effective electricity price that the electrolyzer pays?

Project Goal and Brief Summary

This project aims to demonstrate cost-effective supply of in-house hydrogen consumption at an Exelon nuclear power plant. A 1 MW polymer electrolyte membrane (PEM) electrolyzer and supporting infrastructure will be installed at an Exelon plant, providing an in-house supply of hydrogen. Researchers will also simulate the scale-up of electrolyzer participation in power markets. The project will demonstrate the potential for hydrogen production to increase the value of nuclear power plants, both by supplying plants' onsite hydrogen needs and by providing hydrogen to regional markets.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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 integration of an electrolyzer with a nuclear power plant for onsite demonstration is meaningful. The integration of hydrogen production with a regional hydrogen end user is also commendable.
- Project objectives are clearly identified as installing an electrolyzer, providing in-house hydrogen, and simulating operation of a larger system. Key barriers are identified as identifying criteria for site selection, regulations in play, and an effective electricity price that the system must pay. The approach uses a combination of research and demonstration to verify the dynamic operation of a 1 MW electrolyzer at a nuclear power plant, review aspects of regulation and safety, and perform an evaluation of scale-up. The approach for the economic feasibility assessment is not described well. Argonne National Laboratory (ANL) estimated local demand for hydrogen for one site (presumably prior to the New York site being identified), but it is unclear what approach will be taken for estimating cost and performance targets (before transportation costs are even considered).
- The project has clearly articulated goals, objectives, and challenges. Progress toward these objectives is on or ahead of schedule and is well-presented in the material. The project is also well-defined and appears to be feasible on the timescale established. However, the presentation does not demonstrate how achieving these objectives will address critical barriers for the U.S. Department of Energy Hydrogen Program (the Program). This information may be available but could have been brought out more clearly in the presentation.
- The approach is clearly identified and seems likely to address the needs and barriers toward which the project is targeted. As the presenter noted, the approach could be improved by exploring the potential to supply hydrogen for different onsite and offsite use cases. However, the project, as scoped, makes sense as a first step in this line of empirical demonstration and research.
- This approach seems to address many of the barriers to integrating hydrogen production at a nuclear plant, at least in terms of small-scale initial barriers.
- A methodical, thoughtful approach was used. The research element is not clear, though the presenter claimed it to be. This is a demonstration project, and as such, the presenters need to be transparent on lessons learned and best practices. There is no task or milestone that includes lessons learned, best practices, or other dissemination of information.
- The project addresses the need to explore issues around siting an electrolyzer at a nuclear facility. However, no clear plans to demonstrate how electrolyzers could interact dynamically with nuclear operations are shown.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made excellent progress with the identification of a site with hydrogen and switch gear infrastructure. The Exelon partner agreed to move forward with the pilot, an identified source of hydrogen. National Renewable Energy Laboratory (NREL) and Idaho National Laboratory (INL) partners have made excellent progress conducting simulations of electrolyzer operation and dispatch, including developing the front-end controller (INL) and completing the factory acceptance task (NREL). ANL has made good progress toward addressing market-related questions prior to starting its economic analysis task. The analysis progress (slide 7) was not clearly linked to the question presented on slide 2, “What is the effective electricity price that the electrolyzer pays?”, for the base case of power generation.
- Goals and milestones for this project are well-articulated, and progress toward these goals seems strong. There is little to criticize here.
- Progress toward project objectives has been made and measured against go/no-go milestones. In some areas, specific performance indicators (e.g., factory acceptance tests and voltage degradation thresholds shown on slide 8) are included in addition to these more qualitative measures. As noted in question 2, the linkage of these efforts to critical barriers for the Program could be more clearly articulated.
- The progress seems fairly on track, especially given the COVID-19 pandemic.

- It is confusing that the 750 kW stack was installed in NREL, which is far from Exelon's nuclear plant (slide 8). Major progress has not been seen in the past year for such a high budget ($13.8 million). The project spending should be reported on slide 2.
- There is a concern that there is still substantial regulatory uncertainty so close to the go/no-go decision.
- The reported progress seems modest for the team and budget. It is not clear whether the market demand analysis took into consideration the hydrogen price or what the hydrogen selling point would need to be for the market to materialize. There is no analysis on the quantity of greenhouse gas emissions that would be displaced by the hydrogen. It is unclear whether the front-end controller will be useful for other installations or whether a new controller will need to be designed and calibrated for each site. The balance-of-plant considerations are not reported. For example, it is unclear how hydrogen will be stored or whether a compressor will be used.

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.

- Outstanding coordination is described across multiple portions of the large Exelon Corporation (Exelon) as well as well-defined research and pilot teams (as shown on slide 12). The project's focus on coordination with partners and outreach to other interested groups (also on slide 12) is extensive and notable.
- There is excellent collaboration with partners contributing to the project. Better alignment of the ANL task with NREL's and INL's work may be necessary to ensure the economic analysis and electrolyzer simulations are assuming the same operation cycles.
- There is excellent collaboration with national laboratories and an electrolyzer company.
- It is encouraging to see the Exelon team actively engaged with multiple national laboratories and the electrolyzer vendor.
- Collaboration seems good overall. It might be worthwhile, though, to explore collaborations with potential hydrogen end users who might procure the hydrogen produced by this demonstration project.
- There is good cross-laboratory coordination, but it would be good to collaborate with the U.S. Nuclear Regulatory Commission (NRC). (This might already be happening, but it would be good to report on that next year.)
- There is good collaboration between the entities. It is not clear whether the project has engaged the Center for Hydrogen Safety in its work. If the researchers have not done so, they should use this important resource.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is highly relevant and supports and advances Program goals. It investigates potentially impactful methods of hydrogen production and use. Further, it does so with real empirical demonstration of the technology, from which much will be learned about the feasibility of this production strategy. This will be critical to determining whether hydrogen production at nuclear plants is a strategy that may be viable at commercial scale.
- The project plays a critical role in demonstrating the use of nuclear power for generating carbon-free hydrogen and using that hydrogen for peak power generation and other end uses.
- This is highly relevant and is the vision of H2@Scale. The relevance can be increased with intentional efforts on lessons learned and best practices. These could easily be reported on the H2Tools.org website that the DOE supports. The relevance can be increased by identification of codes and standards that are particularly onerous or in need of updating.
- The potential impact is great and definitely supports the H2@Scale vision.
- This project is very relevant to the Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.
- As with other nuclear-related projects, this effort to develop both supply and demand modeling for a new source of hydrogen has the potential to advance progress toward Program goals (though, as noted above,

linkage to critical barriers could be clearer). It is at an early stage, so it is challenging to characterize the impact as advancing or significantly advancing.

- This is an important early-stage nuclear–electrolyzer integration project. However, since the electrolyzer operation will be largely disconnected from nuclear operations, the impact on demonstrating the nuclear-to-hydrogen pathway will be limited.

Question 5: Proposed future work

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

- Planned future work seems likely to lead to project success. As the presenter noted, the approach could be improved by exploring the potential to supply hydrogen for different onsite and offsite use cases. However, the project, as scoped, makes sense as a first step in this line of empirical demonstration and research.
- Progress and future work are very well-defined (e.g., slide 13). Given the recent initiation of the project, the future work presented in the main portion of the slides is within the scope of this project. Additional materials (slide 16) provide thoughts on future scale-up and fleet hydrogen use that were not discussed in detail but could advance the Program.
- This is an obviously involved plan. With respect to nuclear regulations, it appears to be on target.
- This is outside the scope of this project, but it would be good to see future work leverage the learnings here and work on larger (and high-temperature) electrolyzer integration.
- Future work is mostly clearly described. Some future work, such as DOE reporting and attending conferences, is quite trivial. The original plan is to install a 1 MW electrolyzer next to nuclear power, but slide 13 changed it to a simulated nuclear power plant.
- The future work details how to demonstrate the 1 MW system. It is not clear whether the future work would include identification of how a 100 MW or 500 MW system could be integrated into a nuclear site.
- Project milestones and future work are well-aligned. Risks associated with the project are not clearly stated, and a risk mitigation plan is not clearly discussed.

Project strengths:

- The project has strong project management, dedicated staff at Exelon for both research and pilot project scopes, and strong external communication with state and local governments, as well as presentations to nuclear societies. There is strong collaboration and participation by partners and progress with a site toward demonstration, and a dedicated hydrogen supplier has been identified.
- The project includes clear understanding of the many interfaces (internal and external to the project) to make it successful. The engineering detail completed to date is significant and reflects progress on or ahead of milestones. The presentation slides themselves are very clear and laid out well.
- The learnings regarding compliance with regulations and safety, codes and standards will be important to enabling larger-scale production of hydrogen at nuclear power plants.
- There is strong relevance to Program goals. There are well-articulated goals and milestones.
- The project uses the combined capabilities of the team of two industry leaders and three national laboratories.
- This is a meaningful electrolyzer–nuclear power plant demonstration project, if it succeeds. The team is very strong, with complementary expertise.
- This is a well-funded project with a solid team. It has the potential to have a significant impact.

Project weaknesses:

- The project could benefit from a more detailed consideration of end uses. The market demand analysis is a strong start, but a good next step would be to conduct outreach with potential users to define what might be needed to establish these relationships.
- Given the strong progress articulated in the presentation, additional information of any risks to completion could help the project sponsors understand the remaining work.
- There should be a formal and public report detailing some of the learnings, especially with regard to safety, codes, and regulations.

- The electrolyzer is being tested with dynamic signals to see how it can handle ramping, but it is not clear what the real-world cases are on which this work is based. It is unclear what onsite hydrogen consumption is or where decision points are for onsite versus offsite use of the hydrogen. It is unclear what approach will be taken for estimating break-even costs or how the economic analysis will be coordinated with the information and knowledge developed in other tasks.
- There is no plan to explore dynamic operation of the electrolyzer based on local market demands and nuclear plant supply. The project should identify specific hurdles for a large-scale electrolyzer system (e.g., 100 MW) at a nuclear facility and make recommendations for how to address those hurdles.
- The project’s milestone table does not show quarterly milestones (it jumps from month 1 to month 9) or milestone numbers. Some major milestones have not been explained well enough (how and when they were completed). It is unclear what the go/no-go milestones due on July 30, 2021, are. It is not clear where the 1 MW electrolyzer is supposed to be installed, whether at NREL or Exelon. It is not clear why a simulated nuclear plant, instead of real power plant, will be used.
- There are no lessons learned or best practices in the scope of milestones. The project may benefit from engaging the Hydrogen Safety Panel and some of the safety, codes and standards experts who have designed filling stations and/or modeled releases of large volumes of hydrogen.

Recommendations for additions/deletions to project scope:

- To the extent possible in future cycles, the project participants and DOE are highly encouraged to pursue the onsite and offsite hydrogen use cases identified as 4, 5, and 6 on slide 4 of the presentation. This would both be a logical extension of the current work and highly valuable as a collaborative demonstration of the potential for nuclear plants to supply hydrogen to other users.
- If it is not already included within the scope, the project may benefit from identifying what information or technologies are needed before “scale-up” (as described in slide 16) that are not covered by this work. Specifically, the response to multiple audience questions on regulatory challenges was fairly general (this is a first-of-a-kind project, so there is some uncertainty), and this may need further attention. As a note, these thoughts provide this reviewer’s personal perspective on the presentation provided at the Program Annual Merit Review and do not represent any endorsement or approval by the NRC on this or any future project.
- Lessons learned or best practices should be included in the scope of milestones. There may be a benefit to engaging the Hydrogen Safety Panel and some of the safety, codes and standards experts who have designed filling stations and/or modeled releases of large volumes of hydrogen. A design for a 100 MW or 500 MW electrolysis capability could be done to better understand what it would take to implement at that scale.
- The project should evaluate the need for onsite hydrogen storage and possibly a compressor beyond the existing storage tank. The team should size the storage system and look at its operation based on the electrolyzer operation and market analysis.
- Additional tasks likely are not feasible within this project budget and scope, but it would be good to see larger projects with high-temperature electrolyzers funded in the future.
- With the help of a partner, the project should test pump capabilities against performance needs under different heavy-duty refueling station scenarios.
- The project can have more executable milestones to ensure good progress quarterly.

Project #TA-030: Demonstration of Integrated Hydrogen Production and Consumption for Improved Utility Operations

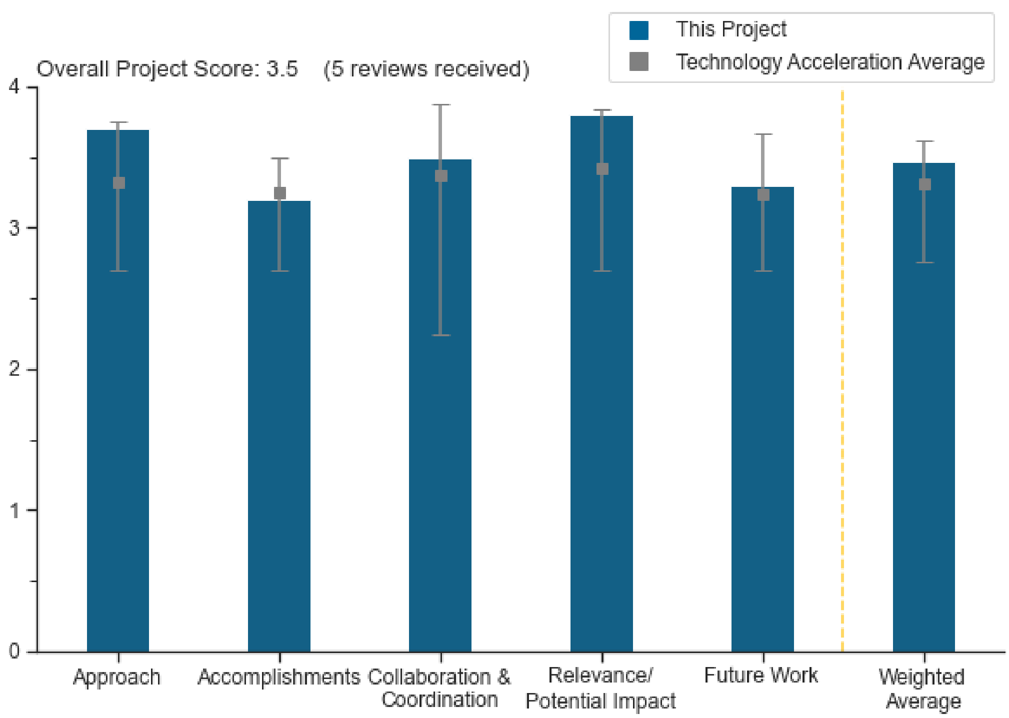
Monjid Hamdan, Plug Power Inc.

DOE Contract #	DE-EE0008851
Start and End Dates	5/1/2020 to 4/30/2023
Partners/Collaborators	Orlando Utilities Commission, OneH2, Inc., University of Central Florida, National Renewable Energy Laboratory
Barriers Addressed	• Systems integration • Reliability • Cost • Performance • Efficiency

Project Goal and Brief Summary

The project goal is to demonstrate grid-level hydrogen assets to bolster the hydrogen economy across sectors. Using grid-integrated hydrogen assets, a system operator can leverage variable renewable sources to produce hydrogen, which can then be stored or deployed for use in fuel cell electric vehicles (FCEVs), emergency back-up power, or grid operations. The project will manufacture and assemble an integrated system that incorporates polymer electrolyte membrane electrolysis for hydrogen production, compressed hydrogen storage, hydrogen dispensing for FCEV refueling, and stationary fuel cells for electricity generation.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project team provided an excellent presentation of its approach and the way in which task leads will get the work done. The approach has a strong focus on optimization of electrolyzer units with storage, the grid, and FCEVs, as well as stationary end uses. The approach addresses key technical barriers including systems integration, cost, performance, reliability, and efficiency. The approach for taking data from the Orlando Utilities Commission and elsewhere to model dispatch and grid-scale services for electrolyzer operation was compelling.
- The approach represents demonstration of an integrated solution from generation to end use, which is important for providing confidence to the market for commercial projects. Another interesting component of the project is cybersecurity analysis, which is likely to be an important consideration, based on recent ransomware attacks in other industries.
- The approach speaks to Plug Power Inc.'s experience in carrying out projects, and the equipment is off-the-shelf. The description of the project has a number of moving parts, but they seem well-connected.
- Overall, the project approach seems effective. The project goals and barriers to address seem clear. The project appears well-suited to address the barriers identified. One area that could be improved is to articulate how the project will capture and report challenges to achieving the $2/kg hydrogen cost target. While project participants clearly articulated a modeled path to sub-$2/kg hydrogen, uncertainties and potential roadblocks were also articulated during the presentation. It is not clear how the project will benchmark real-world results against these modeled conditions or how the project will analyze performance against these benchmarks and articulate lessons learned. Developing and articulating a clear plan for doing so would improve the project's likelihood of success and ultimate value to DOE.
- The approach seems solid, although it would be good to hear a bit more about how the team is going to catch up on their Year 1 milestones and keep the project on track.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Excellent progress has been made toward completing the technoeconomic analysis (TEA) and developing a path to <$2/kg. There is a very clear presentation of bottlenecks and the way in which the TEA task identifies bottlenecks to a <$2/kg hydrogen target. Good progress is being completed toward developing economic dispatch models.
- The team and partners are motivated to see this through, even with the delays due to the acquisition of Giner ELX. Equipment has been delivered, procurement has started, and design specifications/details are well on their way. Some of the barriers may be out of the team's control, but the remaining project partners have the capabilities and are motivated to complete this work, contingent on funding.
- The project progress against the identified performance indicators seems to be strong. The participants have proven themselves flexible, for example, when pivoting from fueling light-duty vehicles to medium-duty bucket trucks. One area for improvement would be a more detailed description of cost modeling methods. An explanation of what it is about these methods that gives the participants confidence that they have demonstrated a feasible and realistic path to sub-$2/kg hydrogen could have been articulated better in the presentation and subsequent question-and-answer period.
- The project seems somewhat behind schedule as an understandable result of the Giner ELX acquisition.
- The project has just started, so it is difficult to assess accomplishments this early.

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 team is making good progress on Year 1 milestones, and each requires close collaboration and coordination with project partners.
- The team covers a good range of disciplines, from research to hardware to analysis to utility expertise.

- The use of partnerships in this project appears to be strong. There are no criticisms here.
- This portion of the project seems very good; there is a nice team of partners with complementary strengths.
- The flow of work between partners in the three years of the project is clear and logical. More integration of industrial partners into the TEA modeling would be important.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is very necessary, as it is demonstrating the role of electrolyzers in hydrogen production for grid energy storage and load management. Initial analyses of production and storage needs that are linked to the sizing of equipment illustrate the potential to use a similar approach to design and implement such an application at a larger scale.
- The project supports H2@Scale concepts and is an important part of showing the feasibility of this vision.
- The development of a utility control architecture to dispatch the system for both power and hydrogen sales is critical for achieving <$2/kg hydrogen.
- This is a well-targeted project to work toward integrated renewable and hydrogen systems for reduced hydrogen costs—a key goal of the DOE Hydrogen and Fuel Cell Technologies Office.
- The project could benefit from some clearer articulation of uncertainties regarding hydrogen costs. Identifying these potential barriers up front and then tracking progress against them would be valuable to DOE as the Department considers future projects of this type. The participants may have a plan to do exactly this, but if so, it was not well-described in the presentation. This minor criticism aside, the relevance and impact of this project are clear. This is a highly valuable demonstration project for the DOE Hydrogen Program.

Question 5: Proposed future work

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

- The next steps for Year 2 are clearly laid out and, once implemented, should enable a robust demonstration and analysis.
- The proposed future work is well-thought-out and addresses the key identified barriers.
- The future work identified in the presentation seems logical and well-planned. The key risk to success seems to be whether the project can deliver hydrogen at the target cost. The project could benefit from scenario planning around the greatest potential barriers to achieving this target. Otherwise, the project seems well-positioned.
- It seems like a logical set of next steps. Other than the potential difficulty in obtaining an FCEV to test, it would have been effective to present a little more about other potential barriers/issues, such as integration of the various systems.
- Cybersecurity analysis is listed as part of the project as “in process” with 0% complete but is not listed in future work. Other aspects build on the project start and specifically call out showing a pathway to $2/kg in the analysis.

Project strengths:

- This is an ambitious project to test an interesting concept for integrating hydrogen systems with high penetration of renewables. The prime has a proven track record of real-world deployments. Overall, the project team looks fairly strong.
- Despite setbacks, the redistribution of the project’s scope and progress made are impressive.
- There is good use of partnerships and flexibility in the face of project challenges.
- The project lead and partners are experienced and motivated. Additionally, the project is located in the sunshine state, Florida.
- The strengths include overall team and project scope, which seems to be off to a good start after novation delays.

Project weaknesses:

- The preliminary design may not be scalable to other locations or fuel cell and storage architectures. The presentation did not discuss adequate critical analysis of assumptions and inputs in modeling the path to <$2/kg hydrogen. It would be important to understand the limitations of the models and cost forecasts.
- This project is lacking a sufficient off-take vehicle for hydrogen fuel. It is suggested that the team look for a transit agency or college campus nearby that may be interested in a bus pilot.
- The project is somewhat behind on Year 1 milestones. A clearer plan for catching up on those milestones and expectations for Year 2 work would be useful.
- The project could benefit from more thorough uncertainty analysis and planning.

Recommendations for additions/deletions to project scope:

- The project should conduct further analysis of institutional, utility, policy, regional, economic, and regulatory impacts on optimization of system integration. Also, more integration of the TEA with the individual system units and site architecture is needed, specifically with how the select site design is representative and scalable.
- For market analysis, the team should extrapolate findings from this project to model economics and feasibility of larger-scale deployments.
- Uncertainty analysis should be incorporated explicitly into TEA and planning for future work.

Project #TA-032: Electrolyzer Integrated Modular Nano-Array Monolithic Catalytic Reactors

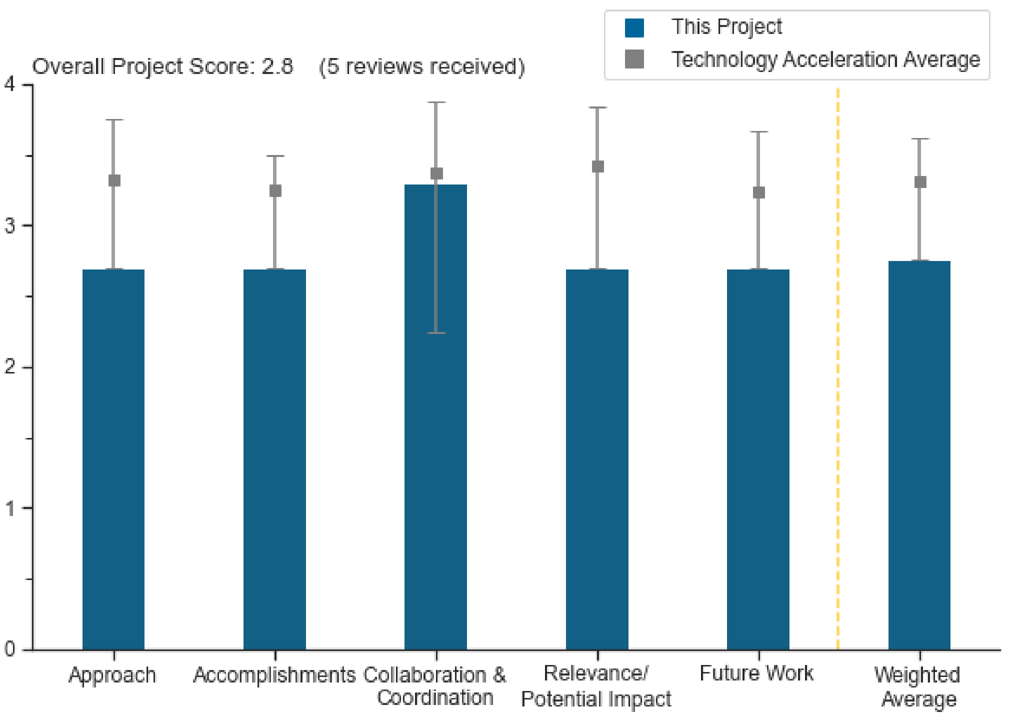
Trent Molter, Skyre, Inc.

DOE Contract #	DE-EE0008423
Start and End Dates	10/1/2018 to 12/31/2021
Partners/Collaborators	University of Connecticut, Connecticut Center for Advanced Technology, Advanced Manufacturing LLC, University of Tennessee, Knoxville, Stony Brook University, Brookhaven National Laboratory
Barriers Addressed	• High cost of hydrogen and fuels due to reactor expense/efficiency—particularly relevant when integrated with renewables • High cost and low reliability of gaseous and liquid hydrogen fueling infrastructure • High cost to convert CO_2 to chemicals and fuels using intermittent renewable power • Hydrogen fueling safety

Project Goal and Brief Summary

The project aims to demonstrate methanol synthesis with cost-effective hydrogenation reactions under low-temperature (<200°C) and low-pressure (<10 atm) conditions, which will significantly reduce the energy demand for the entire process. If successful, the project will provide a method to produce a widely used chemical and fuel with renewable energy and minimal greenhouse gas emissions.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **2.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This is a good approach to demonstrating the production of a liquid fuel from an intermittent renewable energy source. This project can help to promote the H2@Scale concept.
- Renewable hydrogen production combined with utilization of CO_2 to make synthetic fuels provides an alternative to CO_2 sequestration and an energy storage medium that may be easier to store and transport than hydrogen. The approach to combine electrolysis to provide green hydrogen with more traditional thermal conversion of H_2 and CO/CO_2 to methanol may provide some benefits and should reduce CO_2 emissions compared to traditional synthesis from natural gas and may improve on the current low selectivity of direct electrochemical conversion to methanol. A large focus of the project appears to be on developing nano-array catalysts for the reaction of H_2 with CO/CO_2 for methanol production. It would have been beneficial to do a comparison of the results from modeling the flow and mass transport in the nano-array catalysts to a commercial methanol synthesis catalyst as a baseline, showing where the nano-array catalysts have benefits. The presentation suggested improved transport properties could be achieved with the nano-array catalysts. It is not clear how mass transport limitations affect the current commercial catalysts, and modeling results or experimental data showing reaction and transport properties were not provided. The project work directed toward electrolyzer electrode development lacks a baseline using a current commercial state-of-the-art electrode for comparison.
- The critical barriers for converting CO_2 to value-added chemicals have been clearly identified, including the high cost of hydrogen and the high cost of converting CO_2 to chemicals or fuels. It is unclear whether the project has identified the actual cost drivers that contribute to the high cost of hydrogen production and CO_2 conversion technology and, consequently, focused its research to address those issues. While the high cost and low reliability of gaseous and liquid hydrogen fueling infrastructure are major issues, it is not clear that this is a critical issue for this project. Hydrogen safety is always an issue, particularly regarding deployment in new technologies that employ hydrogen, but it is unclear how this project is addressing hydrogen safety.
- The project approach is defined fairly clearly and integrates with other relevant efforts. The core "integrated systems" approach is not well-supported. The "integration" is not evident, as the project approach seems to be an independent electrolyzer followed by an independent methanol reactor. There appears to be no linkage between the two unit operations. The diagram on the "Approach" slide is particularly helpful in explaining the system.
- The project claims to be targeting the barrier of high-cost, low-carbon e-fuels at scale. However, it is not clear how the technology being developed will lower costs, nor what the carbon footprint of the resulting e-methanol will be, nor the scale at which it will be produced. It feels more like an early-stage proof of concept than a technology acceleration effort. The key should be the design and demonstration of a scalable, high-performance methanol reactor. There is not a clear reason for diluting the effort by also developing a novel electrolyzer technology.

Question 2: Accomplishments and progress

This project was rated **2.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has exceeded the go/no-go criteria established for the methanol production rate and selectivity. The project has demonstrated methanol synthesis with high selectivity at low temperature. The principal investigator (PI) has demonstrated improved performance in the team's electrolyzer from utilizing a Pt nanowire (NW) array electrode through an improved three-phase boundary and enhanced interfacial contact between Pt NW array and polymer electrolyte membrane (PEM).
- Good progress has been made on fabricating the various structured materials for supporting the catalyst and for the heat exchanger and catalyst testing. It would be beneficial if the performance targets for these structured materials and catalysts were defined so that progress against expected quantified performance targets could be evaluated. For example, it would be helpful to know whether the observed methanol yield per kilogram and selectivity of the catalyst are sufficient to meet the required performance. Since some of these technologies, such as the methanol synthesis catalysts, are mature industrial technologies, it would be

beneficial to identify the shortcomings of the current technology and how the new technologies will address those shortcomings. A lack of defined performance targets for materials and technologies being developed makes it difficult to judge progress.

- The project has achieved significant results and shows focused activity and relevant testing. Fabrication of the aluminum scaffold for the methanol reactor is interesting, but it has not been compared to a conventional substrate. The testing appears to be on cordierite rather than the aluminum structures. Thus, the advantages of the novel structures are not demonstrated. The additively manufactured manifold–microchannel heat exchangers are, presumably, to remove the exotherm from the methanol reaction. However, the diagram on the “Approach” slide does not include a cooling system. Thus, it is not clear whether a cooled reactor or adiabatic reactor is envisioned. The PI’s opinion on the implied/best operating point (to balance yield and selectivity) is not stated. The reactor size implications of operating at 200°C (low yield) are not discussed. Testing over 24 hours, although far short of ultimate system requirements, is of sufficient duration to demonstrate the performance degradation rate. The testing of Pt dopants appears to show advantageous effects. Using comparative test results between Pt NW arrays and assemblies is a very good approach. The use of an ultralow (2 micrograms/cm^2) Pt loading is a good development. However, this is for hydrogen evolution reaction (HER), which has already achieved competitively low Pt loadings (~0.05 mg_{Pt}/cm^2) with conventional electrodes. While “ultralow” is better than “low,” there are diminishing returns. From an economic perspective, reduction of the oxygen evolution reaction (OER) catalyst would make more sense.
- The progress is good, especially taking into consideration the obvious COVID-19-related delays. There are many nice, but relatively modest, technical accomplishments. There are nine “Accomplishments” slides (which are all legitimately distinct items), yet due to some inexplicable repeated numbering system, they are shown only as slide 1 to slide 4. The revised completion date was not clearly communicated, and the reason for that was not clear. The only indication of the project schedule was the final slide, and the statement that the project is “currently progressing to meet all the milestones and no report submissions are due at this time” is not very informative.
- This is a technology acceleration project that, as of 2020, had spent 65% of its budget, yet the main accomplishments are still studies and lab-scale investigations. There is a good chance the project will not meet its goals. If this is a mischaracterization, a clearer description of the proximity to a working unit would be beneficial.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- Multiple organizations, including industry, national laboratories, and academia, are involved in this project. Each partner has a defined primary role, and from the results presented, it appears that the various partners are fulfilling their roles.
- There appears to be substantial and well-selected collaboration on this project.
- There is an impressive number of team members (six), and it is very clear what they are all contributing, both with respect to their roles (slide 5) and what they have delivered (with the appropriate logos on the “Accomplishment” slides). It is not clear how much collaboration has been done on the integrated system. It appears that the electrolysis folks and the catalytic reactor folks are acting independently. That should become clear when integration begins. The presenter did not seem to be very concerned about the integration task, but it was not clear whether that was because of his high confidence in the design and collaborations or because of his lack of familiarity with the overall project details.
- The engagement with four different university professors is encouraging. It would be good to see more commercial interactions that would facilitate confidence in scalability.
- The collaboration within the project appears to be working. The collaboration with external partners is not apparent. Collaboration with electrolyzer companies or DOE consortia involved with electrolysis would be beneficial.

Question 4: Relevance/potential impact

This project was rated **2.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project addresses developing new technology for producing methanol using CO_2 and green hydrogen, focusing on lowering the cost of production. CO_2 conversion using green hydrogen is one of the major opportunities identified in the Hydrogen and Fuel Cell Technologies Office (HFTO) H2@Scale initiative. For CO_2 conversion to be cost-competitive with current fossil-fuel-based technologies for producing methanol, the production costs for hydrogen and methanol need to be significantly reduced. While the project aligns well with the DOE Hydrogen Program's (the Program's) research, development, and demonstration objectives, the project is trying to develop new technologies for too many process steps/unit operations, and given the limited budget, the potential for making significant advances in all areas explored is lower than if the project focused on only one or two new technology advancements. There is a slide identifying progress toward DOE targets, but it is difficult to judge whether the project is actually making progress toward achieving those targets. Also, unless there is a plan to convert methanol into a transportation fuel, it is not clear that DOE targets for vehicle fuels are appropriate targets.
- This project has high relevance to overall DOE goals. However, the overall project goals are not linked well to the DOE goals. There is no consideration of how the approach would reduce overall methanol cost or enable greater system efficiency. The slide on progress toward DOE targets describes top-level DOE goals without stating how this specific project helps achieve them.
- The portion of the effort directed at improving catalysts for electrolysis is aligned with HFTO goals. The main focus of this project appears to be developing a better catalyst for methanol synthesis, and methanol synthesis is not a major HFTO focus. The impact of this project is not clear. It is not clear whether this process can compete with conventional methanol synthesis routes or what hydrogen cost from electrolysis would be needed to compete.
- This is good but could be more convincing by being more qualitative about the comparison with alternatives. Simply stating that the project is "significantly reducing the energy demand for the entire process" (slide 3) and "significantly reducing the energy demand" (slide 4) is repetitive and not very convincing. Some comparison of the alternative options should be shown, and better yet, some semi-quantitative estimate of the energy required should be provided. Qualitative statements about the project's robustness and its compatibility with intermittent energy sources are fine, but providing only "hand-waving" statements is not too compelling.
- The need for low-carbon methanol production options is recognized, but without the context of applicability (i.e., centralized or at-station), scalability, and relative economics, it is not clear what the impact of this project might be. It feels like an early-stage proof of concept that others may build on later, rather than a technology that could be put into the hands of even early adopters.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- The future work is well-defined and detailed.
- The proposed work is moving toward more integration of workstreams, which is good. It is suggested that the project focus more on demonstrating a working methanol reactor, even if just fed bottled hydrogen, and on evaluating economics. Leave "optimization" for later—unless the current status is unacceptable, making optimization required for viability.
- If this system is to be tied to renewable energy for electrolytic production of hydrogen, the electrolyzer, and then presumably the methanol synthesis reactor, will not be operating in a steady-state production mode but will be experiencing multiple start-ups/shutdowns. Methanol synthesis catalysts and supports should be tested over multiple start-up/shutdown cycles to ensure they can survive the pressure/temperature cycling. The economic analysis proposed is important. It will be important to know the hydrogen price at which the suggested process can compete with current methanol synthesis (in terms of the price of methanol) and how competitive it could be if carbon credits or a carbon tax is in place.
- There appears to be significant effort in the future work plan to evaluate new synthetic techniques to optimize the CO_2 conversion catalyst. The expected performance target at which the team is aiming is not clear, nor is the timeframe for identifying the optimal synthetic technique, given that the first task in the

future work plan is to evaluate the performance of the CO_2 reactor. If the current CO_2 conversion catalyst does not meet the performance target and the time to optimize the performance is long, it would be helpful to know what the benefit of the reactor optimization task is if the team uses a less-than-desired performing catalyst. It is not clear why the team is focusing on reducing the Pt loading on the HER catalyst and not addressing the precious metal content (particularly iridium) on the OER catalyst, when it is the OER catalyst that drives performance and hence cost.

- It is doubtful that all of the future work presented on slide 17 can be completed in just a couple of quarters, especially since some of this work needs to be done in series (i.e., all of the components must be done before the integration). However, perhaps the complete integration of both major subsystems is not even included, since this is not listed on this slide. Additionally, if one looks at the last slide (slide 22), it appears to show that everything is done except for milestones 9.2 and 9.3, which does not at all seem to match the status. Despite some questions on this topic, the reviewers were left a bit confused as to the actual current status and the future plans.

Project strengths:

- The development of CO_2 conversion technology addresses one of the major opportunities for utilizing green hydrogen, as well as addressing CO_2 emissions in the Program's H2@Scale initiative. There appears to be good collaboration between all the participants in the project. The project appears to be moving forward and to have met all defined milestones, despite having to deal with the COVID-19 pandemic.
- The project is mostly well-defined and -described. The project's strengths are its system diagram, the 24-hour reactor testing at different temperatures and pressures, and the concise yield versus selectivity graphs.
- The proposed process has shown good selectivity at the low operating temperature it is able to achieve.
- The project has a good approach and a good team, to which all team members seem to be adding value.
- This is a cross-functional group. There is faith in the scale-up potential for laboratory-based technology.

Project weaknesses:

- The weakness of this project is the poor communication of the project status, future plans, and end goals. Perhaps this could have been better if the project's PI had presented. However, the slides have many issues, so this was just part of the problem here.
- The project is proposing to develop Pt-based methanol synthesis catalysts. It is not clear whether the benefit from adding Pt to the methanol synthesis catalyst offsets the increased catalyst cost by reducing the cost of the overall process, assuming better overall process performance from the Pt-based catalyst than the non-Pt-based catalyst. The lack of performance targets for the various technologies being developed makes it very difficult to judge the progress.
- There is poor integration between the electrolyzer and the reactor. This could easily be two separate projects. There is a major lack of comparisons to the current status. Electrolyzer test results should be compared to current PEM stacks. Catalyst loadings should be compared to current statuses. There is no discussion of cooling the reactor and whether that is a key and necessary aspect of the overall concept.
- The weakness is the project's pace, if the objective is technology acceleration versus proof of concept for new laboratory-based ideas.
- The focus on methanol synthesis does not seem to be a good fit with HFTO.

Recommendations for additions/deletions to project scope:

- The project needs to complete a technoeconomic analysis (TEA) of its process technology. The TEA will serve numerous purposes, including the following: (1) letting the team know how its technology compares to alternative technologies for producing methanol, both from fossil fuels (as currently practiced in industry) and from renewable feedstocks; (2) identifying the cost drivers that may make the technology non-cost-competitive; and (3) identifying where to focus research and development to reduce costs, making the technology more cost-competitive. During the question-and-answer session, the presenter mentioned potentially pursuing Advanced Research Projects Agency–Energy (ARPA-E) funding in the future as follow-on funding for this technology. Based on the reviewer's experience participating in multiple ARPA-E projects, a TEA will be a critical aspect of any proposal and will be one of the first deliverables required by APRA-E if the proposal is funded. Given that the technology is essentially a "green" technology, the analysis should consider the additional cost of carbon capture and sequestration for current industrial fossil-fuel-based methanol synthesis processes for a fairer comparison. This project is working to develop several new technologies for both the electrolyzer and the CO_2 conversion process. It is suggested that the project team evaluate each of the technology development areas being targeted and rank them, from highest to lowest, on impact and potential for achieving success in moving the technology forward. Then the project should focus only on one or two of the areas that have the highest impact and are achievable.

- DOE needs to do more of these types of projects (i.e., making various products using renewable energy), if the Department really wants to promote the H2@Scale concept. These should be processes that can be highly distributed, such as renewables. However, DOE should seek more innovative projects than this one, which is primarily the integration of two known processes with some minor modifications (e.g., low-pressure hydrogen generation and different catalyst supports for methanol production).
- The project should add comparisons to current state-of-the-art or status systems in areas of electrolyzer polarization curves, Pt loading, methanol synthesis reactors, etc. The issue of the OER electrode and catalyst loading should be addressed. There needs to be a comparison to a system with a conventional PEM (or alkaline) electrolyzer. Economic estimates should be added to the analysis, both for the capital cost of the electrolyzer and reactor and for the product methanol.
- This project should drop the electrolyzer development and focus on the methanol reactor exclusively. The team should add information on the energy balance for the process, including heat and compression, and identify the origin of the claimed energy savings versus competitive processes. The team needs to address the implications of modest selectivity to methanol and explain what happens to the remaining CO_2 and what the by-products are.
- The project should add durability testing of the methanol synthesis reactor with on/off cycling to ensure it can be operated to match the cycling seen with renewable hydrogen production.

Project #TA-033: Developing Novel Electrodes with Ultralow Catalyst Loading for High-Efficiency Hydrogen Production in Proton Exchange Membrane Electrolyzer Cells

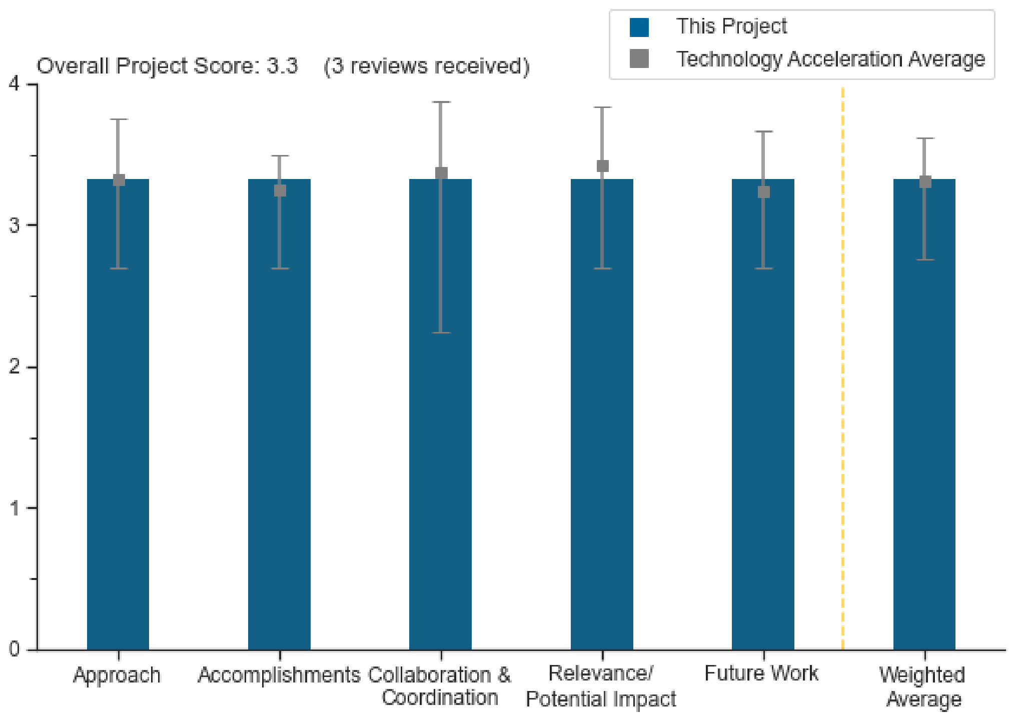
Feng-Yuan Zhang, University of Tennessee Space Institute

DOE Contract #	DE-EE0008426
Start and End Dates	10/1/2018 to 6/30/2021
Partners/Collaborators	University of Tennessee, Knoxville, Oak Ridge National Laboratory, National Renewable Energy Laboratory, Nel Hydrogen, University of Connecticut
Barriers Addressed	• Capital cost • Efficiency and durability

Project Goal and Brief Summary

This project aims to develop thin engineered liquid/gas diffusion layers (LGDLs) and catalyst-coated LGDLs for low-cost, high-efficiency hydrogen production in polymer electrolyte membrane (PEM) electrolysis cells. If successful, this work will reduce the cost of producing hydrogen in PEM electrolysis cells, supporting the U.S. Department of Energy goal to produce hydrogen for less than $2/kg.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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.

- Optimization of the electrode/transport media is emerging as a critical topic for PEM electrolysis cell membrane electrode assembly integration. The unique LGDL approaches pursued by the team appear to

have strong potential to provide significant contributions and knowledge. Controlling the macro-scale porosity and the thickness and other properties of the LGDL and incorporating a catalyst layer appear to be strong approaches, at least for learning about the dynamics of the gas evolution reactions. The optical imaging is a critical aspect of the approach. Cell modeling and cost analysis are strong elements.
- This is a very interesting approach to push toward generation of hydrogen for ≤$2/kg by increasing catalyst activity tenfold. The manufacturing cost of making these layers is unclear, but the assumption is that it would be less than savings associated with a 90% reduction in catalyst loading.
- Objectives and barriers have been identified.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The progress appears to be strong. Good understanding of the reduction in loading and improvement in mass activity has been achieved. Performance has been shown to be improved versus a baseline cell. There is very interesting work looking at the impact of the size and spacing of the LGDL pores. It would be interesting to understand the trends that were observed in more detail. Likewise, further understanding of the break-in requirement would be helpful. There are interesting results with the Ir catalyst application using the Ni template, where the Ni appeared to provide protection from the membrane without a separate protective coating on the Ti substrate. This should be verified in more detail, as the protective layer needed for the porous transport layer (PTL) is an open question for the community. It looks like there is good progress on the cell performance model, though it is not clear whether the model actually helped the project at all. It is unclear whether the model was used, e.g., to guide experimentation, in any cases.
- The technical accomplishments associated with this work are excellent, with clear progress in regard to catalyst activity and with further efficiency improvements related to flow enhancement, the addition of Nafion™ and TiN coatings, and parallel flow channels. It is unclear at this time whether the accomplishments will meet the goal of reducing the overall system cost, as there is no indication of the cost of manufacturing these parts in volume.
- It is unclear how much of the hydrogen production cost is allocated to the PTL + catalyst-coated-membrane production addressed by this project, as well as any corresponding over-voltage. It is unclear how much cost improvement is projected.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- The project shows excellent collaboration between all of the institutions listed, with a clear delineation of work responsibilities.
- The team is well-formed and appears to be working well. There is a good combination of capabilities.
- The project team includes a broad array of laboratories, universities, and industry.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is highly relevant to providing information to the community about the critical electrode–PTL interface. This is very relevant to integration activities within Hydrogen from Next-generation Electrolyzers of Water (H2NEW).
- The work done is excellent and the achievements are remarkable; however, the impact of the project is difficult to assess. The technology is very promising, but there is no indication on manufacturability (maximum size, uniformity, continuous versus discrete processing, etc.), cost of materials, or construction. If these materials can be manufactured at high volume with good uniformity and reasonable pricing (accounting for the cost savings associated with efficiency and catalyst reduction), then the impact on the electrolyzer market could be very large.

- Improvements made by lower costs and improved performance through this project will have direct impacts on operating expertise and capital expenditures, thus reducing hydrogen cost. It is unclear how much impact is projected if the project is completely successful. The project has Ir loading and voltage improvements. It is unclear what this project does in terms of dollars per kilogram of hydrogen.

Question 5: Proposed future work

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

- The proposed future work addresses the concerns related to the project and continues to push the boundaries of this cutting-edge technology.
- It was stated that all milestones were met, and according to the overview slide, the project ends in June 2021, and yet five activities were listed in proposed future work. That is confusing. It is not clear whether all of the future work had already been accomplished as of the DOE Hydrogen Program Annual Merit Review. Perhaps a no-cost extension will be pursued.
- This question is not applicable, as the project concludes this summer.

Project strengths:

- There is a great approach and a great combination of capabilities and activities within the project. The outcomes seem to be highly informative. The combination of bubble imaging, current density mapping, and performance modeling is really a great approach. The team is well-constructed.
- The strength of this project lies with the key developments in process efficiency and catalyst activity. If these results can be scaled easily and cost effectively, then the project could have a significant impact on next-generation electrolyzer production.
- Overall, this is impressive work. The focus on bubble evolution pre- and post-break-in is good. The project may consider ways to influence bubble evolution based on surface defects/pores in a similar manner to multiphase heat transfer optimization.

Project weaknesses:

- There is no weakness, just uncertainty about how the project is ending.
- The main weakness in this project is the lack of clarity on scale-up and cost associated with the technology. Additional work can and should be done to further understand the underlying reactions and push the boundaries of the technology.
- It is unclear whether durability testing was performed beyond the single 100-hour test presented on slide 10, e.g., start–stop, power cycle, and voltage cycle testing. The impact of the hole pattern on durability at differential pressure is also unclear. It seems like these tests would be performed by the industrial partner.

Recommendations for additions/deletions to project scope:

- The project appears to be complete, or nearly so. If there is an opportunity going forward, it would be interesting to assess the LGDL structures from a fabrication and manufacturing point of view in comparison to standard PTLs, which are generally available via some level of volume manufacturing.
- The group is addressing the key concerns and has a strong proposal for future work.
- This question is not applicable, as the project is concluding.

Project #TA-034: Rail, Aviation, and Maritime Metrics

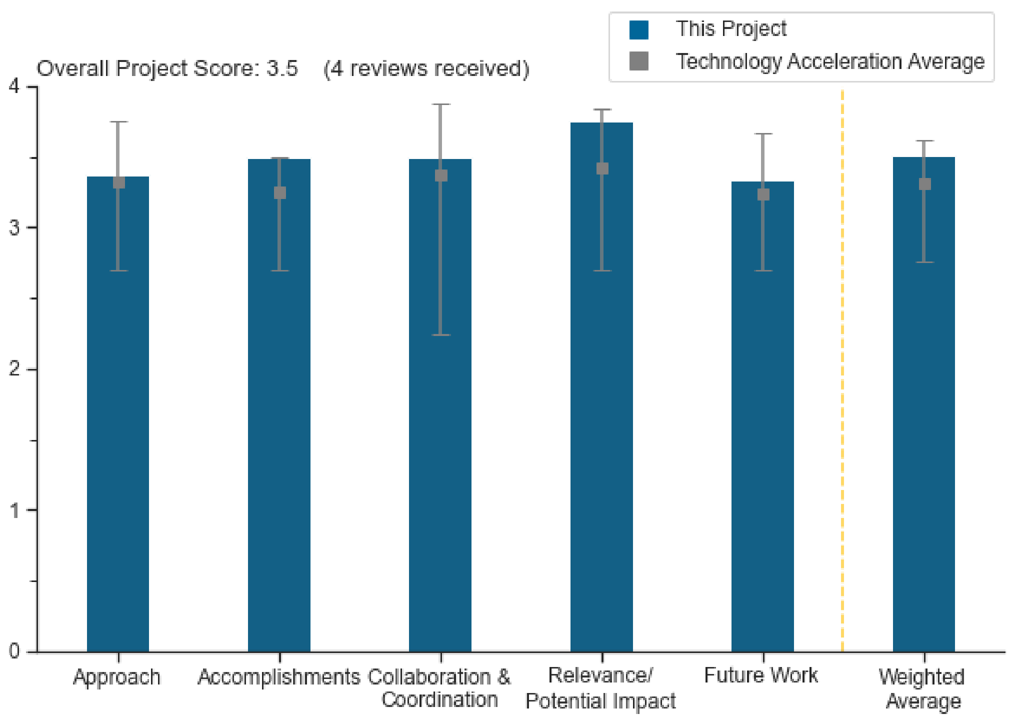
Rajesh Ahluwalia, Argonne National Laboratory

DOE Contract #	WBS 9.2.0.21, 9.2.0.22, 9.2.0.23
Start and End Dates	10/1/2020
Partners/Collaborators	Caterpillar, Cummins, Alstom, Stadler, North Country Transit District, San Bernadino County Transit Authority, CalTrain, Massachusetts Bay Transit Authority, Wabtec Corporation, Sandia National Laboratories, Chart Industries, Golden Gate Zero Emission, Swift Maritime, Universal Hydrogen, Ballard Unmanned Systems, Alaka'i Technologies
Barriers Addressed	• High hydrogen fuel infrastructure capital costs • Market uncertainty around the need for hydrogen infrastructure versus timeframe and volume of commercial fuel cell applications

Project Goal and Brief Summary

This project aims to determine how hydrogen and fuel cells compare with incumbent technologies in rail, maritime, and aviation applications, as well as what performance metrics are needed for hydrogen technologies to compete on a cost-of-ownership basis. Researchers will evaluate and identify opportunities for heavy-duty fuel cell adoption in rail, maritime, and aviation sectors, as well as opportunities for introduction of large-scale hydrogen into markets.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- By evaluating the total cost of ownership (TCO) and the potential economic and performance targets for each application, the project provides a holistic and robust perspective.
- The TCO analysis was comprehensive and systematic. The project team analyzed numerous important and interesting use cases in these sectors. If anything, the team tried to include too much in the presentation in such a short time. There were also too many acronyms to really follow all the assumptions.
- The analysis is conducted at a high level, and it is quite a logical plan. The baselines seem questionable, e.g., diesel trains are generally electric, yet batteries were put only on fuel cell trains; and use of the piston engine in aircraft is pretty much limited to very small planes, and the team did not explain why fuel cells are not usable in jet aircraft.
- The approach is unclear as to whether only liquid hydrogen (LH2) is being considered or gaseous hydrogen is being considered as well. The project team needs to say something more about the Hydrogen Delivery Scenario Analysis Model (HDSAM) that patently underlies all of this analysis. The methodology section is a bit weak, as the presentation states that the team started by choosing a “representative use case,” but it was not clear whether there was a selection for each main application or how many were to be selected. Further, the researchers wrote that they applied an internal rate of return (IRR), but IRRs are normally calculated rather than selected. The team might want to calculate an IRR and then compare it with a hurdle rate of X%.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made outstanding progress characterizing targets and TCO for all applications, as well as variations such as regenerative braking. The approach of developing representative cases for analysis allowed the team to make outstanding progress toward objectives. Several excellent variations were presented to show the influence on results; however, further discussion on the selection of variables and scenarios modeled in the analysis would be useful to get a sense of what barriers and uncertainties remain.
- This project has made good progress. This study did not look at regeneration on diesel, but fuel cell trains are the best choice even if regeneration were part of the base case. If hydrogen and fuel cell targets are met, fuel cell trains are predicted to be competitive. For private piston aircraft, fuel cells can be competitive at $8/kg LH2 and $430/kw for fuel cells. There is a clear advantage in fuel cells in unmanned aerial vehicles (UAVs), which should be followed up, as the use of UAVs is growing. Analysis of ferries suggests they are competitive at around $4/kg hydrogen.
- The results of this project were outstanding, and the TCO benefit of UAVs was particularly compelling. In future presentations, it would be helpful to rank the applications in terms of business case viability. It sounds like UAVs are economically viable today, while marine applications need better fuels and cheaper hydrogen.
- There is some very good progress here, but other aspects of the analysis need better explanation, especially around key baseline assumptions for fuel costs of hydrogen in different forms for the different applications. It seems they are being considered as “breakeven costs with conventional fuels” (hence higher for light aviation) rather than very much aligned with DOE costs and projections. Perhaps both could be considered in a somewhat more clear and nuanced analysis.

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 management and transfer of information among partners was not clearly described, but the project team is very strong, and the input of many industrial partners significantly improves the quality of the work.

- Collaboration seems very good. There is a good amount of industry engagement, and that is important for this project.
- The project got information from a large number of appropriate partners.
- It is good that there are numerous industrial collaborators contributing to the analysis.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Understanding what needs to be improved to get hydrogen into a wide range of transportation modes is essential to the DOE goal of a hydrogen economy. Figuring out where the barriers are likely to be surmounted first allows better use of resources by choosing to help those early modes of transport move to hydrogen and, thus, bring up the supply chain that will serve the entire economy. While these are hardly the most important vehicles to model, that is because they were covered earlier in the project.
- By conducting system analyses of hydrogen use in rail, maritime, and aviation transportation, the project addresses a critically understudied hydrogen market sector and provides technical targets that can help guide industry investments and research and development.
- It is very important to understand the economic potential of the different applications to promote H2@Scale. It would have been nice if more context had been provided about the differences between applications.
- This project is certainly well-targeted to define better metrics for these emerging hydrogen sectors.

Question 5: Proposed future work

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

- Agriculture and construction are important applications for future work, and the project should consider adding mining equipment, as well.
- The proposed next steps for studying off-road vehicles are potentially impactful, but no sense of the market size was provided.
- Off-road trucks are a very good area to study.
- The project is seeming a bit rushed, as it is a one-year effort, so it is to be hoped that the project can be completed thoroughly, as there is significant scope left to accomplish.

Project strengths:

- The team took a challenging scope and completed it by selecting representative use cases and representative systems, both incumbent and hydrogen, for each form of transportation. The team chose reasonable options for all representative cases. The project presents a clear and consistent analysis and a comparison of systems. The project also calculated TCO using approaches consistent with Hydrogen and Fuel Cell Technologies Office research and economic assumptions.
- The overall strengths of this project are that it provides a comprehensive and quantitative analysis of the value proposition for fuel cells in rail, aviation, and marine applications. The project provides a clear comparison to the baseline incumbent technology.
- There is a good analysis of hydrogen for emerging transportation sectors that have generally been understudied in the past. The analysis generally seems sound and leverages previous work.
- This project references a deep base of other simulations, and a wide range of transport is covered.

Project weaknesses:

- In terms of weaknesses, some aspects of the analysis could be explained more clearly, such as the various hydrogen costs assumed, why they were assumed, and the impacts of those base case assumptions. In terms of the slide presentation, there was too much material for the presentation time allowed and the limited question-and-answer period. A bit less-dense information could have conveyed the project detail/ complexity more effectively. There was some seemingly good work here nonetheless; this is more about the explanation of approach, methods, and presentation of results for future Annual Merit Reviews and general presentations.

- The overall weakness of this project is that there was just too much analysis to comprehend in too short of a time period and too many undefined acronyms. For example, it was not clear what FCD [fuel cell-powered drones] or FCH [fuel cell-powered helicopters] is. While it can be guessed that FC is fuel cell, the D and H were a mystery to the reviewer. The key takeaways need to be summarized more clearly.
- There was no presentation of the lifecycle analysis approach or results, nor was there integration with the technoeconomic analysis. There was also no guidance as to whether the proposed technical targets are contingent on a certain hydrogen production technology, its availability, or transportation market sector growth.
- Compared to other vehicle analyses, this analysis was not very deep.

Recommendations for additions/deletions to project scope:

- The project team should look for what level of hybridization in conventional systems is required to beat the best of the fuel cell hybrid electric vehicles (FCHEVs) (if indeed they can ever beat FCHEVs) to find the real competition for future markets.
- The team should include mining in the future analysis and maybe start considering the entire site development for a farm or a mine. Some of the TCO may be larger than the vehicles themselves.

Project #TA-035: Power Convertor for Electrolyzer Applications

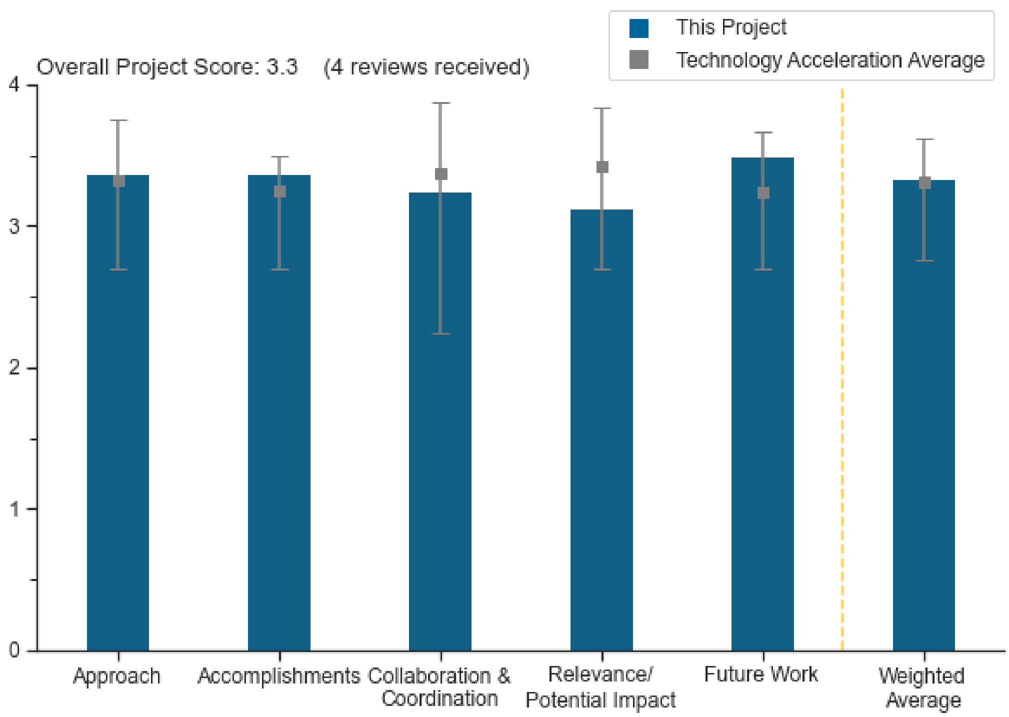
Robert Hovsapian, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.5
Start and End Dates	3/1/2020
Partners/Collaborators	EPC Power Corporation, NEL Hydrogen, Typhoon HIL, Dynapower
Barriers Addressed	• Lack of standardized controls interface for electrolyzer applications in real-world operation as per grid codes and interconnection, inter-operability standards • Coordinated control of multiple electrolyzers, including interaction with other power electronically interfaced distributed energy resource technologies • Optimized control for hydrogen and electricity co-production, including renewables

Project Goal and Brief Summary

The National Renewable Energy Laboratory (NREL) is developing a smart converter for dedicated electrolyzer applications. The converter will enable grid services by standardizing control interfaces between hydrogen electrolyzer system low-level controls and power converter controls. Project outcomes will improve the ease of adoption, maintainability, and reliability of electrolyzer systems.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is quite well-developed. The team is following the highly successful approach used by the solar photovoltaic power generation industry to develop power converter electronics for solar cell applications. It is a bit early to tell in practice how universal the approach will be for the very different electrolyzer technologies on the market today.

- The project has a good approach to achieving the objective, which appears to be to develop a standardized power convertor for electrolyzers that are integrated with renewables, using off-the-shelf components as much as possible (i.e., standard power converter hardware).
- There is a clear need to standardize the communication between the situation on the grid and the control interface of the power electronics. The best practices are adopted from the solar field, and the partners represent strong players in the field.
- The approach is well-defined, with clear connection on how the work would be conducted to support the integration of low-temperature electrolysis and the grid.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team has made excellent progress despite the challenges of the COVID-19 pandemic. More progress is foreseen as the nation returns to work.
- There is excellent progress toward meeting the project's (modest) objectives.
- The project is off to a good start with a clear view on the design and its implementation. The project is focused on polymer electrolyte membrane electrolysis, and it is not clear whether the people involved have hands-on experience operating electrolyzers in the field already. This would help build a "feeling" of what the electrolyzer is/should be capable of.
- The project had quite a few lists of accomplishments, but it was difficult to tell whether these were associated with milestones or just reporting of tasks completed. No mention was made of Budget Period 1 milestones; there was only a slide at the end that had forward-looking milestones for upcoming quarters.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- It seems that the consortium was well-selected. It would be interesting to know whether there is an inside view or technical limitation of the maximum power level for the expressed modular approach. Considering the wide range of stack sizes (and number of stacks in a system), the partners will be able to anticipate a degree of flexibility.
- Collaboration with industry was very good, despite the challenges of 2020.
- The project has multiple collaborators but appears to be working with only one electrolyzer company. The project should also be working with more power converter manufacturers, which is the team's goal (but it is not clear why this has not already been done by this point).
- Collaborators appear to be well-suited for the project, but it would be nice to see a better breakout of their specific roles and what accomplishments they have made to date in support of the project.

Question 4: Relevance/potential impact

This project was rated **3.1** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project clearly shows the relevance, as it pertains to electrolysis deployment in a grid service application. Areas of impact are well-described, with numerous areas defined as being improved by this effort.
- The development of electrolyzer control electronics is essential to the integration of hydrogen generation into the grid. The transient nature of renewable energy dictates the need for sophisticated power conversion.
- The objective is sound, but there was no clear presentation of the economic drivers to adopt a new standardization over the status quo. Many stack suppliers argue that their proprietary solutions are the best and the power electronics should listen to their requirements (from low-level control), while everybody has learned the hard way how much influence the power supply control can have on the lifetime. Perhaps the

standardization demand comes from the regulations for guaranteeing grid stability, but again, this incentive could be clearer than just the vision “hydrogen stabilizes the grid.”
- It is not really clear what DOE objectives this project addresses. Presumably, the objective is to reduce the cost of power electronics, but cost is not mentioned at all. The objective may also be to enable higher value for electrolyzers paired with renewables (e.g., fast response), but that is also not clearly shown.

Question 5: Proposed future work

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

- The proposed future work represents a logical path forward toward the development of high-technology-readiness-level prototypes and pre-commercial testing of the control electronics in real-world environments.
- Actual demonstration with hardware at scale is proposed as future work. Description of testing, size, and location is well-defined, and there is a planned webinar to gather industry perspective on how best to integrate.
- The future work plans are clearly described, and the remaining milestones are also shown.
- Integrating the >1 MW electrolyzer system is a key part of the learning and validation of technology, and it remains to be seen how transferable this operational strategy could be to other electrolyzer makes, models, or types.

Project strengths:

- The project strengths lie in the ability to leverage hardware at scale to verify the concept. The use of power converter manufacturers for megawatt-scale implementation is good, and the development against existing grid codes and standards will show this end device and the testing results as having more validity. Using the webinar to engage industry and end users to solicit feedback for development and integration will gain more support from the grid/electrolyzer community.
- This project is strongly encouraged to continue the endeavor to achieve standardization and translate the grid status to a power control strategy for electrolyzer operation. If successful, there will likely be a similar strategy and architecture being applied for fuel cells (delivering to the grid) and other energy storage systems.
- There is excellent integration into the H2@Scale project goals. The highly capable teaming facilities and equipment are suitable for achieving project goals.
- The project plan includes demonstrations of real hardware. The results to date are promising.

Project weaknesses:

- There is strong focus on providing a technical solution, but there is a risk that this will become a one-off demonstrator if the technical, economic, and regulatory benefits are not made obvious through public dissemination in the near future. Overall, some elements seem to be missing: the feedback loop from the electrolyzer, the input from artificial intelligence, learning what the limitations are in (over)loading the electrolyzer, or anticipating the timing for stabilizing the grid (probably there is a pattern).
- The project appears to be using converters used for solar and batteries as a starting place, but the team is not looking at what has been done with convertors for fuel cells that have voltages and currents that are more similar to electrolyzers than batteries. Of course, fuel cells send power in the opposite direction from electrolyzers, but it is at least worth looking to see whether there are things that can be leveraged from that technology/hardware. The principal investigator should make much more of an effort in communicating the value of this work. For example, showing qualitatively how the value proposition for renewables and electrolyzers can be improved with a fast-response convertor would be great. It is likely that his colleagues at NREL have this already.
- The question of how “universal will the final product be” is yet to be answered.
- No weaknesses were identified.

Recommendations for additions/deletions to project scope:

- Designing in room for two-way optimization (grid to electrolyzer power control and also stack efficiency to power control to grid) could encourage all stakeholders to adopt the standardization while making room for artificial intelligence to anticipate patterns and parallel systems operating down the road. For example, perhaps battery electric vehicles could also contribute to grid stabilization simultaneously while already taking care of the worst dynamic grid irregularities.
- There does not seem to be any interest in seeking or identifying potential technology improvements. The goal of using off-the-shelf hardware as much as possible is understandable here, but the team should also strive to identify what technologies could enable even better future power convertors for this application. This should be a valuable additional output of this project but does not seem to be in the plan; namely, the project should communicate to power convertor hardware developers a “dream convertor module.” Then, the project should discuss with the convertor community what might be possible with some technology improvements.
- There are no recommendations for additions or deletions to scope.

Project #TA-036: Advanced Electrode Manufacture to Enable Low-Cost Polymer Electrolyte Membrane Electrolysis

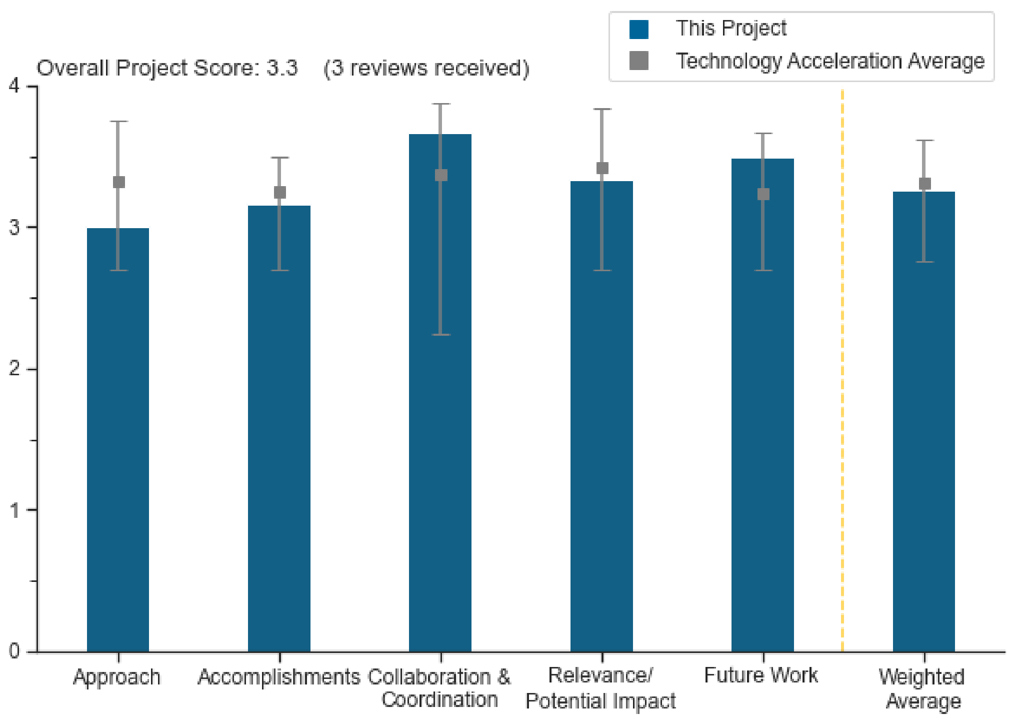
Chris Capuano, Nel Hydrogen

DOE Contract #	DE-EE0008638
Start and End Dates	7/1/2019 to 6/30/2021
Partners/Collaborators	National Renewable Energy Laboratory, Oak Ridge National Laboratory, General Motors, Kodak
Barriers Addressed	• Capital cost • System efficiency and electricity cost

Project Goal and Brief Summary

This project aims to develop coating inks and roll-to-roll (R2R) coating process parameters specific to ultra-low-loaded catalysts used in polymer electrolyte membrane electrolysis. If successful, the project will greatly reduce the cost of membrane electrode assembly (MEA) manufacturing by improving manufacturing speed rate, reducing the total platinum group metal (PGM) catalyst loading by 75%, and reducing labor costs by a factor of 10.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

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 approach to move toward R2R processing for catalyst layers on substrate is absolutely the correct approach for the long term. The transition from screen printing to R2R poses a significant number of challenges, but it has been done successfully already in the fuel cell industry.

- The approach is good, albeit mainly empirical-focused, and it is unclear how the dissemination will happen. The outline of work is well-suited to look at scale-up and translation. The project needs some more characterization to understand some of the observed performance changes.
- The project listed areas of interest and targets and gave a flow chart of tasks. There was no discussion of what would be done in the tasks; just their titles were provided. This is not very helpful for reviewing the project.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- R2R coating was demonstrated using gravure direct coating. This is very important for both electrolysis and fuel cells. Nel Hydrogen's new ink formulation (new catalyst material) and R2R were demonstrated successfully with this gravure direct coating. This work demonstrated the research team's capabilities. Knowledge was transferred to Kodak for the pilot operation. There is correlation of mixing results in the laboratory with results in the pilot processing facility. There is good coordination between research organizations. The project determined that coatability improves with moderate-viscosity inks (through coordination with Oak Ridge National Laboratory). The adhesion issue was observed. The recombination layer down-select identified the bilayer concept as more effective than the single-layer concept. The thinner membrane increased rates of degradation at the end of the test at 1,500 hours.
- The accomplishments on this project are adequate, as they are moving toward the goals of the project. It does feel a bit like reinventing the wheel compared to the work done by W.L. Gore on three-layer MEA coating. Overall, the goal was to take a process dominated by sheet-to-sheet screen printing and make it continuous, thereby reducing the cost. There are some challenges in ink development related to the shear thinning nature of the ink, the inclusion of oxygen evolution reaction catalyst materials, and coating uniformity issues that can be solved by dual-pass coating. Overall, the progress is acceptable and on track to meet the targets as defined.
- The project needs more understanding and not just a few two-point correlations. There appear to be many accomplishments that were mentioned, but it is not clear what exactly was learned. It is hard to judge everything since the presentation ran out of time.

Question 3: Collaboration and coordination

This project was rated **3.7** for its engagement with and coordination of project partners and interaction with other entities.

- There seems to be good collaboration between all the partners on this project. The partners have expertise in their relative fields and have shown success with this type of development effort previously.
- The partners and team are good. They should reach out to work alongside other DOE manufacturing projects and the R2R and other consortia. The project leverages expertise across the partners.
- Three industry groups and two national laboratories brought their specialties to a successful project.

Question 4: Relevance/potential impact

This project was rated **3.3** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is driven to achieve DOE targets of reducing catalyst loadings, lowering cost, and maintaining performance. These are all positives.
- Overall, the work done on this project is important to achieving long-term, low-cost electrode manufacturing for hydrogen production. The scale-up of this technology is limited to only the main partners associated with the project, however, and the impact on the overall goals of the DOE Hydrogen Program will be limited in this case, as is clear by the proprietary nature of the ink and coating properties, as shown in the presentation.
- The project is tackling key scalability problems in the manufacturing and translating that to R2R. It is unclear how the impact will extend beyond Nel Hydrogen.

Question 5: Proposed future work

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

- The proposed future work shows a good understanding of the challenges that currently exist with the process and moves toward creating a uniform, continuous coating process and validating the performance in a stack. It is highly likely the team put together will achieve the goals and produce a good R2R process for coating these electrodes.
- The project identified three challenges and barriers and addressed how to resolve issues. Future work is outlined. Moving to pilot plant production and establishing tests are what this project needs, and the project team plans to do those things.
- Future work is aligned in terms of scale-up and is reasonable.

Project strengths:

- The project is clearly addressing a barrier to low-cost electrodes through the development of a continuous coating process. The team has put together a solid plan for moving away from sheet-to-sheet processing and toward R2R processing, and that plan has a high likelihood of success.
- There is a comprehensive down-select approach of multiple components and technology transfer to the R2R and manufacturing process.
- The team is very talented and is the source of strength.

Project weaknesses:

- There are no conspicuous weaknesses.
- The major weaknesses associated with this project are the lack of any breakthrough technology to advance the cause and the minimal impact the success will have on the DOE Hydrogen Program, aside from the collaborators directly involved. It is important work that needs to happen, but the proprietary nature of the coating ink design and coating parameters makes it unlikely that others will benefit from the efforts made on this project.
- This project is performing an empirical optimization that may be specific to proprietary multiple sets. It is focused on performance but not so much on understanding.

Recommendations for additions/deletions to project scope:

- The scope of the project is adequate to meeting the defined project goals, with a high likelihood of successfully developing an R2R coating process for electrode materials.
- The project should provide some more translational findings that will help the community. It is unclear what the underlying structure–function relationships are. The project needs some more characterization to understand some of the observed performance changes.
- Stack testing would be next.

Project #TA-037: Demonstration and Framework for H2@Scale in Texas and Beyond

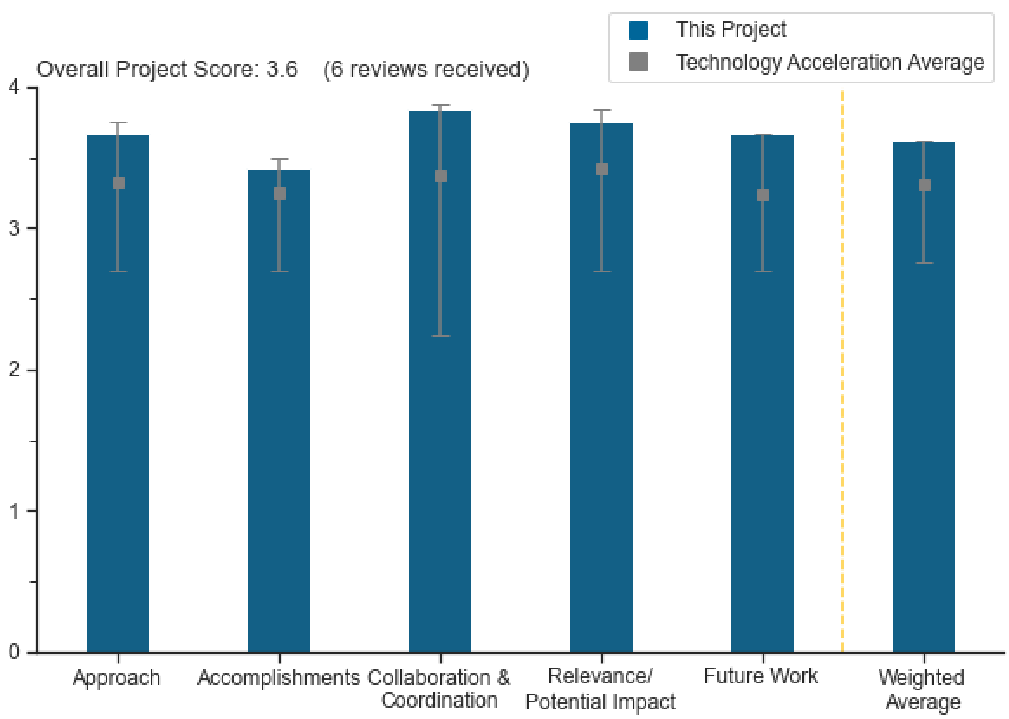
Nico Bouwkamp, Frontier Energy, Inc.

DOE Contract #	DE-EE0008850
Start and End Dates	1/10/2019 to 7/31/2023
Partners/Collaborators	Air Liquide, Chart Industries, ConocoPhillips, Gas Technology Institute, Mitsubishi Heavy Industries, OneH2, Inc., ONE Gas, Inc., ONEOK, Inc., Shell, Southern California Gas Company, Toyota, University of Texas at Austin, Waste Management
Barriers Addressed	• Hydrogen and fuel cell technologies need to be demonstrated in complete, integrated systems operating under real-world conditions • There is a high investment risk for developing hydrogen delivery infrastructure, given the current absence of demand for hydrogen from the transportation sector

Project Goal and Brief Summary

This project will determine how hydrogen production costs can be minimized by using multiple generation sources, including steam methane reforming (SMR) units that use renewable natural gas and electrolysis that uses wind and solar power. The project will also demonstrate hydrogen end uses, including using a 100 kW fuel cell to power a computing center. Base-load stationary power generation will be co-located with hydrogen vehicle fueling. The project will also develop a five-year plan for the Port of Houston area that considers existing hydrogen generation, distribution, and infrastructure assets to enable deployment of stationary fuel cell power and hydrogen-fueled vehicles. The plan will identify key barriers and partners, as well as the economic and environmental benefits of hydrogen deployment for the region.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The demonstration section is an especially useful approach, and much will be learned (including what stumbling blocks lay hidden ahead). Using multiple forms of renewable hydrogen is also a good approach, as the team will learn about more options and what works well and where. The team should also learn, by operating the system for interconnected generations and users, about timing and logistics issues in this simple case (no lag due to transport and minimal cost of transport). The framework for the Port of Houston is a good first step but will yield its real value only if it is then implemented in a project. To that end, the team should be proactive in seeking buy-in to move forward rather than just data from the many partners. Technology modeling is a key part.
- The project uses a combination of two research, development, and demonstration (RD&D) tracks, demonstrations and a deployment framework, to address well-defined key barriers to hydrogen scale-up. The demonstration tasks contribute new knowledge of paths and barriers toward low-cost, near-term integration of a variety of hydrogen systems with grid and end-use applications. The deployment framework via industrial outreach, workshops, and research is essential for mitigating the high upfront investment risk for developing hydrogen infrastructure.
- The acceptance of hydrogen and fuel cell technology in Texas and other "red states" will be aided by showcasing real-world applications applied in Texas and proving out the value in terms of economics, resilience in extreme conditions, and appealing to Texans' strong sense of independence and non-reliance on other states. While there may be high risk, if the project is successful, the framework developed from the project, the project team, and stakeholder involvement seems nicely set up for high reward when replicated elsewhere.
- The demonstration addressed multiple aspects of H2@Scale, from different hydrogen sources to different hydrogen uses. The one potential drawback is that spreading the demonstration across so many facets may prevent pieces from being demonstrated at a representative scale for these applications.
- The dual RD&D tracks are well-explained. The approach seems sound. Understandably, there are some delays due to the COVID-19 pandemic.
- This project has a sound approach.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Most progress of this project is in its modeling and planning. Very few funds have been spent to date, considering the number of partners in the project. Good progress has been made on site selection and preparing equipment, as well as the modeling of Texas Computing power requirements completed for sizing of fuel cells and electrolyzers. The regional analysis for Houston will also be a key portion of the project, and although it was somewhat unclear, progress on that has started.
- This project has made good progress in a difficult time. The team has made good choices, such as changing location even though that increases the project timeline. The project has also made sufficient progress on the site and models. It looks like there is good opportunity based on hydrogen generation and peak shaving opportunities from modeling. Logically, the team chose electrolyzers and fuel cells based on needs. The team has had discussions about how its system would handle severe weather and other disruptions. Fuel cells could help in such events by releasing stored energy in times of need.
- The project is on track with meeting its milestones and go/no-go. The team made impressive progress on getting site approval, finalizing negotiations, and contracting. The project's first workshop already yielded interesting feedback from stakeholders and highlighted a critical question around the transition from pilot projects to commercial-scale hydrogen hubs and systems.
- The project is making very good progress, despite some delays on the deployment task. The project really seems well-conceived and targeted to DOE goals.
- The timeline is long enough that the project can make up the time lost to the COVID-19 pandemic.
- The progress made is significant, considering that work on this project started only one year ago.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- The partnerships on the project stand out the most. Having major energy companies (especially petroleum), utilities, original equipment manufacturers, and a major supplier of renewable natural gas (RNG) involved not only speaks to the potential impact of a successful project but also lends credibility and could elevate the project's visibility.
- This team consists of a large group of partners working toward this goal. It is an inherently cooperative project. Also, the principal investigators have partnering companies that could scale the results nationally or internationally.
- This is a very good team of collaborators that combines an innovative set of elements at the port, the data center, etc.
- The collaboration and coordination of academic, government, and industrial partners are excellent and clearly described.
- There is good definition of partners across the range of stakeholders and the supply chain. It was not clear whether there are regular team meetings or other interactions.
- There is a good variety of collaborators, especially in industry.

Question 4: Relevance/potential impact

This project was rated **3.8** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Determining multiple ways in which hydrogen production costs can be lowered by using different generation sources (electrolysis and renewable [SMR]) and power and fuel cell electric vehicle (FCEV) end uses is highly relevant to H2@Scale goals. The region of analysis, the Port of Houston, is a promising area for a hydrogen hub because of existing infrastructure, availability of renewables, and historical experience and demand for hydrogen. The feedback confirms the importance of de-risking investment in hydrogen infrastructure. Data center application is a growing demand for hydrogen, and this project will help to determine whether it is a promising and scalable early market for hydrogen.
- The project will prove out small-scale microgrid-type installation, but the analysis is scalable. The hydrogen production may be small (100 kg/day), but the approach and solution are scalable for sites requiring far more energy/storage for stationary and mobile fuel cell applications and having access to more resources (e.g., solar, wind, and RNG).
- This project has the potential to demonstrate key principles of the H2@Scale vision, from hydrogen generation to use. The project also includes interactions with local stakeholders of an important geographic region.
- This project is aligned well with the later phases of the DOE Hydrogen Program goal of adoption of hydrogen technologies. Reducing costs is, of course, key to implementation. The much larger project plan, the Port of Houston, is moving to hydrogen at large scale. Both are clearly aligned.
- This project is very much in line with the H2@Scale vision. The work on optimal sizing of systems for data centers is a great example.
- This project combines a critical set of elements around hydrogen at ports, integration of renewable resources, and fuel cells for power—highly relevant and likely impactful, once fully executed.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- The project's technical plans make sense. It is doing workshops to elicit concerns of potential participation in the larger Port of Houston project.
- A number of challenges facing the project were described, and logical contingency plans were discussed for barriers that are within the project manager's control. The proposed future work aligns with the scope and is consistent with the project objectives. The organization and data collection conducted at the Port of Houston workshops were not well-described. Strong outreach with stakeholders and publications will enhance the impact of the project prior to the project's end date.

- The proposed work appears to be more focused (versus progress to date) on local engagement with quantified workshops and communication plans. The modeling will be completed, and the demonstration will be initiated.
- The proposed future work, with outreach integrated from the beginning, aligns well with H2@Scale objectives.
- The team has its work cut out for it, but progress seems to be good, and the easing of the COVID-19 pandemic should improve the prospects for the demonstration progress.
- The future work seems appropriate, although there does not seem to be a resolution to the cost increases, so the project seems at risk.

Project strengths:

- This is an ambitious and exciting project that combines a number of critical elements in an innovative way. There is some degree of technology risk related to the source of hydrogen and the SMR element. This will be an interesting project to hear more about next year.
- Evaluation and comparison of different generation sources in a hydrogen hub, including renewable SMR, is an understudied area of research. This is a promising demonstration project for critical infrastructure, specifically a campus and data center, which may be an important early market for hydrogen.
- The project is located in Texas, where businesses care more about their independence and economics and elected officials seem to care less about the environment. The project approach integrates, from the beginning, the ability to replicate in other ports. Economics and factors other than environmental ones will ”speak to” officials in other red states.
- This project addresses a very valuable topic. The team has partners who could take this to the national or international level, if they wanted to do so. Also, the project is looking at smaller- and larger-scale issues. The results will be at least partially scalable. At worst, they will serve as a template of how to proceed and show the issues that one would need to address in a new region.
- The white paper/case study for the Port of Houston is a great first step in expanding hydrogen demand in the region beyond conventional uses.
- The project’s strengths include the breadth of team and scope, engagement with the local jurisdiction, and modeling to support business case and demonstration relevance.

Project weaknesses:

- Perhaps some technology risk associated with integrating the SMR generator is being understated, as the reviewer does not know much about OneH2, Inc.’s track record, especially for gas cleanup. Nonetheless, it is clear that the project team is well aware of these challenges. It would be ideal to have combined the two elements into a slightly more coherent overall project at the Port of Houston, according to the original plan, but it is understandable that those were best pursued in this way.
- The approach for extrapolating findings of the study to other promising regions of the country is lacking. The integration of systems was addressed at inconsistent levels of detail. It would be good to see more review on the potential challenges associated with resource availability of RNG or renewables for hydrogen generation, impact of carbon policy, and the need for storage.
- The planned work in the Port of Houston portion of the project is simply a plan, with no assurance of implementation. The value will come in the implementation, so this portion needs commitment from all partners and many groups that are not yet included to implement at least a major segment of the plan to reap its full value.
- The project’s breadth may lead to the use of hardware that does not accurately project costs to scale. For example, small electrolyzers and reformers are quite expensive and involve long extrapolations with changes in manufacturing methods and design approaches versus multi-ton systems.
- The hydrogen station seems to be small and thus does not really support further deployment of fuel cell vehicles.
- The small capacity of the hydrogen production systems is a weakness, but it is clear why that is necessary.

Recommendations for additions/deletions to project scope:

- The highest value will come from expanding the project to other buildings on the campus, and the cost of expansion will be lower than the initial effort because part of the infrastructure will exist already. However, expanding the system requires buy-in from many groups. Likewise, the plan for the greater Houston area really yields true value only when it is used and thus helps bring up the hydrogen supply chain, as well as implement the technology. Accordingly, the project needs to partner with social, political, and business groups to get the process going. There will be many hurdles that a good technical plan and analysis will not overcome, such as “not in my back yard” (NIMBY), entrenched interests, and political polarization. These take time, will, and momentum, and it is certainly not too early to start accumulating the support needed. There should be a much stronger effort toward setting the groundwork for these future expansions of the project. It does not work to end this project and then start working on getting a new one going. One needs to flow smoothly into the next, even if the funding shifts from DOE to the state of Texas.
- The approach for evaluating the use of hydrogen for the data center beyond “typical” operation, such as powering backup power and emergency energy needs of the data center, was not well-defined. This seems to be an important area for mitigating risk of investment but was not covered.
- The project should broaden statewide acceptance by enhancing messaging in the communication plan to align with the project benefits that are important to stakeholders, such as economics and resilient energy systems, and then find a way to sneak in the health and environmental-justice-type benefits into the messaging.
- If anything, perhaps small simplifications can be added to the physical part of the project to streamline, given the project demonstration status. A few more bells and whistles could perhaps be added after the basic system is running, with thought for forward planning.
- The project could strategize how to leverage the vehicles for outreach to help promote FCEV adoption.
- Technoeconomic analysis should include reference data for larger-scale equipment, if it is not included already.

Project #TA-041: Truck Duty Cycle Analysis

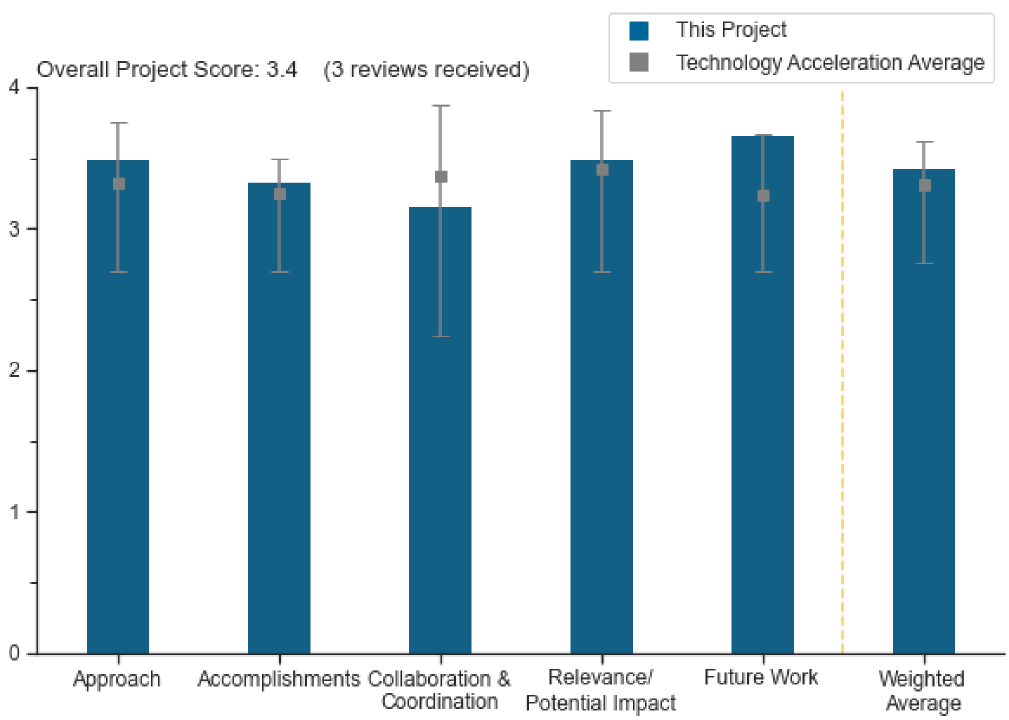
Jason Lustbader, National Renewable Energy Laboratory

DOE Contract #	WBS 7.3.8.2
Start and End Dates	10/1/2020
Partners/Collaborators	Argonne National Laboratory
Barriers Addressed	• Lack of package delivery vehicle performance data • Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools

Project Goal and Brief Summary

Operational drive cycle data are limited, making it difficult to analyze opportunities for hydrogen fuel cell vehicle design and adoption. This project aims to close that gap by developing real-world representative operational duty cycles for commercial vehicles to improve medium-duty hydrogen fuel cell vehicle simulation and technical target analysis. The project team will leverage existing fleet data to develop initial drive cycles for development, use data analytics to quantify the importance of existing data and identify areas where more data are needed, partner with fleets to collect additional data to fill gaps, and develop region-specific duty cycles to enable broad vehicle optimization. The work will support development of zero-emission hydrogen fuel cell delivery vehicles for last-mile delivery, reducing fleet emissions.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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 team summarized their approach concisely in a milestones chart showing how tasks relate to one another. The approach appears quite sound. The intent to develop the capability to estimate national-level duty cycles appears feasible based on the presentation.
- This is an excellent presentation and a great start. Using population and geographic considerations is a great start. Adding vehicle-to-load (auxiliary) loads for different types of services will be of interest in future projects. Connecting the project to include grid services based on the duty cycles would also be an ideal next step.
- The project is very well described and understood. The presentation flow where the approach of each separate task was described right before each accomplishment rather than presenting the entire approach upfront is appreciated. It allowed for much better understanding. The presentation is missing some discussion for why certain vehicles and regions were chosen.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has been meeting its milestones, as shown in several charts on results for Class 5 and Class 6 vehicles.
- Great insight has been presented to date. There are a few areas for improvement. The representative and bounding design cycles appear to have been identified but would benefit from a clearer graphic. It is curious how different the average is from the actual boundary design point for the vehicle (range, performance requirements, etc.). A lot of great work went into mapping the population density and hilliness, yet all of the initial data comes from just one section. The project could have provided more benefit with some strategic thinking upfront to capture a few more regional differences.
- The project is in preliminary stages. A bit more preliminary results and trends that may be emerging from the project would have been nice to see.

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.

- Collaboration and coordination between ANL, National Renewable Energy Laboratory, and DOE was well described and well received.
- More collaboration with industry partners to prioritize what vehicle types and regions to gather data from is suggested. The project should also have more discussions with the fleets to bring their insight beyond simply collecting data on their trucks. There is a great connection with Argonne National Laboratory (ANL) to leverage this data.
- While it's difficult to get delivery services to offer up their routing plans (usually quite proprietary), having some delivery services as a partner to offer generalized guidance on routing may be useful.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project will be useful in understanding vehicle sizing requirements, total fueling infrastructure requirements, and important use case scenarios.
- The combination of gathering real-world data and segmenting the entire United States is very interesting and valuable. More data and insights are anticipated.
- The project aligns well with DOE's research, development, and demonstration objectives and has the potential to advance progress toward DOE goals and objectives in these segments of the transportation sector.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- The proposed future work shows a clear understanding for what gaps remain and how to expand the project. This actually stands out compared to many other projects.
- The proposed activities are very logical continuations of this year's activities. The data collection effort will be a very important piece involving industry input.
- Adding vehicle-to-load (auxiliary) loads for different types of services will be of interest in future projects. Connecting the project to include grid services based on the duty cycles would also be an ideal next step.

Project strengths:

- This is an outstanding analysis topic. The project has a sound approach and a highly qualified principal investigator and partners. There is excellent progress and collaboration or coordination between partners and DOE.
- The project is well set up from an algorithm perspective to capture the variations in routes and frequency that can be expected in the United States.
- Access to more real-world data is always valuable, especially when it is already being utilized in a related project. The broad scope to categorize national operation is also surprisingly insightful and will help establish performance benchmarks.

Project weaknesses:

- There is a good amount of data collected, but the presentation and summary of key metrics could be compiled and improved to create more impact and understanding. The project also could have benefited from more diverse regional data rather than all from a similar category.
- The project needs some coordination with actual last-mile delivery fleet owners to better capture scenarios and considerations that might be missed with a model/algorithm-only approach.

Recommendations for additions/deletions to project scope:

- The project needs to get more data (as already intended). This includes both a variety of vehicle types and U.S. regions. Also, the project should look for a more effective way to package the key insights of the representative and boundary condition (design condition) data. The work is well done.
- Adding vehicle-to-load (auxiliary) loads for different types of services will be of interest in future projects. Connecting the project to include grid services based on the duty cycles would also be an ideal next step.
- As the presentation shows, additional vocation vehicles will be considered once this phase is completed.

Project #TA-042: Next-Generation Hydrogen Station Analysis

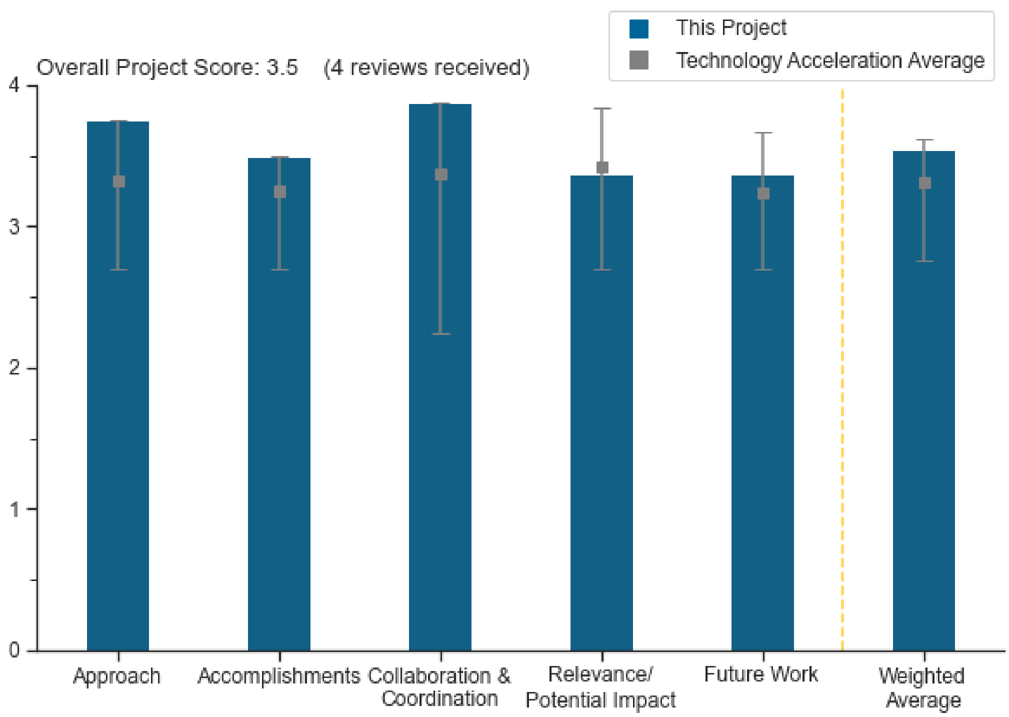
Genevieve Saur, National Renewable Energy Laboratory

DOE Contract #	WBS 7.3.8.2
Start and End Dates	10/1/2011
Partners/Collaborators	California Energy Commission, California Air Resources Board, South Coast Air Quality Management District, California Fuel Cell Partnership, IPHE (International Partnership for Hydrogen and Fuel Cells in the Economy), Association of Hydrogen Supply and Utilization Technology, Gas Technology Institute, California Department of Food and Agriculture's Division of Measurement Standards, Air Liquide S.A., Air Products, California State University, Los Angeles, Equilon Enterprises LLC, FirstElement Fuel, H2 Frontier Inc, ITM Power, Iwatani, Linde plc, Messer Group GmbH, Proton OnSite, Nel Hydrogen, Shell, StratosFuel, Inc
Barriers Addressed	• Lack of current hydrogen refueling infrastructure performance and availability data

Project Goal and Brief Summary

This project will evaluate existing hydrogen stations and equipment to provide an independent analysis of advanced hydrogen and fuel cell technologies operating in real-world conditions. The evaluations will provide insight into the research and development needed to improve performance and adoption, validate existing technologies against technical targets, provide regular technology reporting to align industry without revealing proprietary information, and establish the status and trends of durability, fuel economy, range, and driver behavior.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

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 is excellent and has proven so over the years through composite data products (CDPs) used by DOE and stakeholders.
- The project has a great approach and does an excellent job obtaining a robust data set through collaboration with industry partners.
- The approach is optimized over years of data collection.
- Additional data cleaning and investigation of outliers would be helpful, though it is understood that the input data and communication with the station operators are limited.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has been generating highly useful data on an emerging industry, thanks to the trust placed in the National Renewable Energy Laboratory (NREL) by industry.
- A vast set of CDPs are available. The CDPs are useful and relevant.
- This project achieved all goals laid out in objectives/goals set by DOE. The project could benefit from shifting from light-duty (LD) vehicles and an LD infrastructure focus to heavy-duty (HD) vehicles and an HD infrastructure focus, where more transparency of equipment performance and durability is needed because of the expected rapid transition from conventional technology to zero-emissions technology. This could also help to better align expectations of future LD vehicle station capacity and gaps where lessons can still be learned. The comparison to compressed natural gas and liquefied natural gas station equipment components and maintenance may be helpful for benchmarking purposes and knowing when data collected are satisfactory.
- The consistent updating of the CDPs is of great value to the community in identifying where improvements for stations are needed the most, though better analysis of how downtime and other unplanned events affect costs would be even better.

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 with those who provide confidential information has been outstanding.
- The project has great collaborations, which are necessary to obtain statistically significant and broad data sets.
- Collaboration in this project is excellent.
- The collaboration with California agencies seems strong, but better communication/collaboration with station operators would improve this project (though that is understandably difficult).

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is very relevant and useful to both DOE and the broader industry for making decisions. The data appear trustworthy and reasonable. Where it is possible, CDPs should be used to inform and validate future-looking (modeling- and simulation-based) DOE programs.
- The project aligns well with DOE's research, development, and demonstration objectives and has the potential to advance progress toward DOE goals and objectives related to hydrogen infrastructure and fuel cell electric vehicle (FCEV) deployment.
- This is not the most exciting project, but it is definitely impactful. This work helps in understanding trends and estimating future costs of hydrogen and refueling stations.

- The current project objectives appear outdated compared to the state of technology and the rate of technology development by industry. NREL is delivering on the set objectives, but it is recommended that the project shift focus and re-align to provide cutting-edge value.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- More work on component reliability and maintenance trends will be very helpful. It is good that this was proposed by the team.
- The future work is on target. It is good to hear that new CDPs can be developed by reaching out to principal investigators/researchers.
- The future work is good, but it is business as usual. The team should consider exploring how this can be accelerated to align with the pace of technology development and industry focus on rapid acceleration of infrastructure rollout. The team might consider assessing whether some ultimate targets from the Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan may be too high and whether industry and users are satisfied with current equipment performance (e.g., slide 14).
- Including an analysis by station and component age would be very helpful.

Project strengths:

- Obtaining and aggregating fueling station data are very important for the industry, both to benchmark where progress has been made and to help predict where it is going. This project does a great job of doing that in a controlled and consistent manner.
- Tracking performance parameters of technology components is useful for public understanding of these parameters.
- The project has a sound approach and a highly qualified team. There are great partners, particularly from California. The project has useful results.
- The project is developing a great data set for the community, in particular the maintenance/downtime data.

Project weaknesses:

- The project's weakness is the ongoing data collection on the same components and variables, while expanding and refocusing the scope over the years. The focus should shift from "collection of all data available" to "key station components or variables that are new to industry data collection." Another weakness is the state of technology focus. Technology is developing rapidly, with increased attention on station rollout and scale-up. With every new round of government-incentivized station rollout, shifts in use of specific technology and capacity of technology occur. It appears that industry is learning rapidly, and by the time data are assessed and analyzed, the data collected are already "old news."
- The project could be improved through further analysis on the costs of downtime (estimated missed fueling events) and clear presentation detailing station capacity.
- It is unclear whether private transit bus fueling stations are included in this analysis. It would be important for our industry to be able to produce results and CDPs specifically for these fleets.
- There are no weaknesses.

Recommendations for additions/deletions to project scope:

- The project could benefit from a shift from LD vehicles and an LD infrastructure focus to HD vehicles and an HD infrastructure focus, where more transparency of equipment performance and durability is needed because of the expected rapid transition from conventional technology to zero-emissions technology. This could also help to better align expectations of future LD vehicle station capacity and gaps where lessons can still be learned.
- More CDPs are recommended for private stations, including and separated by transit bus fleets, Class 8 truck fleets, and medium-duty truck fleets.
- An age-based and FCEV stock-based analysis of utilization should be included.

Project #TA-043: Electrolyzer Stack Development and Manufacturing

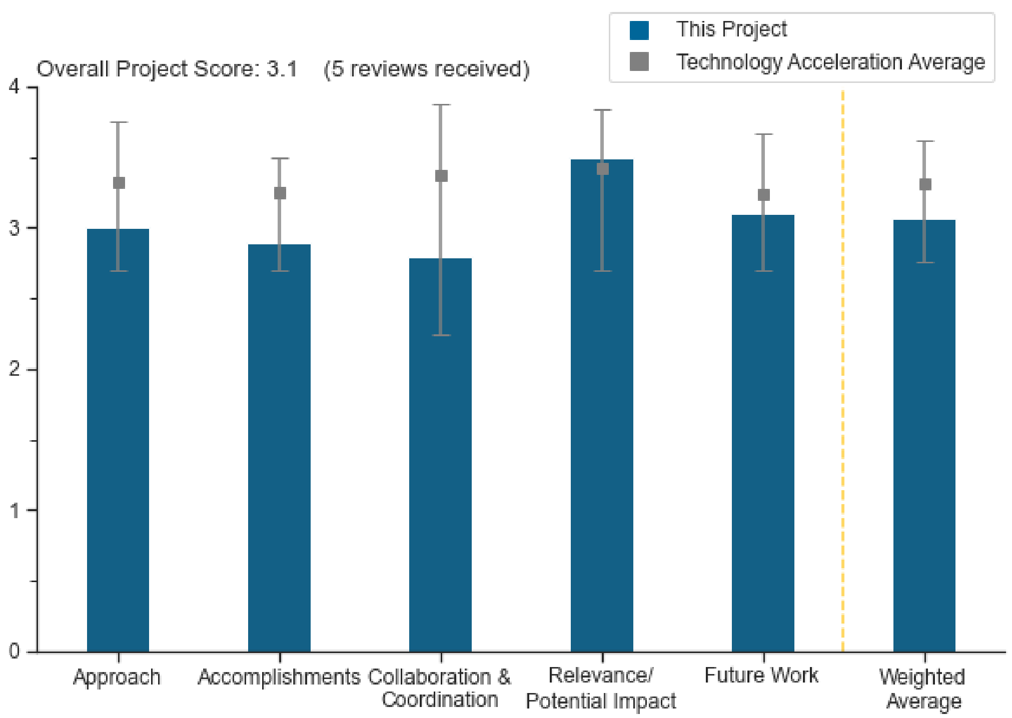
Olga Marina, Pacific Northwest National Laboratory

DOE Contract #	WBS 7.2.9.2
Start and End Dates	10/1/2019
Partners/Collaborators	Pacific Northwest National Laboratory, Idaho National Laboratory
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Renewable electricity generation integration • Manufacturing

Project Goal and Brief Summary

Pacific Northwest National Laboratory (PNNL) and Idaho National Laboratory (INL) are collaborating to develop complete high-temperature electrolyzer membrane electrode assemblies (MEAs) and make them available to other national laboratories, universities, and industry for testing and further development. The project team will also initiate stack and related component degradation studies using a baseline stack, investigate new fabrication techniques to lower cost, and develop a predictive stack digital twin.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

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.

- Establishing a baseline solid oxide electrolysis cell (SOEC) and SOEC stack from which material and process development studies can be launched seems to be a useful concept for the Hydrogen and Fuel Cell

Technologies Office (HFTO) and its support of SOECs within HydroGEN and the high-temperature electrolysis (HTE) part of Hydrogen from Next-generation Electrolyzers of Water (H2NEW). PNNL has worked on solid oxide technologies for a long time and brings a good deal of material and process knowledge. The degree to which the designs of the PNNL cell and stack are similar to what industry may be pursuing should be further detailed. If this is to be an ongoing testbed and capability for HFTO, then relevance to industry should be well-understood and improved if needed.

- The approach to achieving a goal to develop anode-supported cells and make them available to laboratories, universities, and industry is feasible, but more focus should be truly given to validation of large cells in a stack (at least a short stack of three to five cells). The cells seem to have significant camber and should be evaluated in stacks (for both performance and durability) before significant efforts are made to reduce the cost since the data may identify different priorities, such as cell forging, which will significantly affect the cell cost.
- The project framework fits into a larger program and has an array of single cell sizes, as well as 300 cm^2 stack platforms, to conduct the experimental testing. However, it is not clear from the presentation how the small cell test results transfer to the larger-scale stacks. The items being developed are key to obtaining good efficiency and a low degradation rate.
- PNNL is leveraging its considerable experience in stack design and development from its many years of working the solid oxide cell technology and, specifically, in stack development with Delphi Corporation. PNNL also is using its stack modeling expertise to support the design of the stack platform. The focus on large-area cells for the stack being developed by PNNL should be explained. A stated project goal is to "develop complete HTE MEAs and make them available to other national labs, universities, and industry for faster transition material development progress to realistic testing." If this is the goal, the reason for designing the stack for large-area cells is unclear. This needlessly increases the cost of the validation testing of the developmental cell and stack materials. Further, stack development is an extremely challenging endeavor in the first place and is made much more difficult when stack active area is increased. Another pragmatic question about 375 cm^2 active area cells is related to how current will be delivered to the stack when operated at high current density (1 A/cm^2). This corresponds to 375 amps, which may be difficult, given the high temperatures involved. PNNL has likely identified a solution to this challenge.
- While generally the approach seems reasonable, it is unclear exactly how the standardized HTE MEAs will enable faster transition of material developments to realistic testing. It would be useful to provide more information on the exact vision of how this will be implemented once the project is complete. PNNL noted that commercially available MEAs are cost-prohibitive, and one objective of the project is to provide MEAs to laboratories, universities, and industry (presumably) at a lower cost. It is unclear at what scale PNNL is intending to make the MEAs and at what price PNNL is intending to sell them. Moreover, since PNNL is not a manufacturer, it is unclear what quality control steps can realistically be put into place to ensure high-quality MEAs at scale for testing unless the project intends to set up a pilot production facility. This may not be the ultimate goal, but without more information, it is unclear how to fully gauge the approach. Similarly, in addressing performance and cost targets, PNNL described moving toward a thinner yttria-stabilized zirconia (YSZ) in a flat part of a relatively large part, but details on how yield was assessed are somewhat lacking (even after the presenter answered questions from the reviewers); the advantages of larger cell size are clear, but yield can be much lower, both in cell production and in use in stack assembly. If not already part of the approach, PNNL may want to look at such relationships as a way to achieve the cost and performance targets of the U.S. Department of Energy.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Establishing cell materials, cell build at a useful scale, stack build, stack testing, and thermal/mechanical models all appear to be strong accomplishments, presumably highly leveraging past efforts on solid oxide fuel cells (SOFCs). The microchannel vaporizer is a nice example of how the team innovated to overcome challenges on the project.
- The primary accomplishments were the successful fabrication of large-area anode-supported cells and the establishment of a stack platform based on these cells. PNNL completed a milestone for making 20–30 cells with a yield of >90%, but the yield metrics were not specified. Certainly, cell camber was one of the

metrics, and PNNL demonstrated a substantial improvement in camber by reducing YSZ membrane thickness (as shown in slide 6). That said, even the "flatter" cell shown on slide 6 had more camber than would be desired for use in actual stacks. It is suggested that quantifiable quality control (QC) metrics are needed for cell yields (e.g., camber and geometric measurements, dye intrusion for quantifying defect density, high-pot testing, etc.). PNNL will be making many cells over the next year to support stack testing, so there is opportunity to obtain these QC data.

- Taking into consideration delays due to COVID, the team has made significant strides in successfully scaling the cells to 300 cm and has achieved over 90% yield using the tape casting process. This is indeed a great achievement. Based on the milestones, there has been significant delay in 1 kW stack testing with 200-hour runs, which is understandable, but the team is at 80% completion on the task, meaning that a stack will be tested any time now. However, it would be beneficial to at least demonstrate short stacks of three to five cells as soon as possible and see whether cell and/or stack modifications need to be made (camber, performance, durability) before perhaps committing to durability testing and performance targets.
- It is good to see that the MEAs were made with very thin YSZ membranes, but the key achievement will be to show the stack performance (degradation), which will show the true value of the development. The 1,000-hour test data shown in a graph were obtained in different operating conditions, making it difficult to self-assess the degradation rate.
- While progress seems to have been made on making a thinner electrolyte to reduce cell cost, additional details would be useful in gauging actual progress toward project objectives. The thinner electrolyte was described as being 6–7 microns and made using tape casting. It was further mentioned that there were no issues with handling the thin tapes. While tape casting is done on a carrier film, which can help with handling of thin tapes, tapes in production environments are rarely done below ~10 microns, especially when further laminating multiple tapes together (because of handling issues). To gauge progress and comment on potential risk in scaled-up manufacturing, it would be helpful if PNNL provided additional details on the exact cell structure and process, the cost target for cell manufacturing, and the intended scale of manufacturing the team eventually intends to use to meet the goal of providing cells to national laboratories, universities, and industry for faster transition of material developments. To gauge progress on the 5 kW stack testing platform, it would be useful to know if this unit benefited from designs and approaches used by PNNL for the laboratory's SOFC stack test stand. Since that equipment has already been built and evaluated, it would benefit the PNNL researchers to mention whether they reduced risk in this way. If they did not do this, then PNNL should go into more detail regarding what they did to ensure the test platform functions as intended and can be used throughout the remainder of the project without any issues.

Question 3: Collaboration and coordination

This project was rated **2.8** for its engagement with and coordination of project partners and interaction with other entities.

- There is strong need for these material developments for the SOEC industry, so it should not be too difficult to gain interest from third parties to adopt this technology and subscribe to the roadmap at an early stage (also in the international arena). The technical achievement to make steam in situ also looked like something partners and peers would be willing to adopt quickly.
- Partnership between PNNL and INL makes a good deal of sense and is good to see. Going forward, a more explicit connection with the HTE part of H2NEW should be pursued and incorporated, especially if the intent is for this to be an ongoing development testbed. More explicit and direct connection to industry really should be pursued in the next budget period to ensure relevance and address industry interest and needs.
- The team has been collaborating and working closely with INL, has engaged with SOEC manufacturers, and has been establishing collaboration with supply chain companies. It would be helpful to get more details for each of the statements made in the presentation, such as the feedback from the U.S. manufacturers and supply chain companies and whether any bottlenecks or areas of prioritization were identified based on the customers' needs.
- PNNL is working in close coordination with INL. While PNNL researchers mentioned that they are also engaging with U.S. SOEC manufacturers, it is unclear how the project intends to engage with them. Since a primary goal of this project is to provide standardized MEAs to national laboratories, universities, and industry, it would benefit PNNL to discuss the approach with as many of these organizations as possible so

as to avoid potential issues with the eventual sale of MEAs and/or sharing of knowledge (e.g., cell/stack manufacturing) that will ultimately help the U.S. accelerate its HTE technology development.

- No real evidence of collaboration was presented, aside from PNNL's collaboration with INL. The nature of collaborations that will be possible with U.S. SOEC manufacturers is unclear, given that all of them are pursuing stack designs that are significantly different from the one being pursued by PNNL.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project will make significant advances toward the DOE Hydrogen Program goals and objectives by scaling small anode-supported button cells to large cells and making them available for testing and product development. This will allow teams to accelerate development of electrodes, seals, and coatings. Moreover, the capital cost target, along with an aggressive current density target at high efficiency, will help the mission of hydrogen production at lower cost.
- If PNNL is successful in developing the SOFC stack platform on this project, there is potential for significant future impact if this platform can be used for future stack material developments, especially in conjunction with long-term stack testing at INL. A good example could be in developing improved contact paste materials, in addition to more commonly mentioned seals and air electrode materials.
- Achieving this thin membrane successfully is key to getting SOEC to deliver on its efficiency promise, making it more attractive as a technology to make hydrogen cheaply. The work on the electrodes was not discussed as much but is also essential, and this area (including interfaces with YSZ) is not yet understood well. The team has key expertise that will generate the right answers soon.
- The potential benefits in some operational cases of SOECs over polymer electrolyte membranes do demand support from HFTO in the broader H2@Scale and H2NEW pictures, so this testbed and activity are highly relevant in the big picture. Closer into the details, industry feedback and participation is a large need. Also, if this is meant to be an ongoing activity, then a mechanism for this activity to connect with and support other HFTO/H2NEW activities needs to be established. Otherwise, the benefit of an ongoing activity is not clear.
- Generally, the project seems to have a good objective in mind and could potentially have the intended impact. However, a concern is that, in practice, there will be issues that may limit the effectiveness of project outcomes on achieving the intended goal. (Some of these limitations—e.g., tape size and handling and confirmation that the test platform functions as intended—are discussed in the response to question 2.) The PNNL team may have thought through many of these potential issues, but if that is the case, it would be beneficial to discuss them.

Question 5: Proposed future work

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

- The combination of process, testing, and modeling efforts seems very appropriate for a testbed type of activity. Integration between these efforts will be very important. The digital twinning could be very interesting; more information about how it will be developed and used will be necessary. If the intention is for this to be an ongoing support ("core lab") activity, more direct connection to H2NEW seems like it should be an absolute necessity. Otherwise, the value of the ongoing activity is questionable. There were good comments during the presentation about quality; further work here could potentially be useful and could leverage other HFTO capabilities in this space. H2NEW could be a vehicle for this.
- The plan for future work is reasonable. Understanding whether the large cell camber/forging needs to be modified, based on the preliminary stack tests, should be included.
- It will be good to see the 300 cm^2 stack being validated with the new developments included in the MEA design. The next steps are unclear, as it was mentioned that the thickness of the membrane was already minimized.
- PNNL has an aggressive set of milestones to be achieved in 2021, such as a 200-hour test of a 1 kW stack in June and achieving high performance in a 5 kW stack in September. Without knowing what the stack "improvement opportunities" (mentioned on slide 10) are, it is difficult to assess the plan to meet these milestones.
- Logically speaking, it makes sense for PNNL to shift now to short stack testing. However, given that quality control was described as having been assessed as a simple visual check (e.g., no evidence of

obvious pin holes), it is advised that PNNL also strive to truly determine whether the quality control yield is as high as the team says it is. Combined with various metrology methods, the testing should probably include making batches of cells and testing single cells to assess performance. Then the team should shift to short stack testing and do the same thing. Very little detail was provided about the digital twin model and the purpose of this method over past efforts.

Project strengths:

- The project has a comprehensive understanding of the MEAs for SOECs, including electrodes, membranes, and interfaces, with results presented that were cutting-edge according to the status quo in industry.
- PNNL seems to have achieved a manufacturing process that can make cells of different sizes, which may be useful for the intended eventual use of different national laboratories, universities, and industry for the purpose of speeding up of the transition of material developments into actual HTE systems.
- PNNL is leveraging its considerable stack design, modeling, and development experience in this project. Cell fabrication skills are evidenced by the team's successful cell size scale-up work to date.
- The project has benefitted from great leveraging of past capabilities at PNNL and INL. The project has a good combination of experimental and numerical work efforts.
- The demonstration of large cells with reduced electrolyte thickness is encouraging. The initial performance in SOEC mode is encouraging, but it is not clear what cell size (button or large) was used to generate such data.

Project weaknesses:

- It was initially unclear how the initial results on small cells will translate to bigger plates, taking into account the variability of operating conditions, but this question was answered after the presentation. Also, strong interest from industry in these pending results (on a stack) is expected, but this "channel to market application" was not elaborated clearly.
- The overall intention of this project is not clear. It is unclear whether this is supposed to be an ongoing testbed supporting HFTO SOEC activities broadly. If so, a broader approach and understanding of how this activity should connect with HydroGEN, and especially with H2NEW HTE activities, seems like a must. The approach cannot look like just a separate research project doing some testing and modeling. The approach has to be how the activity will support the community. Industry connections also seem like a necessity.
- It is still early to say (based on the presentation) whether cell warping remains a challenge and whether forging/flattening can be eliminated. Stack tests are needed to fully address this area. The electrolyte leakage/absence of such has not been addressed/quantified on the large cells.
- The details of the project are lacking. It is unclear whether the described status (e.g., yield) is actually as good as described and/or whether such metrics will hold as scale is increased.
- There is questionable focus on large-area cells for the stack.

Recommendations for additions/deletions to project scope:

- The team is asked to elaborate on the performance degradation, utilizing the multiphysics and the array of cell platforms, to identify clearly whether the good performance is lost as a result of off-specification conditions, non-uniformity, or just basic material degradation mechanisms (diffusion). The variety between small to large cells and five-cell stacks should provide sufficient statistics.
- More focus should truly be given to validation of large cells in a stack (at least a short stack of three to five cells). The cells seem to have significant camber and should be evaluated in stacks (both performance and durability) before significant efforts are made to reduce the cost, as the data may identify different priorities, such as cell forging, which will significantly affect the cell cost.
- The project needs to clarify the scope and intention of the activity. If it is supposed to be an ongoing support testbed, then how that will be accomplished within related HFTO and industry activities needs to be clearly defined and pursued. It cannot be an ongoing project but support only its own goals. To be clear, there is a good opportunity here for an ongoing supporting testbed, but that aspect needs to be better defined and enabled.
- It is unclear what the purpose of the digital twin modeling is and how it supports the project. This is not an advocation for the digital twin modeling's deletion, but it would be beneficial for PNNL to emphasize the purpose of this particular approach and how it helps achieve the overall project objectives.

Project #TA-047: Rail Refueling Analysis

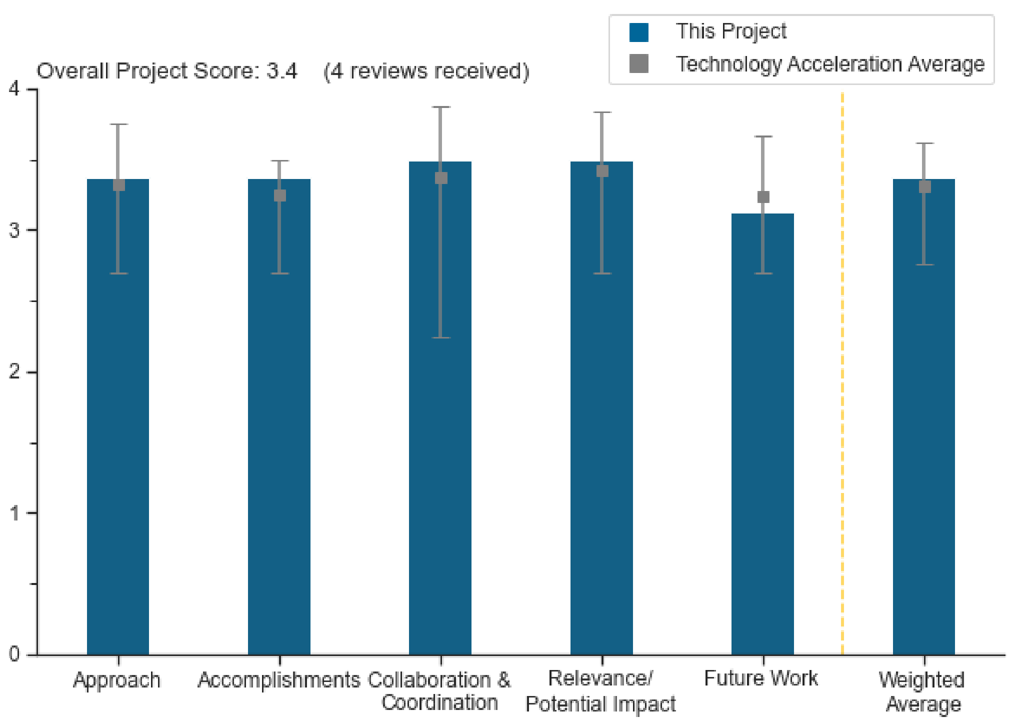
Brian Ehrhart, Sandia National Laboratories

DOE Contract #	WBS 9.2.0.2
Start and End Dates	5/1/2020
Partners/Collaborators	Argonne National Laboratory, California Department of Transportation, San Bernardino County Transportation Authority, DB Engineering & Consulting
Barriers Addressed	• Lack of hydrogen/carrier and infrastructure • Options analysis • Other fueling site/terminal operations • Safety, codes and standards, permitting

Project Goal and Brief Summary

This project aims to assess gaseous and liquid hydrogen refueling for freight and passenger rail to identify examples of scale, size, and cost of refueling infrastructure. This assessment will better inform future efforts to design and construct rail refueling infrastructure and identify areas for future improvement. Sandia National Laboratories (SNL) is collaborating with Argonne National Laboratory (ANL), California Department of Transportation (Caltrans), the San Bernardino County Transportation Authority (SBCTA), and DB Engineering & Consulting on this project.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- SNL has made a good start on bottom-up designs for rail refueling. The range of options for gaseous hydrogen (GH2) to liquid hydrogen (LH2) storage and the low number of 10 trains to 200 trains show how difficult it may be to build out fuel depots. The project has identified the key metrics (and barriers) quite well: scale, footprint, and a very rough estimated cost. It will be interesting to see how this information can be used to inform passenger versus freight transition priorities. These figures will be key to overcoming knowledge gaps and barriers holding up deployment of hydrogen trains in the United States.
- The project approach addresses the identified barriers. Assessing both LH2 and GH2 fuel options, along with varying numbers of train assets and configurations, provides a lot of information in a concise manner. Providing example station design concepts, but not complete solutions, gives potential interested parties an idea of cost, complexity, and footprint.
- Bounding the infrastructure requirements for rail using analysis is a very logical first step in informing key stakeholders about this future application. It was not clear what level of analysis was performed and if the analysis is a full process simulation or more of a mass/energy balance in a spreadsheet.
- The approach of a bottom-up design is reasonable. The various trade-offs being considered, such as GH2 versus LH2 , large versus small fueling, and passenger versus freight operations, are the major items to be considered given the vast difference in size and operations of the various segments in the rail industry. The key metrics are scale, footprint, and cost, with cost and footprint having a major impact on the feasibility of utilizing current hydrogen fueling concepts and the need to develop new technologies and designs. There is some concern that the hydrogen fueling station designs rely too heavily on hydrogen fueling station designs for heavy-duty (HD) trucks and buses. These designs may not be adequate to meet the rail needs, particularly with respect to the footprint of the station relative to the footprint of the current diesel fueling pads.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- SNL has made good progress in scoping out the design parameters. This is critical to meeting the DOE goals for costing out infrastructure and determining what the main barriers are to decarbonizing transportation beyond cars and trucks. Detailed attributes have been scoped out such as passenger refueling pressure (350 bar) and refueling rates. The project goal is straightforward in assessing both GH2 and LH2 for rail using key infrastructure attributes such as scale, size and cost. This short, one-year progress has shown the trade-offs needed when considering LH2 or GH2 fueling for trains relative to footprint, refueling speed, and codes and standards requirements.
- The progress on this project has been extensive. The project has done a thorough job at developing refueling designs and the equipment required with each selected refueling option.
- The initial results were illuminating. Providing more context by comparing to the incumbent technology would be appreciated, especially for the larger freight systems. For example, the following information could be provided: (1) how diesel refueling is accomplished today; (2) if the depot has a fuel pipeline or if diesel is trucked or shipped in; (3) whether the technology is refueled overnight in series or parallel; (4) if a new approach to refueling needs to be invented or if the previous one can be copied with right-sized equipment for hydrogen.
- The project is developing cost estimates for various hydrogen refueling designs and is reported to be on schedule for delivering a final report at the end of June 2021. A comparison of the estimated cost for a hydrogen fueling pad and the cost of installing and maintaining a new diesel fueling pad would be very beneficial for identifying potential research and development needs to reduce costs and enable deployment within the current confines of existing fueling pads. In the table of results shown for “Multiple Units Passenger Rail Preliminary Results,” explain if 341 cascade storage tanks for the compressor cascade and the cryopump cascade is really a reasonable conclusion.

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.

- SNL has done an excellent job of coordinating stakeholder input and finding key partners who are most likely to pilot and enable hydrogen-powered rail here in the United States. Caltrans is instrumental in getting the first projects in the ground for California. ANL has a wealth of knowledge on refueling costs and hydrogen delivery design choices. Deutsche Bahn (DB) Engineering and Consulting is closely related to the relatively mature and expanding fuel cell train pilots currently being tested in Europe. Chart Industries, Inc. has extensive knowledge on large-scale hydrogen storage and is embarking on studies of LH2 tanks. SBCTA appears to be the nearest and most interested location to trial a hydrogen train in California. This extensive group of collaborators is critical to SNL starting with the correct input and demand required to complete the project of estimating needs of rail infrastructure.
- The project has good collaboration with ANL, which is developing the total cost of ownership (TCO) for locomotives in the three different types of rail operations to understand the fueling requirements for each type of locomotive. It is not clear if SNL is collaborating with ANL staff who developed the Hydrogen Delivery Scenario Analysis Model (HDSAM) tool for fueling delivery analysis. If not, it is suggested that the team collaborate with ANL's Systems Analysis Team. Collaboration with Caltrans and SBCTA provides an understanding of the fueling requirements for different types of commuter operations. Collaboration with DB Engineering and Consulting provides insight into the design and operating requirements for current hydrogen fueling stations. The project would greatly benefit from collaboration with a Class I railroad, The Association of American Railroads, or a consultant familiar with the industry to better understand the fueling needs and requirements for long-haul diesel locomotives, which constitute the majority of locomotives and fuel consumption in the rail industry.
- The team is strong and has a good number of stakeholders that appear to be providing feedback. Since this project is highly design-focused, it is expected to have a smaller team due to no physical build requirements.
- The extensive list of industrial collaborators is admired.

Question 4: Relevance/potential impact

This project was rated **3.5** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This work on evaluating hydrogen rail will be critical in bringing hydrogen demand to the scale that is required to be economical. This is a key objective of DOE. The size of these stations and the breadth of both passenger rail and freight rail will be important to support emerging passenger car demand and may outstrip demand from hydrogen trucking. This early evaluation of station types and identifying key barriers is the first step in meeting DOE's research, development, and demonstration objectives for additional hydrogen fuel cell deployments.
- This project is providing an extensive amount of information for stakeholders to review. The impact of this work is great in that it provides information required for decision makers. Additionally, the setback distance analysis will have a far-reaching impact on current LH2 users and those that have not used it due to the current safety requirements.
- Understanding the infrastructure requirements and the associated costs required to support the deployment of hydrogen-fueled/fuel-cell-powered locomotives and multiple units in the rail industry is critical for enabling the railroad operators to make the decision to convert to hydrogen/fuel cell locomotives and multiple units (MUs). TCO focused solely on the locomotive or MU is not sufficient for the railroads to make this decision. This project supports the DOE Hydrogen Program (the Program) goal of developing the technologies needed to enable the conversion of HD transportation, in this case railroads, from diesel to hydrogen/fuel cell technologies.
- This work is very important to understand the potential hydrogen-in-rail applications and if rail yards can function as mega hydrogen hubs.

Question 5: Proposed future work

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

- Developing cost estimates for the various designs is critical for developing a path forward for determining the best fueling option for the various types of rail service. Estimating the footprint for the various fueling options being studied is critical for accessing the feasibility of deploying a hydrogen fueling pad at an existing diesel fueling pad. Depending on the outcome, new designs and/or new safety regulations and codes may be required to enable deploying hydrogen fueling pads at existing diesel fueling pads. It is assumed that the work scope, focused on estimating basic delivery or production needs for each design, will only address the amount of hydrogen needed on a daily, weekly, or monthly timeframe and will not address how the hydrogen will be produced or delivered to the hydrogen fueling pad. This reviewer does not see any benefit to addressing how the hydrogen will be produced or delivered given that there are many factors that will determine how this is done in the future and it is beyond the scope of the project.
- The proposed future work to further refine cost estimates and facility designs will keep the project on track. The most interesting work may be on how to look at combined fuel depots or radical new fueling schemes as the throughput of hydrogen outstrips LH2 truck delivery, and even hydrogen pipeline throughput. These facilities will likely require an integrated production and refueling facility, which can further reduce boil-off and enable further economies of scale with extensive process integration.
- The proposed work is in line with the current approach. Obtaining accurate cost and additional footprint information will be critical to decision makers.
- The 2021 goals are logical, but the project states that the 2022 goals will be presented in a later report. It would have been preferred to hear a clear vision for 2022. Also, remove the caveat about future funding; it is tacit and comes off as hesitant. Present a bold vision; even if it is missed, at least it is aiming high.

Project strengths:

- The strength of the project lies in the clear quantitative analysis of refueling needs: throughput of hydrogen (refueling rates), footprint, and storage of onsite fuel with required setback distances. Very quickly, SNL has captured the scale of a few trains at a few tonnes per day all the way up to 1,500 tonnes per day for a major freight train fuel depot.
- The overall strength of this project is that it is important work to inform an important application with a clear approach. It is systematic and comprehensive at looking at different vehicle configurations and different fueling configurations. The results are interesting, especially when put into context with the scale of U.S. LH2 generation.
- The strong analytical approach with a great deal of useful and informative information is the project's strength.
- Understanding the cost of hydrogen fueling pads is a critical factor in understanding the overall cost of the infrastructure changes required to support the deployment and operation of hydrogen-fueled/fuel-cell-powered locomotives and MUs. From the railroads' perspective, a TCO focused solely on the locomotive or MU does not provide a true picture of the total cost that will be incurred in switching from today's diesel locomotives to hydrogen-fueled/fuel cell locomotives. For example, when railroads switched from steam to diesel in the 1940s–1950s, a TCO focused solely on the locomotive would have shown that the cost of the diesel locomotive and diesel fuel were significantly higher than the cost of a steam locomotive and coal. However, the lower cost for the supporting infrastructure and manpower for diesels more than offset the higher cost of the diesel locomotive and diesel fuel. Understanding the cost of the infrastructure required for hydrogen-fueled fuel cell locomotives is important in understanding the total cost railroads will incur in switching to hydrogen.

Project weaknesses:

- If ANL's HDSAM is being used in this analysis, it should be acknowledged. If not, it is unclear what the shortcomings are in HDSAM that would not make it applicable for this application, since HDSAM is used in the vast majority, if not all, of the Program's hydrogen delivery analyses. The team should speak with Class I railroads to better understand their fueling requirements, such as the required fueling rate and expected fueling times, as well as the design of the fueling pad. The design of the fueling pad can have a major impact not only on cost, but also on operations, which will equate to a cost. Freight locomotives are often operated in combinations of two to three units, and the locomotives are fueled simultaneously without uncoupling the locomotives. These factors will have a significant impact on the hydrogen fueling station design. A fueling rate of 10 kg/min, as shown on the "Freight Rail Preliminary Design Inputs" slide, is unrealistic given the volume of the fuel required for long-haul freight. For regional passenger locomotives, the fueling infrastructures will differ significantly depending on the size of the operation. For example, a smaller commuter operation, Virginia Rail Express in the Washington, D.C., area, has two routes that diverge from a single route out of Washington, D.C., and it operates a limited number of trains daily. One fueling pad may be sufficient to meet its needs. Larger commuter rail systems such as Chicago's Metra have multiple routes with multiple fueling pads. Again, understanding their fueling requirements is critical for costing and designing hydrogen fueling that meets their requirements.

- It would have been interesting to see how these results could be applied to a physical location to better understand the true barrier of dispensing hydrogen at this scale. Presenting the figures and numbers alone, without an overlay to a real-world location, is a weakness. This would be especially interesting at the higher end of demand with freight rail. The chart comparing the different compression and cryopump options with flow rate was interesting but could have been more relevant if power was also included in the table. The transformer and power connections could have an impact on footprint when considering the throughput required. This may be outside the scope of the project.
- The overall weakness of this project is the lack of pipeline consideration and adequately describing the current incumbent technology/methodology.

Recommendations for additions/deletions to project scope:

- The project needs to take into consideration the larger footprint required for a hydrogen fueling station compared to a diesel fueling station. It is unclear if space is available at existing fuel pads to accommodate a hydrogen fueling station. Space is limited, particularly in urban areas where many fueling pads are located. It is unclear if existing designs for hydrogen fueling stations, based on station designs for HD trucks and buses, will be adequate for rail or if new designs will be required. It is not clear if the design of the hydrogen fueling pad accounts for the need for large hydrogen storage tanks to support the fueling pad; however, this will be critical to meet demand. Again, this will be an added footprint issue as well as introduce additional safety requirements.
- Where appropriate, it would be interesting to have closer coordination between the first few rail project demonstrations in California and the United States. SNL has a wealth of knowledge, and it would be good to see this more directly applied to upcoming pilots and demonstrations. It would be interesting to further understand practical implementation at 1,500 tonnes per day or the average upper limit for freight rail fuel depots in the next five years.
- It is recommended, in future presentations, to outline how the incumbent technology performs refueling and the infrastructure required. Highlight where hydrogen can copy and where innovation is needed. Optimization was mentioned in slide 8, but it was unclear what property the project was optimizing for (e.g., cost, footprint, etc.). Please clarify in the future. Also, it is not clear why the project uses 350 bar and not 700 bar, as many HD applications are considering 700 bar. That raises a question of whether rail has a special concern.

Project #TA-048: Advanced Research on Integrated Energy Systems (ARIES)/Flatirons Facility – Hydrogen System Capability Buildout

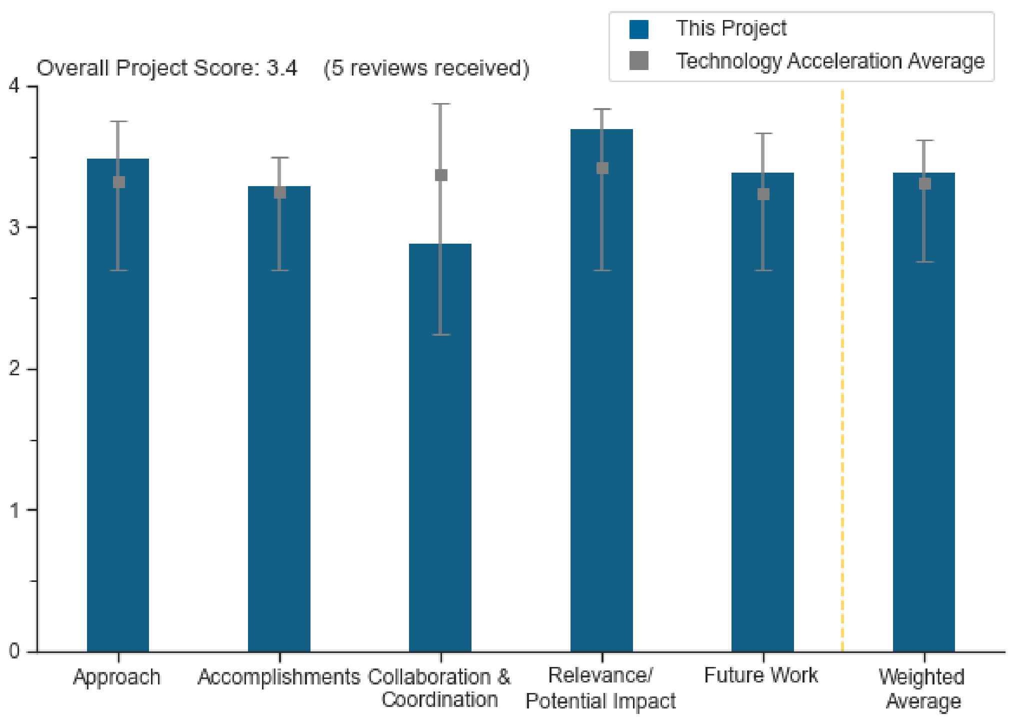
Daniel Leighton, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.9
Start and End Dates	5/6/2020
Partners/Collaborators	N/A
Barriers Addressed	• Demonstration of electrolyzer and stationary fuel cell technology under real-world conditions • Production of hydrogen using directly coupled zero-carbon energy sources • Hydrogen energy storage and grid stabilization for high-penetration renewable electric grid

Project Goal and Brief Summary

This project will design and commission a megawatt-scale electrolyzer, storage system, and fuel cell generator at the National Renewable Energy Laboratory's (NREL's) Flatirons Campus. The system is designed with flexibility to demonstrate systems integration, grid services, energy storage, direct renewable hydrogen production, and innovative end-use applications. If successful, this project will support H2@Scale goals by enabling integrated systems research and development to study the science of scaling for hydrogen energy systems.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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.

- Building an Advanced Research on Integrated Energy Systems (ARIES)/Flatirons facility to study both fuel cell and electrolyzers at NREL is highly significant. The project combines hydrogen production, compression, ground storage, and fuel cell application.
- The overall approach to the work is great. If non-technical project-based learnings from the facility buildout and safety analysis can be made available to the public, then that would be very helpful, especially for entities now getting involved in the piloting or build-up of large-scale green hydrogen and associated storage, as well as power systems.
- The approach is very well-defined and shows a clear path to hydrogen-at-scale demonstration.
- Overall, the researchers should highlight what is unique about their microgrid approach in future presentations. Some context of what can be learned with scale that cannot be learned from smaller previous grids would be helpful. It is unclear whether the lessons learned from previous programs scale—and why they would or would not.
- Long lead items ordered by the project appear to have comfortable budget flexibility to take interim steps to address length of infrastructure construction timelines. The 2021 project start date on slide 3 does not align with other dates/timelines presented throughout the slide deck. It is unclear what the NREL contribution is for this project (if any) in addition to U.S. Department of Energy funds that appear to pay for design and hardware.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has shown progress toward milestones and successfully accomplished, or nearly accomplished, all as required when the presentation was submitted. The project clearly identified discrete accomplishments that support the project milestones.
- The project has progressed well, and most major milestones have been met. System design and procurement have gone well.
- The project has been making excellent progress, given supply chain and logistics issues due to COVID-19.
- There appears to be good progress for a project that has been under way for less than a year. It is challenging to compare to projects that have cost-share requirements. The impression is that this is mostly a fully funded, typical construction project in progress (with limited concerns about budget restrictions).
- The rating would have been higher, but the supply chain problem has hampered some of the milestones, which have to be captured somewhere. After the pandemic, this should be excellent.

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.

- It is great that the project is working with a major industrial partner such as Nel Hydrogen. It would be good if the project could disclose its fuel cell collaborator in future presentations. This energy campus seems like an excellent opportunity for outrage, especially to environmental justice communities. Maybe the project could partner with the local school district for outreach.
- The full extent is to be determined because this project is working toward becoming a research capability for future projects.
- The collaborators are primarily equipment suppliers. These suppliers have been involved with design and development activities, as well as in hazard and operability studies for the planned systems.
- It is recommended that the project collaborate with an industrial gas or energy company with experience in hydrogen production/handling to further accelerate the project. Also, it would be a good opportunity for the industrial partners to get more practical experience in terms of deploying emerging green hydrogen technologies.
- Collaborators other than Nel Hydrogen were not evident.

Question 4: Relevance/potential impact

This project was rated **3.7** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project addresses a very important problem in the overall green hydrogen space, i.e., integration with upstream electricity production and downstream storage. Megawatt-scale systems are the right size capability to build as well, as it provides relevant technology de-risking data for full-scale deployment (hundreds of megawatts or even gigawatts).
- The potential impact is well-defined, and the relevance of the work is made clear. Building the capability to conduct research on integrated systems will help the deployment of commercial systems and show value.
- This project is very important for showing how hydrogen can work at scale for the grid.
- The project should bring in/line up contracts with interested industry and research partners to execute applicable projects on this equipment.
- This project can be a significant demonstration project for hydrogen production, storage, and application. It is uncertain what electricity source will be used. It would be more meaningful if it were integrated with solar or wind.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- Future work is clearly described, as well as expected dates of completion. All show a path to the culminating commissioning activity.
- The proposed future work seems logical. Some discussion of water arability and the possibility of well water is recommended. Trucking in water seems non-ideal. The caveat about funding should be removed. That is tacit and comes off hesitant. The project should present a bold vison; if missed, at least the project is aiming high.
- A generally good future plan is included. More concrete timelines could be included in the future plan.
- This project could benefit from an assessment to add operational flexibility that allows for hydrogen production for time periods longer than 27 hours. The project should consider looking into a way to be able to "dump" hydrogen either through a virtual pipeline or use of hydrogen (blend) in a large genset tied into the grid. The project should explore how to address the missing permanent tie to the water supply source (instead of trucking in deionized water), such as using NREL campus wastewater.
- Adding industrial players from the utilities, gas, or energy sectors to the team would be great, especially as applications of the capability are being developed.

Project strengths:

- The project works with equipment experts throughout the design and development process. Establishing a fully integrated research location to understand integration, response, total consumables, and optimization of each device, independently and connected to each other, will support deployment of these devices in a commercial setting.
- This project provides an important scaling-up demonstration with real-world equipment and connection to the grid. The project helps enable the H2@Scale vision. Slide 6 shows a graphic with an overview of the equipment, coupled with slides 10 and 11 that show that the graphic has engineering rigor behind it. It would be great to see it in person someday—or at least see the results at future DOE Hydrogen Program Annual Merit Review (AMR).
- A significant demonstration project includes hydrogen production, storage, and application. The project has completed system design and most procurements in less than a year.
- The project overall builds a very important capability on integrated green hydrogen production systems and at a relevant scale.
- Overall equipment capabilities and capacity are strengths.

Project weaknesses:

- There are no weaknesses. The project is doing well so far.

- The biggest weakness of the project is not highlighting its uniqueness or how it builds on past microgrid projects. Slide 13 was not very effective. Maybe there is a better way to communicate the lack commercial off-the-shelf items. The slide reads as an incomplete computer-aided design rendering. A standard human reference model could be added for scale. A secondary weakness is the lack of onsite water. Looking at well water and a water purification unit is a must to make it "real-world." A leech field or sewer is also important.
- The external collaboration is weak. Only Nel Hydrogen is listed as a collaborator. The future plans need to include more details for such a big project.
- There are limitations for longer-term hydrogen production (projects) due to hydrogen storage system size.

Recommendations for additions/deletions to project scope:

- The project should add an option to allow for continuous hydrogen production, either through virtual pipeline partners or use of hydrogen (blend) in a large genset tied into the grid. The project needs to resolve the water supply source issue to replace the practice of trucking in deionized water. A study, a collaboration with the U.S. Environmental Protection Agency Office of Water (or another office with water-related expertise/responsibility), and/or an exercise in ideation can provide more robust insight into how this issue could be resolved in arid or drought-stricken regions around the United States where electrolysis is desired, but water availability is the limiting factor. This could help address a gap in understanding about required resources for hydrogen from electrolysis and therefore add significant value for this project.
- In addition to AMR, a quarterly review meeting with DOE is recommended for a project with such a high budget. It would be great if solar or wind could be integrated in the system so the intermittency of renewable energy could be studied.
- The project should use continuous instead of batch water handling of both feedstock and effluent.
- The end use of the hydrogen was a bit unclear. It is unclear whether it can be sold or used for other downstream applications. It is recommended that the team look into this further and make a concrete plan.
- No additions or deletions are recommended.

Project #TA-049: High-Pressure, High-Flow-Rate Dispenser and Nozzle Assembly for Heavy-Duty Vehicles

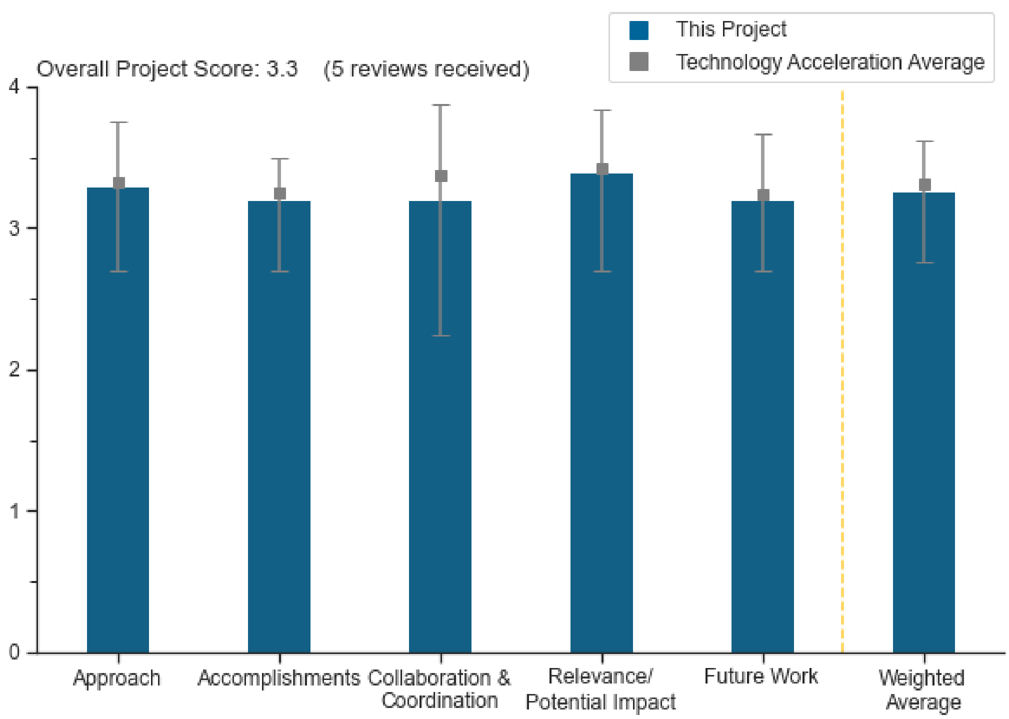
Spencer Quong, Electricore Inc.

DOE Contract #	DE-EE0008817
Start and End Dates	10/1/2019 to 8/31/2022
Partners/Collaborators	WEH Technologies Inc., Bennett Pump Company, Quong & Associates Inc., National Renewable Energy Laboratory
Barriers Addressed	• Need for a robust, domestic manufacturing and component supplier base for hydrogen and fuel cell technologies • Lack of hydrogen refueling infrastructure performance and availability data to revise standards

Project Goal and Brief Summary

This project team will develop, test, and demonstrate a hydrogen fuel dispenser and nozzle assembly (nozzle, receptacle, hose, and breakaway) capable of fueling heavy-duty (HD) vehicles. Based on industry feedback, the assembly's fuel transfer rate will be 100 kg in 10 minutes at a nominal pressure of 70 MPa. If successful, this project will accelerate the development and adoption of sustainable transportation technologies.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration 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.

- An excellent approach was taken to the high-pressure, high-flow-rate dispenser/nozzle project for HD vehicles for several reasons:

    - The industry stakeholder survey and required specifications are fundamental to providing a working product, and the deliverables are quite logical, including a costly real-world demonstration.
    - The project surveyed 27 companies/organizations, with a good breadth and depth, where important representation is needed both downstream of the nozzle and upstream of the dispenser. However, the limited interest in hydrogen at 50 MPa (500 bar) is questionable, when the largest fleet of fuel cell trucks in the world are using 350 bar, with a few hundred on the road now and about 1,600 planned.
    - There is a clear outline of challenges to high-flow dispenser design and various components.
    - The project has a clear explanation and quantitative results from the dispenser flow analysis, with a detailed pressure drop reported for each component.
    - Barriers were clearly communicated and mapped to project goals, giving confidence that the project will be successful.

  It will be interesting to see what companies commit to using the project's design.
- This project has an excellent approach, starting with the industry (i.e., the customer) survey to establish goals and constraints. Also, it is good to see the inclusion of failure modes and effects analysis and coordination with the Hydrogen Safety Panel.
- There are rational steps toward the development of a robust solution for a HD dispenser and nozzle assembly and inclusion of dispensers in addition to a breakaway, hose(s), and nozzle.
- The project demonstrates a sound approach to accomplishing tasks. The project objectives are clearly identified, and the project addresses barriers in the hydrogen fuel cell HD vehicle sector. It is not clear whether the cost analysis is part of the project; it would be great to better understand the economic impacts of the technology development.
- It would be good to see a piece of work around external interfaces, as this is where the value of this project will or will not be realized. The dispenser by itself is valuable only if it integrates with the storage/compression/thermal management balance of plant (BOP) effectively, which is a controls and data issue, not so much a mechanical or electrical power issue. Also, the flow rates required will need new vehicle interface standards. It is not clear whether there is engagement with pre-normative working groups to ensure this work is influencing those efforts. It would be good to see some emphasis on packaging and constructability. Light-duty (LD) dispensers were difficult to build and costly, with maintenance issues in part because their components were distributed throughout the site (the in-ground heat exchanger, for example). The HD dispenser development should have a clear strategy for implementing the full system on site; an integrated product approach has value for quality and verification in production.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- DOE goals are clearly outlined, and three goals were tightly linked:
    - Accelerate HD high-flow nozzle development where no commercial products are available, as well as enable easy introduction of these to the zero-emission vehicle market.
    - Increase domestic jobs in clean energy and local manufacturing.
    - Expand zero-emission trucks, which will support DOE goals of inclusion, equity, and diversity. Often, pollution from ports and high-density/use transportation networks are at the border of low-income communities.

  When this project is successful and can be moved beyond trucks to rail and maritime, this small element of the supply chain will unlock enormous demand for hydrogen, thereby increasing demand for low- to zero-carbon hydrogen production, which could further increase the demand for variable energy such as wind and solar power. In the coming decade, the grid will have more difficulties integrating these variable renewable energy options; hydrogen storage is the perfect option for storing zero-carbon energy to be used later in zero-emissions transportation.
- The project demonstrates significant progress toward overall project and DOE goals.
- Solid progress has been achieved in the first year of the project.
- Understanding that it is a new project and minimal funding has been expended, there is good progress on solicitation of stakeholder specifications and identification of applicable standards.
- It would be good to see some work on metering strategy.

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.

- The high-flow-rate dispenser project has done an excellent job of coordinating partners and bringing together key expertise. WEH Technologies Inc. is a world leader in hydrogen nozzles, and Bennett Pump Company is critical for simulation and modeling. The National Renewable Energy Laboratory (NREL) will be critical to testing the nozzle and offering third-party validation. It would be interesting to have tighter collaboration between HD70 tank users and a station builder that would purchase the dispenser. For now, it is fine to incorporate stakeholder community input through surveys.
- The number of entities involved in the survey is an indication of the broad collaboration. This is a strong team of leading project partners.
- The project has great collaboration with industry stakeholders in establishing specifications.
- The project demonstrates close collaboration and good coordination with the project partners Bennett Pump Company and WEH Technologies Inc. However, it would be great to see more feedback from potential cross-sector users such as the maritime or rail industry.
- This project really needs to be plugged into ongoing industry working groups and have a strategy for interfacing the dispenser with different BOP components (via an interface control document). The latter requires engagement with hydrogen refueling station manufacturers.

Question 4: Relevance/potential impact

This project was rated **3.4** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- It is clear that this project will be a critical path in the pivot of the Hydrogen and Fuel Cell Technologies Office to focus on HD, rail, and maritime applications for large-scale hydrogen in transportation. The project is aligned well with DOE goals to reduce barriers to HD trucks. Meeting project goals and successful commercialization of the nozzle will have a significant impact on fast-tracking the introduction of new medium-duty and HD trucks using high-capacity 70 MPa tanks. The focus on reducing cooling requirements and enabling refueling temperatures higher than -40°C will be especially helpful to the fuel cell trucking industry.
- The project aligns well with DOE Hydrogen Program and DOE research, development, and demonstration (RD&D) objectives, and the project has the potential to enable progress toward DOE RD&D goals and objectives. If successful, this project would have a relevant impact in the HD fuel cell sector.
- This project will definitely address high-flow-rate fueling equipment needs for the HD market by proving out technology that meets the needs of a broad range of stakeholders. However, the extent to which new standards and/or standards revisions will be necessary to drive compatibility and interoperability is unclear. Changes to driving standards are not part of the scope of this project, but an understanding is needed of whether the solution is completely bound by existing standards and what needs to change, and this should be appropriately identified.
- Fast fueling is a must for acceptance and adoption of HD hydrogen fuel cell electric vehicles (FCEVs).
- High-flow 70 MPa dispensers do not exist.

Question 5: Proposed future work

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

- The future work and next steps look reasonable. A key go/no-go is planned, though a few barriers have been identified with thermocouples and measured flow rates. A key milestone next year will be successful validation at NREL's HD station.
- The project's future work plan is well-established.
- The project demonstrates a satisfactory approach to the proposed future work. It would be good to see the go/no-go decision points in future presentations to better understand project progress and plans. Other issues that can be addressed would be supply chain robustness and manufacturing challenges for technology commercialization, in addition to technology integration with existing stations.

- The presentation should explain whether there are alternative locations for the breakaway device. Considering the difference with the conventional liquid fueling approach (e.g., nozzle spout in the opening, not with the clamping mechanism, but still able to get stuck during driveaway), this may be worth exploring. The breakaway device has a higher weight due to a larger internal diameter (compared to a LD H70 hose assembly) and is H70 and ultra-high flow. Related to breakaway, the team should explore whether the disconnection force (1,000 N) is or needs to be the same as for LD hydrogen fueling (or develop a rationale). The team should include the alternative to the Infrared Data Association (IrDA) protocol, such as the Shell/Bosch wireless option, and how this could improve the design.

Project strengths:

- This project is taking on the challenge of practically resolving the technical barrier to accomplishing HD fast fueling at H70 to make hydrogen FCEVs acceptable to HD fleet operators as an alternative to conventional technology. There are many collaborators.
- There is certainly a need for this development for the fuel cell HD truck industry. The partners are experienced and well-qualified to carry out the project. The project approach is well-planned.
- A major strength of the project is the breadth of stakeholder input and the ability to have key players, such as WEH Technologies Inc., manufacture the first nozzle hardware. The ultimate test will be validation and final demonstration with a full-scale truck refueling to confirm flow rates and potential station economics.
- The project is relevant for HD fuel cell sector development and can have impacts in growing sectors such as trucking, maritime, and rail.
- The topic is on point, with qualified parties participating.

Project weaknesses:

- The extent to which new standards and/or standards revisions will be necessary to drive compatibility and interoperability is unclear. Changes in driving standards do not appear to be part of the scope of this project, but an understanding is needed of whether the solution is completely bound by existing standards and what needs to change, and this should be appropriately identified. The widespread adoption of technological developments will be dependent on interoperability. Also, there was no mention of communication specifications.
- The weaknesses include addressing supply chain robustness and manufacturing challenges for mass commercialization, considering technology compatibility with other hydrogen pressures or cryogenic hydrogen, addressing cost impacts of technology, and challenges with different station integration approaches.
- Building a mechanical design for the dispenser is likely not the highest-risk or most challenging portion of a commercially viable dispenser. External interface standardization and the integration of components into a single package to support quality, testing, manufacturing, and constructability will be commercial roadblocks that need attention as well.
- Possible weaknesses include not having an explicit station customer who will pilot the first hardware and not having a clear high-flow 700 bar tank integrator ready to use the nozzle.
- This is new territory. H70 may not be the ultimate/optimal solution for HD hydrogen fast fueling.

Recommendations for additions/deletions to project scope:

- The project might consider exploring whether there is any need for inclusion of HD nozzle design characteristics that allow for receptacle design that facilitates cryo-compressed hydrogen fueling or other forms of hydrogen (i.e., not only 700 bar gaseous hydrogen).
- The robustness of the nozzle must be higher than that for LD vehicles, considering the higher weight of vehicles that could drive over it. Thus, the project might possibly need to consider abandoning the idea of IrDA altogether for when commercializing the nozzle.
- Additional time could be devoted to nozzle design and scenario planning if the first choice fails at validation. The four options look radically different, and simulation may not capture the optimum nozzle-to-hose configuration options.
- The project should identify necessary standards modifications and communicate those changes with standards committees.

Project #TA-050: Overall Research on Electrode Coating Processes (OREO)

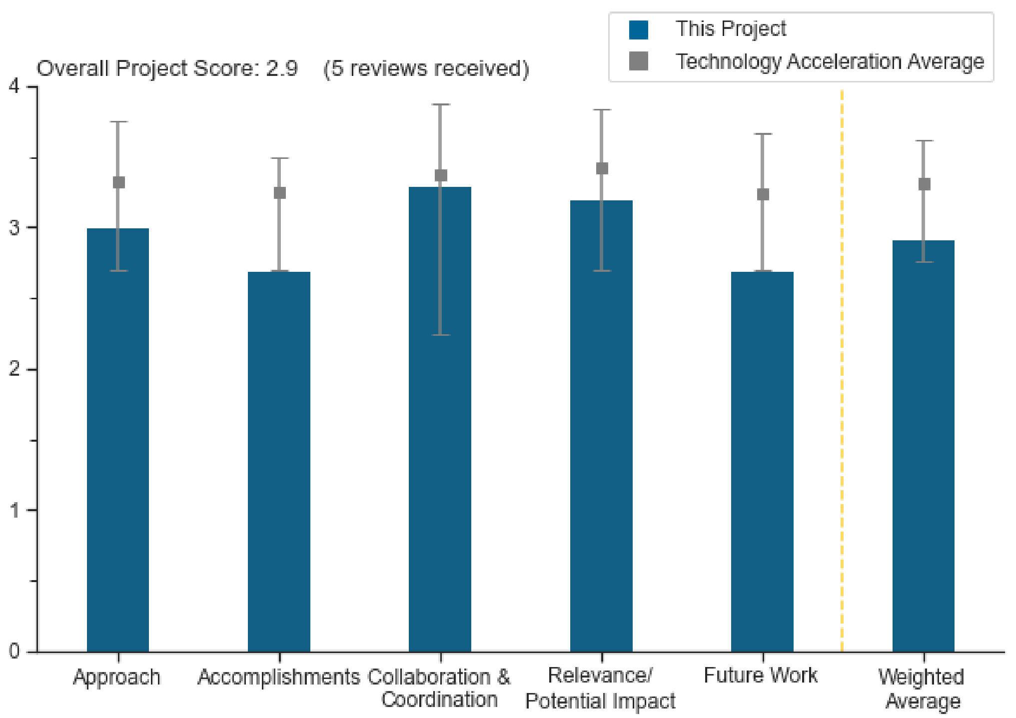
Michael Ulsh, National Renewable Energy Laboratory

DOE Contract #	WBS 10.2.0.502
Start and End Dates	10/1/2019
Partners/Collaborators	Fraunhofer ISE, University of Connecticut, Colorado School of Mines
Barriers Addressed	• Lack of high-volume MEA processes • Low levels of quality control

Project Goal and Brief Summary

Current projections of membrane electrode assembly (MEA) manufacturing costs assume roll-to-roll (R2R) processing technologies that have not actually been proven at scale. This project aims to address the unknowns by bringing together a network of experts in fuel cell and electrochemical ink and electrode fabrication, novel materials, advanced characterization, and in situ device testing. The team will evaluate and compare material and process parameters across a wide range of different processes of interest to the MEA industry. Researchers will use a platform of characterization tools to understand the impacts of materials, inks, and processes on the nano- and micro-scale structure of the electrode and how these structural impacts affect MEA performance.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Technology Acceleration projects.

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 just beginning, but the overall approach looks very promising on addressing critical barriers associated with electrode coatings. Evaluating the cost–benefit analysis of coating type, carbon particle type, and drying conditions on production-style equipment will provide critical feedback to manufacturers, allowing for generalized process improvements.
- This project follows a very systematic approach, from the core fundamentals well below the cell level to one type of industrial-scale manufacturing. Within the scope of work, there are many complex and complicated interactions to characterize and understand for implementing in the identified R2R manufacturing process. From that effort, an attempt will be made to scale what was learned at the laboratory to an industrial scale of production. This is a significant scope of work. The provided materials included no high-level parameter matrices. If one does not exist, this activity would benefit from having a communicable parameter matrix to convey the multitude of parameters to characterize and tests to conduct. This common matrix may help to organize the work across the wide range of formal and informal collaboration partners.
- The approach of various characterizations and testing is good. It is not clear, though, how the data will be used in optimization or in the increased understanding. Linking to modeling efforts and durability and not just performance would be more impactful, but that may be covered in R2R or in other consortia.
- It is not clear whether there is enough data for monolayer. It would be good to see some kind of flow diagram of the different variables being investigated. It is not clear what the budget of the partners is and if that should be included. It is not clear where the materials are coming from in terms of novel catalysts or whether these are commercial or in-development catalysts.
- The reviewer read the Project Goal slide at least five times and still did not fully understand the basis or expected outcomes of the project. R2R manufacturing at scale seems to be the target, but the formal project team consists of national laboratories and universities. It is unclear which companies are running the largest volume today and what issues they have. The project goal is to "Address these unknowns by bringing together a unique network of experts in [fuel cell] and electrode coating (EC) ink/electrode fabrication, novel materials, advanced characterization, and in situ device testing, who have capabilities ... Evaluate and compare material and process parameters ... Access a common and unique platform of characterization tools." It is not clear if there is a specific problem being addressed or if the purpose is to go find a problem to address. This project is building a science-based understanding of how materials and fabrication techniques govern catalyst layer properties. The combination of R2R-relevant manufacturing techniques with physical and chemical characterization and MEA testing represents a strong approach to building necessary understanding of MEA manufacturing processes.

Question 2: Accomplishments and progress

This project was rated **2.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project is just beginning, so the number of data available is relatively limited. The data that are currently available show how the results from this project could be useful for the industry as a whole; for example, the comparison of slot die versus gravure coatings and the comparison between a water- and alcohol-based solution on the surface characteristics will be helpful for any organization looking to improve its coating technology. This project takes a good approach in evaluating the critical parameters necessary to achieve consistent, high-performing coatings.
- Given the pandemic complications and the recent formal additions to the collaborative effort, the project has made reasonable progress characterizing many of the interactions and processes involved in the R2R manufacturing method. Many of these processes remain to be explored at higher production rates and at larger scales.
- There is good progress in looking at different deposition, although most of the work is still very correlative without the understanding that should be seen. Data are being generated but still need some better understanding. The accomplishments do not seem consistent with the budget. There is speculation (e.g., impact of carbon) but not much data and progress, and it is unclear how much is in scope for this project.

Also, there are many words about physics, but no real detail is given, and only qualitative comparisons are shown. It would be helpful to know the cost impact of the overlayer.

- One of the key findings was that gas diffusion electrode (GDE) surface composition is more important than surface morphology in determining performance, with monotonic increases in performance with increasing ionomer content at the interface. This observation seems to indicate that interfacial effects are limiting the performance of the GDEs developed in the project and further suggests that non-interfacial phenomena (e.g., transport and kinetics within the bulk of the GDE) cannot be adequately probed. Approaches are needed that can standardize the interface and thus allow a fair comparison of non-interfacial effects. This could likely be achieved through use of ionomer topcoats on the GDE to standardize the interface. The observations on effects of drying times on catalyst layer properties are potentially valuable and should be expanded to provide a science-based understanding of how drying processes influence the properties of the resulting catalyst layer. The work on effects of catalyst support and Pt weight percent on catalyst layer properties is potentially valuable, though there do not seem to be many results yet.
- It is unclear whether the study of the Mayer rod coating method is appropriate for at-scale manufacturing processes (slide 10). It is unclear why the project runs these tests if they are not relevant (slide 16) to volume manufacturing.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- There appears to be good collaboration between all of the partners associated with this project. The roles of each collaborator are clearly highlighted, and the output from each is evident from the initial project data presented.
- This project capitalizes on both formal and informal relationships and on related projects funded by multiple agencies and organizations. This significantly reduces project risks and increases the probability of producing the desired technical innovations.
- The strong interaction with Fraunhofer ISE, as well as the characterization provided by the Colorado School of Mines and the University of Connecticut, makes for a strong team.
- Industry partners on the core team may have helped to start out with specific manufacturing problems that need to be addressed.
- It is not clear what is being done here and what the overlap is with R2R, Million Mile Fuel Cell Truck (M2FCT), Hydrogen from the Next-generation Electrolyzers of Water (H2NEW), and other related efforts. It is said they are working together, but this should be better delineated. The international collaboration is noteworthy and good. The other collaborations are confusing in terms of whether they are for this project or being leveraged from other projects. Presumably, H2NEW and M2FCT are collaborators—or perhaps this project is duplicative and not aligned with those efforts.

Question 4: Relevance/potential impact

This project was rated **3.2** for supporting and advancing progress toward the Hydrogen and Fuel Cell Technologies Office goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project will establish a common framework and provide an elevated point of entry for organizations intending to use the R2R manufacturing process for electrochemical processes. From a "rising tide raises all boats" perspective, it has the potential for impacts on existing or potential MEA vendors by fostering competition, thereby improving the rate of innovation and reducing the production cost of hydrogen.
- This project is building a fundamental understanding of how material properties, ink properties, and deposition methods control resulting properties of catalyst layers. This is highly relevant to the Hydrogen Program, and there is potential to have significant impact on MEA manufacturing.
- The efforts being undertaken in this project are applicable to anyone using an electrode coating process and should have an impact on improving coating uniformity and consistency on any materials moving forward. The limited data from the project so far make it difficult to assess accurately, but the general trends seen so far show the potential for this type of fundamental study.
- This is important technology and science to go after in terms of ink processing, R2R translation, etc.

- The overall theme of addressing manufacturing challenges is highly appropriate. However, there appears to be very little focus on a specific problem and more of an attempt to find something to go fix.

Question 5: Proposed future work

This project was rated **2.7** for effective and logical planning.

- This project has completed only the early portions of the identified work plan. The future work includes the required in situ testing and scale-up demonstrations necessary to generate the required data to inform the manufacturing process.
- The future work is relatively broad, especially in terms of characterization, and some of it (e.g., in situ testing) seems duplicative of other Hydrogen and Fuel Cell Technologies Office efforts. The focus to look at both EC and fuel cells is good for understanding general trends and similarities, but it is not clear how the GDE work will translate when looking at EC materials. It is unclear whether the catalyst-coated membranes or just GDEs will be investigated. Scale-up to R2R is good.
- The future work is reasonable, but a stronger emphasis is needed on understanding how coating parameters control resulting structure and properties. The future work sounds a bit like a fishing expedition; the team is going to examine multiple deposition techniques and see how the resulting MEAs compare. A more science-driven approach to the future work would be beneficial.
- The proposed future work highlights key areas that need to be addressed moving forward, particularly EC anode catalyst inks and in situ electrochemical testing. There is a general lack of clarity on what process conditions and novel materials will be evaluated in the future work, but the progress so far gives hope that it will be successful.
- It looks like more of the same. A specific focus for this project is not evident.

Project strengths:

- The work so far has done a reasonably good job of exploring the science of how coating techniques control electrode properties. Some interesting initial results have been reported on effects of interfacial composition on performance and drying methods on resulting structure.
- The overall strength of this project is the emphasis on general processing parameters and component impact on processing. The results generated here will give any developer an understanding of how best to create the most uniform, high-performing electrode coatings with the developer's system.
- The primary project strength is the broad range of formal and informal collaborations across multiple organizations, projects, and funding sources. After identifying the critical processes and interactions, the project has started to characterize them and revealed new uncertainties and questions to explore.
- The project is addressing manufacturing scale-up challenges.
- The project is focused on relevant issues of different fabrication techniques.

Project weaknesses:

- It is difficult to assess the weakness in this project, as it is relatively new, and the data collected so far show much promise. The biggest potential weakness that is seen is a limited range of processing parameters available for study, owing to equipment and material availability. Overall, the project looks very promising, however.
- The project is mainly just making MEAs and some correlations. The effort seems very much duplicative of existing consortia, including H2NEW, R2R, and M2FCT, and so perhaps this should be combined with those or be better aligned to focus on specific aspects not covered. There is discussion of bringing in new materials, but it is very unclear how that would happen. It is uncertain how the GDEs and fuel cells will translate to EC materials, as they are very different in terms of materials, coatability, surface tension, etc.
- There is a lack of a specific problem. The stated goal is to address unknowns by bringing together unique experts with certain capabilities. This seems like a very high-level approach to go solve a problem. However, the problem is hypothesized to be cost models having been based on unproven manufacturing processes that might not work. The project basis is weak. It is not clear there is an actual problem to solve.
- Because of the rapidly expanding hydrogen economy, this project will likely encounter intellectual property issues if a particularly advantageous process or configuration develops. The provided materials include no mechanism to address this beyond the "licensing" process.

- The project seems rather exploratory. It lacks a hypothesis-driven approach.

Recommendations for additions/deletions to project scope:

- The scope of the project is clear and well-defined. It may be helpful to include a clear list of what process parameters will be evaluated throughout this project. A list of proposed novel materials and their potential benefits would also be beneficial.
- Recommended additions include the following: the project should get data showing this is a real problem and let those results guide the project, and the project should pull in industrial coating experts who currently perform coatings. Regarding recommended subtractions, the project should stop working on processes that are clearly not in the stated focus of high-volume R2R manufacturing processes. The project should be canceled unless actual manufacturing problems are shown to be addressed (i.e., the project should determine what help W.L. Gore, General Motors, and the Eastman Chemical Company need with process improvements).
- Linking to modeling efforts and underlying physics would be good, as well as focusing on durability and not just performance. The project is missing the understanding, and perhaps the scope should be focused on some key questions to gain more of the structure–function relationships.
- It may be advantageous to periodically purchase industrially produced MEAs to serve as check standards during the in situ characterization testing of the MEAs produced by the project.