Systems Development and Integration – 2023

Systems Development and Integration Subprogram Overview

Introduction

The Systems Development and Integration (SDI) subprogram aligns with priorities in the *U.S. National Clean Hydrogen Strategy and Roadmap* and aims to enable the H2@Scale vision and support the Hydrogen Energy Earthshot (Hydrogen Shot) through targeted hydrogen and fuel cell system integration and demonstration activities. To achieve this mission, the SDI subprogram focuses on:

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

Demonstrations conducted during verification and validation activities provide valuable data and feedback to research and development (R&D) conducted through the U.S. Department of Energy (DOE) Hydrogen Program. The data are also used in techno-economic assessments of various market scenarios to provide essential information regarding market readiness to manufacturers, investors, and potential end users.

The SDI subprogram focuses its activities on key emerging markets and technology applications based on preliminary findings of the Analysis, Codes and Standards 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 SDI subprogram is currently focused on three technology application areas:

- Grid energy storage and power generation applications, with a focus on grid integration and direct coupled renewable and nuclear hybrid systems, as well as distributed and backup power generation. Projects are designed to produce low-cost clean 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. Within this application area, the subprogram also supports manufacturing RD&D to develop techniques to produce advanced hydrogen system components and sub-systems at high production volumes.
- Chemical and industrial processes, with a focus on decarbonizing hard-to-decarbonize industrial sectors through integration of hydrogen technologies. These end uses include industrial processes, such as iron ore reduction needed for steelmaking, and chemical applications such as ammonia, synthetic fuel, and chemical production, among others. The integration of clean hydrogen will reduce greenhouse gas emissions, preserve and support jobs, and support environmental justice by helping build a clean economy.
- Transportation, which includes medium- and heavy-duty trucks, maritime, rail, off-road equipment, and other heavy-duty applications requiring significant power, range, and up-time. The focus for heavy-duty transportation applications is to demonstrate and validate fuel cell durability and performance under real-world conditions. Projects will also demonstrate and validate high-flow hydrogen fueling to support these transportation modes. Analysis will be conducted to determine total cost of ownership and future targets needed to compete with incumbent technologies.

Goals

The overarching goals of the SDI subprogram are to identify and demonstrate new and promising integrated hydrogen production and end uses, expedite private-sector commercialization of hydrogen and fuel cell systems, validate the performance of these systems, and achieve economies of scale as envisioned in the H2@Scale initiative.

Key Milestones

Key milestones for the SDI 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 directly integrated with nuclear and renewable power sources with the goal of achieving clean hydrogen production at <$1/kg.
- Validate 90% efficiency (based on high heating value of hydrogen) for high-temperature electrolysis systems operating at nuclear plants utilizing onsite waste thermal energy.
- Validate an integrated distributed and backup power generation system in real-world operations for power demands at a megawatt scale.
- Demonstrate integrated electrolyzer systems at the megawatt level using multiple electrical sources and targeting hydrogen end uses across transportation, industrial/chemical processing, and power generation.

Chemical and Industrial Processes

- Verify clean hydrogen system cost and technical performance comparable with incumbent technologies for metals production.
- Demonstrate approaches to integrate clean hydrogen to decarbonize iron/steelmaking at a scale of at least 1 tonne/week, with a path to capacities of at least 5,000 tonnes/day to meet the requirements of existing steel mills.
- Integrate emerging concepts with industrial processes for production of synthetic fuels and chemicals; verify costs and validate technical performance.
- Initiate transition to clean hydrogen for hard-to-decarbonize industrial applications and identify specific locations for potential scale-up (e.g., ammonia, refineries, steel).

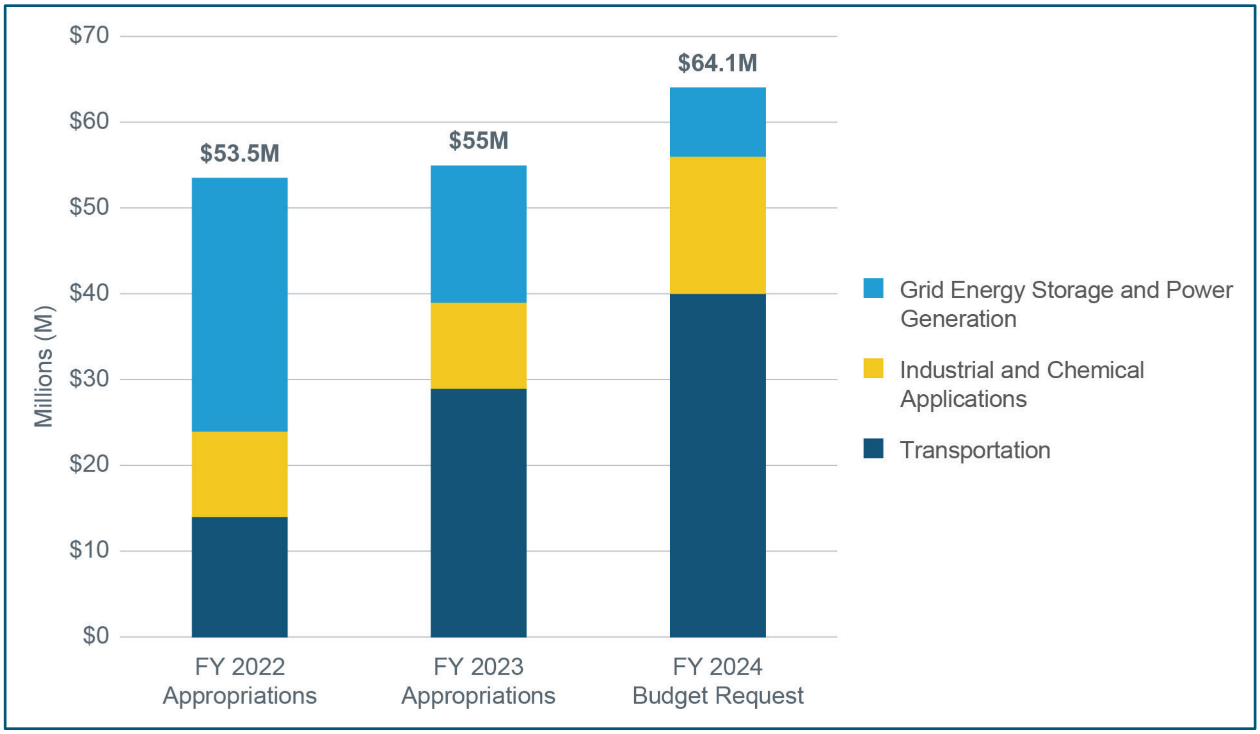
Transportation

- Develop and demonstrate fuel cell systems capable of achieving 25,000-hour durability and 68% peak efficiency for heavy-duty truck applications.
- Demonstrate how a substantial reduction (75% or greater relative to diesel-equivalent trucks) in greenhouse gases and local pollutant emissions from moving goods in trucks can be achieved in a way that is economical and scalable.
- Develop and demonstrate fuel cell systems capable of achieving a 30,000-hour lifetime and a cost of $60/kW for ultra-heavy-duty applications (e.g., ferries, rail, mining).
- Validate technical and economic potential of hydrogen and fuel cells for off-road applications.
- Deploy scalable hydrogen fueling stations to support early fleet markets, such as heavy-duty trucks and buses capable of 10 kg H_2/min (average) fueling.

Budget

The Fiscal Year (FY) 2023 appropriation for the SDI subprogram was $55 million. Additionally, the subprogram is collaborating with the Office of Clean Energy Demonstrations and the Hydrogen Program to allocate $8 billion, funded through the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law), for Regional Clean Hydrogen Hubs.

The FY 2024 budget request is $64.1 million to continue accelerating efforts to demonstrate and validate low-cost hydrogen production integrated with various hydrogen end uses to enable decarbonization, support the H2@Scale vision, and align with priorities in the *U.S. National Clean Hydrogen Strategy and Roadmap*.



Annual Merit Review Results

During the 2023 Annual Merit Review, 34 projects funded by the SDI subprogram were presented, and 25 were reviewed (a breakdown by budget category is shown on the right). The reviewed projects received scores ranging from 2.9 to 3.7, with an average score of 3.3. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

Following are reports for the 25 reviewed projects. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Number of Projects Reviewed by Budget Category	
Grid Energy Storage and Power Generation	11
Industrial and Chemical Applications	3
Transportation	11

Project #SDI-001: Integrated Modeling, Techno-Economic Analysis, and Reference Design for Renewable Hydrogen to Green Steel and Ammonia

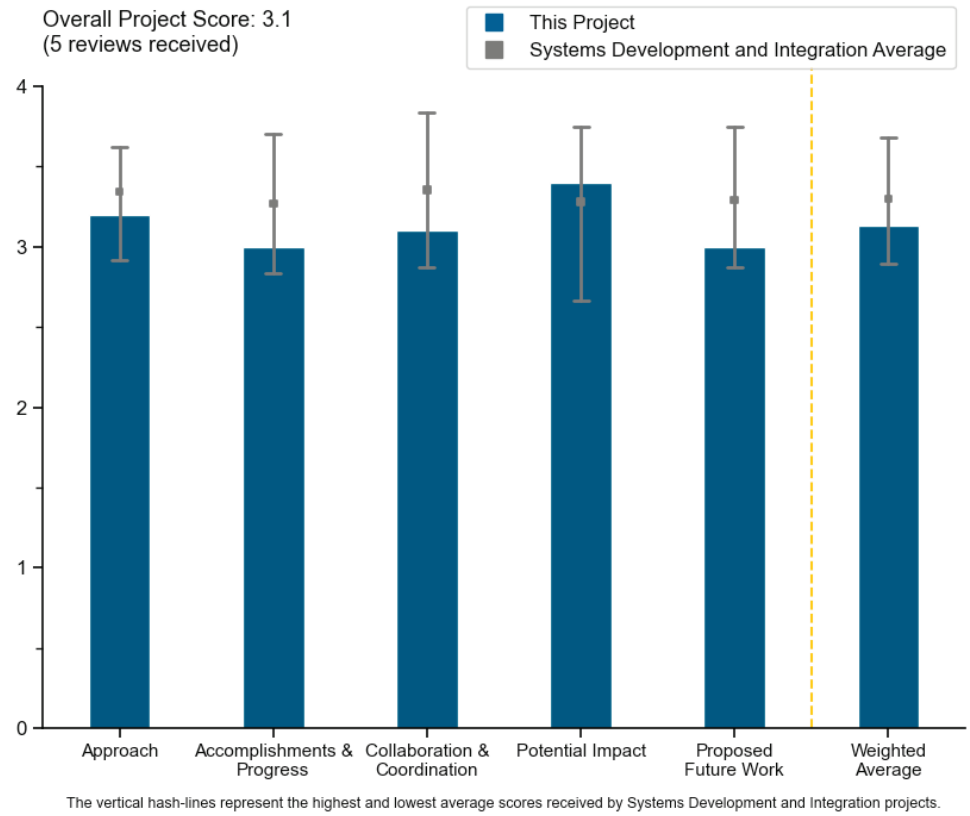
Steve Hammond, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.23
Start and End Dates	8/1/2022
Partners/Collaborators	Lawrence Berkeley National Laboratory, Argonne National Laboratory, Sandia National Laboratories, Oak Ridge National Laboratory
Barriers Addressed	• Design and analyze shared components across renewable power, hydrogen, and steel/ammonia • Integrate tools developed in isolation for individual technologies into one framework to exploit synergies across technologies • Targeting systems that reduce costs 10%–20+% due to tight-coupling and co-locating technologies

Project Goal and Brief Summary

The project aims to develop a national roadmap, integrate component-level modeling tools, and develop reference designs for gigawatt-scale, off-grid, tightly coupled hybrid energy systems specifically designed for green hydrogen production. The project's goal is to accelerate the decarbonization process for hard-to-abate industries, with a focus on lowering costs for green steel and green ammonia production. The project involves designing and analyzing tightly coupled systems with cost projections, comparing them to steam methane reforming and grid-connected designs, and calculating life cycle greenhouse gas emissions. The research aims to demonstrate the viability, cost-effectiveness, and rapid deployment of integrated hydrogen systems, providing a more sustainable alternative to fossil fuel-based methods.

Project Scoring



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.

- Project objectives are clearly identified as analyzing reference designs for gigawatt-scale, off-grid energy systems utilizing green hydrogen production. The approach uses a combination of use case hydrogen production configurations in close proximity or co-located with industry end uses. It is good that the work is building on other modeling work that already exists and is integrating those models to explore this area. The approach for the bulk storage component regarding the use cases is not described well (e.g., the types of storage that were considered in locations where salt caverns are not available).
- Green hydrogen for ammonia production is an important area for research, given the large amount of hydrogen used in this industrial sector. Hence, the project is well targeted, as an analysis-type project, perhaps leading to actual field trials/real-world deployment-type projects.
- The approach aligns well with the project goals. Case studies and regions selected for assessment support the development of a national roadmap for green hydrogen production for industrial use.
- The budget does not make sense. The presentation states a Fiscal Year (FY) 2022 budget of $2.5 million and an FY 2023 budget of $3 million for a total budget received of $2.5 million. It is not clear why the total budget is not $5.5 million. This is an extremely well-funded project for a market analysis. There are very limited locations that have both excellent wind and solar that are not already being developed.
- This project does not have list of tasks and milestones, despite having such a large budget. It is hard to know what it aims to achieve quarterly and ultimately. It is also not clear how the project acquired data and analyzed data. For example, it was not clear what model was used for data analysis. In addition, the project did not disclose the names of steel and NH_3 plants. It would be more convincing if the steel and NH_3 players could be shared. Finally, the project selected five locations, but Wyoming location information is missing.

Question 2: Accomplishments and progress

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

- The analysis provides very interesting results. It seems there are relatively few good locations. The team did not address whether those locations are available and what challenges would be in their development. (For example, Hydrogen Analysis [H2A] assumes a low cost for land, although perhaps this is not reasonable for these prized locations.) It would be helpful if the presentation could show how much each different credit is in the analysis. The presentation has one arrow showing final result. It would be great to see how much each different credit reduces cost (carbon capture and sequestration credit, production tax credits, etc.) since this assumes that cost and performance targets for electrolyzers are attained. A sensitivity analysis would seem prudent since the cost and performance targets for electrolyzers are very aggressive. The use of a proton exchange membrane (PEM) electrolyzer was assumed. For the ammonia and steel production, it is recommended that the project use a solid oxide electrolyzer that could utilize waste heat and achieve efficiencies in excess of 80%. Efficiencies as high as 85% have been reported for solid oxide electrolyzer cells (SOECs) with waste heat at 150°C or lower. The SOEC is a better technology for this application.
- Good progress has been made on exploring the levelized cost of hydrogen production in four land-based locations for ammonia and steel production. The accomplishments are consistent with the DOE H2@Scale initiative goals by enabling low-cost hydrogen produced from renewable power for various end-use applications. Comparing the cost of hydrogen, a total cost was presented comparing all cases. However, a breakdown of all costs (electrolyzer, renewable, and storage) would be meaningful to provide clarity on which component dominates in terms of cost and region. While the storage amount of hydrogen is certainly evaluated, the amount of storage required for the various locations were not discussed in the presentation.
- The project is well aligned with DOE goals. Progress with initial analysis results seems pretty good so far.
- Accomplishments present various scenarios for hydrogen use, depending on region and energy source. Credit- and non-credit-based scenarios are incorporated to show policy impacts.
- The project has spent $2.5 million since August 2022, but the produced data is limited. It would be great to know how funding was spent by category. In addition, the project needs to explain the data more clearly. It is not clear why NH_3 prices varied from state to state while steel prices are nearly constant across different states. It is not clear why Wyoming has the lowest green H_2 and NH_3 prices, and the presentation does not explain what negative H_2 and NH_3 prices mean. The project did not show the data sources and major components for the calculations/models.

Question 3: Collaboration and coordination

This project was rated **3.1** for its engagement with and coordination of project partners and interaction with other entities.

- Multiple laboratories are working on each task; the accomplishments indicate that there is good collaboration between the laboratories thus far. There is no collaboration from industry or academia yet, only from an industry think tank. It would be helpful to collaborate with industry so as to get more realistic input and enable a robust feedback loop.
- Collaborative aspects are limited but not unreasonable for an analysis project.
- Collaboration shows use of multiple national labs for output. Industry involvement or verification of cost inputs would provide more robustness.
- The project is the collaboration of multiple national laboratories. For this kind of project, industry engagement is very important. However, this project did not involve any industry partners.
- The project should have had some input from the steel and ammonia industries.

Question 4: Potential impact

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

- The output of this project is very highly relevant to H2@Scale; one of the greatest benefits of large-scale hydrogen storage is that it allows the economic production of renewable energy and then makes that energy available at a later time when required by the consumer. Therefore, this work is going to inform the economics of which applications make economic sense, as well as where and at what scale.

- This industrial sector is pretty important, so the work is highly relevant and has significant potential impact. The aspect related to continuous operation (steady-state) is very important for these types of industrial applications and so should be even further emphasized for potential industrial up-take.
- The impact of different scenarios is well described and will help to guide the most cost-effective configurations for installations. The project confirms that Inflation Reduction Act policy is of substantial help to accelerate deployment.
- If successful, the project can become very impactful, as it is one of a few projects that focus on renewable/hydrogen integration.
- Industrial decarbonization is a huge challenge. This is the type of analysis that needs to be done to understand whether this can be achieved. For it to be useful, the analysis must be conservative and not use aspirational assumptions. The current assumptions look overly optimistic. The team needs to validate them with an industrial (not academic) advisory board.

Question 5: Proposed future work

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

- Proposed future work aligns well to address challenges and barriers described. It looks to further explore system capabilities to optimize installations.
- Given the fairly recent initiation of the project, the future work presented in the main portion of the slides is within the scope of this project. The proposed details of this work are somewhat vague, but the work scope is important.
- The proposed future work is comprehensive and clear.
- Future steps seem appropriate, given the current status of the project.
- Other electrolyzer technologies must be included. The realistic reference design needs to include significant involvement from an industry player with experience designing and building real plants. At a minimum, an industrial advisory board should be included.

Project strengths:

- The project does a good job of integrating and building on other models that describe the “building blocks” of the overall ecosystem. The project also does a very good job of addressing a very important element of implementing H2@Scale and renewably producing hydrogen for fuel from intermittent renewable power.
- This is a strong team with well-rounded support from multiple national labs and an academic partner. There is a good selection of scenarios to compare and assess.
- The project addresses a very important area, is extremely well-funded, and includes a large team from the national laboratories.
- The project addresses an important and hard-to-decarbonize sector. The project has strong modeling capabilities and good overall assessment aspects.
- If successful, the project can become very impactful, as it is one of a few projects that focus on renewable/hydrogen integration.

Project weaknesses:

- No major weaknesses were identified, but the project could be strengthened with input from industry collaborators to validate that the methods and impacts being researched are the most important to the industry.
- The following are project weaknesses:
    - This project does not have a list of tasks and milestones, despite having such a large budget. It is hard to know what it aims to achieve quarterly and ultimately.
    - The project did not interpret many data calculations clearly.

  - The project is the collaboration of multiple national laboratories. For these types of projects, the engagement of industry partners is very important. However, this project did not involve any industry partners.
- The project is limited to looking at PEM electrolysis, which is currently relatively high-cost but was modeled with low-cost assumptions. It is unclear whether there will be review/validation by industry groups that actually do ammonia production to get their reactions/concerns.
- The project needs to have an industrial advisory board that can provide real-world feedback. The assumption that all of the electrolysis performance and cost targets will be achieved is aspirational. The team needs to do a sensitivity analysis.
- Industry verification would provide additional value.

Recommendations for additions/deletions to project scope:

- Perhaps it is not possible to include, but it would be interesting to look at other electrolysis technologies, including SOEC with potential waste heat recovery. A sensitivity analysis should be conducted around the optimistic PEM electrolyzer costs, as the project team currently seems to be painting too rosy a picture. A near-term case is suggested with higher (current) costs and the future costs with cost targets (as electrolyzer cost reductions have been pretty stubborn to reduce).
- The project needs (1) to have concrete tasks and quarterly milestones, (2) to explain how the large budget was spent for such a simulation/calculation project, and (3) to explain the calculated data more clearly.
- The project needs to have an industrial advisory board that can provide real-world feedback. The assumption that all of the electrolysis performance and cost targets will be achieved is aspirational. The team needs to do a sensitivity analysis. For this type of hydrogen generation, SOEC technology would be preferred to PEM or alkaline.

Project #SDI-002: Hydrogen Energy Storage System at Borrego Springs Toward a Hydrogen-Enabled 100% Renewable Microgrid

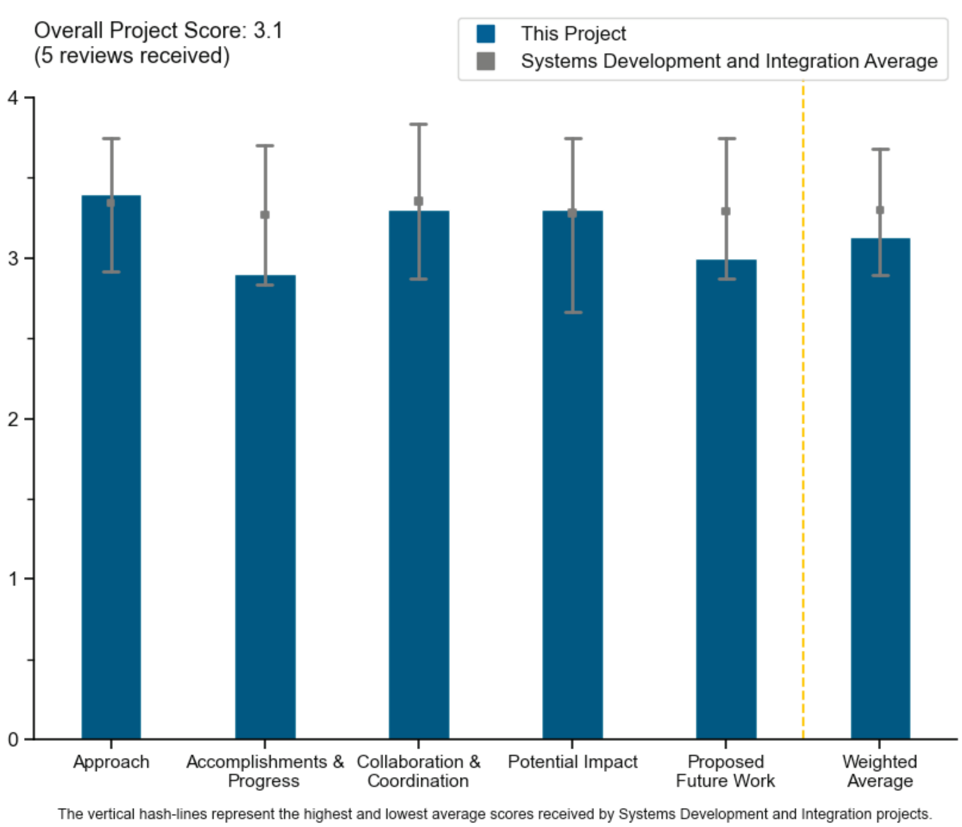
Kumaraguru Prabakar, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.22
Start and End Dates	9/1/2022–8/30/2024
Partners/Collaborators	San Diego Gas and Electric Company, PXiSE Energy Solutions
Barriers Addressed	• Field deployment of electrolyzer and grid-forming fuel cell inverter to support advanced microgrid operation • Disseminate field deployment results and characterize through data collected from the field and technical report • Document and disseminate safety requirements for substation collocated hydrogen assets (electrolyzer and fuel cell assets)

Project Goal and Brief Summary

The project is focused on implementing, characterizing, and analyzing advanced hydrogen distributed energy resources and controls with the goal of achieving a 100% renewable microgrid in Borrego Springs, California. The major goals include establishing intelligent control of hydrogen resources to stabilize the microgrid and reduce photovoltaic curtailment, developing hardware and conducting power hardware-in-the-loop (HIL) performance analysis, and evaluating the microgrid's operational characteristics and resilience improvements under different hydrogen configurations. The project aims to integrate hydrogen energy storage systems into energy system planning tools, quantify emission reductions and resilience benefits, and demonstrate the feasibility of a 100% renewable microgrid. The project will provide insights into the performance, resilience, cost benefits, and system requirements for large-scale deployment of hydrogen-enabled microgrids.

Project Scoring



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.

- This is a very interesting project that includes hydrogen technologies in an existing remote microgrid. Several key aspects to this approach are innovative and well targeted, including integration of several microgrid technologies, benefits quantification of replacing diesel generators, and others. The project is ambitious but potentially impactful.
- The team has a well-laid-out plan for the two phases of research and deployment. Project planning, model development, and optimizations have started. A well-thought-out plan was presented in the presentation.
- Project objectives are clearly identified: implement, characterize, and analyze advanced hydrogen distributed energy resources and controls toward a 100% renewable Borrego Springs Microgrid.
- The approach of HIL analysis and Renewable Energy Integration and Optimization Platform (ReOPT) development to add missing modules is a great approach. However, it is not clear that the objectives of optimal sizing from ReOPT are reflected in the hardware selections.
- This project focuses on energy storage using hydrogen.

Question 2: Accomplishments and progress

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

- The project is a new start, and the team has started the first phase. The team has made an appropriate level of progress and has a reasonable schedule to proceed.
- The project has good requirements toward stated objectives.
- Progress has been good so far but with some equipment and integration challenges.
- The project has spent ~ only $34,000 since its inception in September 2022 and has generated barely any data at this time. It seems that there has been a significant delay, but the cause was not provided. The project does not include clearly described tasks and subtasks, nor does it include clear and measurable milestones, considering the large budget.
- This is a new project. Only the progress made in the first quarter was mentioned. Not enough was presented to gauge the accomplishments and progress.

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 National Renewable Energy Laboratory (NREL) has partnered with San Diego Gas and Electric Company (SDG&E) and PXiSE Energy Solutions, the microgrid controller vender. The project will also require a fuel cell and electrolyzer vendor. This team seems to have the skills and capabilities to successfully complete the project.
- The project has one industrial partner, SDG&E, and a vendor, PXiSE Energy Solutions, a subcontractor to SDG&E. Electrolyzer and fuel cell vendors are not yet finalized.
- Collaboration and coordination seem fine. This is a strong project team with good collaboration/integration and a strong utility partner helping to deal with some cost overruns.
- Even in a relatively narrow project, the team has done a great job of collaborating across the value chain.
- SDG&E and PXiSE Energy Solutions are good collaborators. At this time, fuel cell and electrolyzer vendors have not been identified. It is not clear why these vendors were not determined during the proposal stage.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Remote microgrids anchored by hydrogen/fuel cells with other generation and storage technologies has been a major area of interest from DOE for many years. It is great to see projects finally working to validate these concepts in the real world. The project has high potential to develop important lessons learned for future projects.
- This project will showcase the resilience benefits of additional hydrogen assets to stabilize microgrids. The project will develop both models and hardware to meet the objectives. This project meets many of the DOE goals.
- This is a potentially impactful project. It is suggested that the project team consider multiple uses of hydrogen, which could be important in a resilience event. This could be not only fuel for resilient power generation but also transportation fuel.
- The output of this project is highly relevant to demonstrating the resilience benefits of hydrogen technologies to microgrids.

Question 5: Proposed future work

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

- The work plan and schedule plan are reasonable for meeting all the goals and overcoming the barriers in front of this project.
- The proposed future work of executing this project is great.
- Proposed future work is good. There are probably some significant project risks yet ahead, but the project plan seems sound.
- The proposed future work is perhaps a reiteration of the project's work scope.
- The project team is aware of important future work. The proposed future work is reasonable. However, the project does not specify how to execute this future work, given the slow progress of this project.

Project strengths:

- This is an ambitious project to demonstrate how hydrogen/fuel cells can be integrated into a pretty complex microgrid. Collaboration among the project partners is strong. There is potential for direct impacts to improve the electrical reliability of this real-world community.
- This is a well-thought-out project that incorporates both modeling and HIL. The project will be very beneficial in incorporating hydrogen assets into microgrids.
- NREL has abundant resources to perform this project. SDG&E and PXiSE Energy Solutions are good collaborators.
- Strengths include access to existing facilities at Borrego Springs and the principal investigator's expertise in power electronics and controllers.
- This project addresses a key challenge in the industry today.

Project weaknesses:

- As discussed during the presentation, decisions around equipment sizing have been somewhat arbitrary so far because of financial limitations rather than technical optimization-type analysis. If these are properly caveated for this project, this is a relatively minor but still important limitation. It is suggested for the future that the project allow for a larger system that is more optimized, which would be an important future extension, presumably based on successful completion of this phase.
- The project does not include clear and measurable milestones, despite having such a large budget ($4.67 million), nor does it provide clearly described tasks and subtasks. The project has a significant delay (the start date was September 1), but the cause of the delay is unknown. The project generated barely any data.

- The team lacks resident expertise in hydrogen assets that are planned for addition to the microgrid: hydrogen fuel cell, electrolyzer, and hydrogen storage.
- This project is limited in scope to "electricity" storage.

Recommendations for additions/deletions to project scope:

- It is recommended that the team go beyond California Independent System Operator (CAISO) pricing to look at the true electricity price in a resilience event. This true price may be infinite if no grid power is available. Understanding the actual pricing (based on supply and demand), in collaboration with SDG&E, may influence the techno-economic analysis and get more accurate results.
- The project needs to clearly provide its tasks and subtasks, which is required for DOE projects, as well as quarterly milestones and annual go/no-go milestones. The project needs to identify fuel cell and electrolyzer vendors as soon as possible. In addition, the project needs to accelerate the progress because of the delay in the first year.
- It would be great to learn more about how the microgrid (once completed) would function in a power outage situation, what loads would be picked up or shed, and the implications for the community.
- The project should add external national labs or industrial partners with expertise in fuel cells, electrolyzers, and bulk hydrogen storage.
- Dissemination and publication of the results of this project will be crucial in advancing hydrogen adoption.

Project #SDI-004: Hydrogen Coach Bus Fueling Demonstration

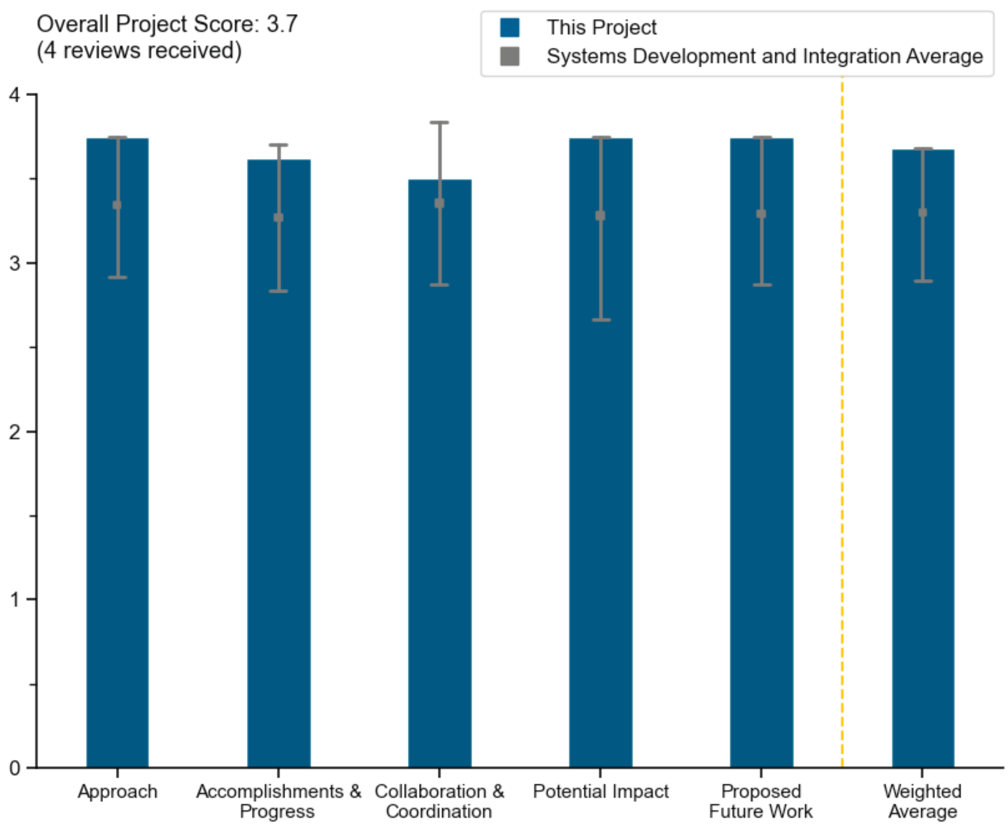
Richard Boardman, Idaho National Laboratory

DOE Contract #	WBS 7.2.9.19
Start and End Dates	10/1/2022–9/30/2024
Partners/Collaborators	FuelCell Energy, Stark Area Regional Transit Authority
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Controls and safety

Project Goal and Brief Summary

The goal of this project is to support the implementation of solid oxide fuel cell hydrogen production at a cost of \$1.00/kg at megawatt scale. The objectives include developing a safe and reliable design for post-processing gases from >100 kW solid oxide electrolyzer cell (SOEC) systems, installing a hydrogen refueling station, demonstrating the operation of heavy-duty fuel cell electric vehicles (FCEVs), and reducing carbon emissions in the Idaho National Laboratory (INL) bus fleet. The project involves various tasks such as system design, installation and commissioning, and detailed process modeling, as well as the integration of SOEC systems and the verification of FCEV suitability, paving the way for the conversion of the INL bus fleet to net-zero carbon options.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 five tasks are clear and are required to build out a successful demonstration. Conceptual process flow is needed for something as integrated as a high-temperature solid oxide electrolyzer to bus fueling. Commissioning will be key to learning to use these new technology components. Stark Area Regional Transit Authority (SARTA) is an excellent location to test with buses, considering SARTA's extensive experience. INL's focus is primarily on post-processing hydrogen from the SOEC, but the most exciting element will be the bus coach fleet demonstration. The listed tasks and approach to technology acceleration are all very logical.
- The project approach is very practical in terms of plan and execution for installing a major hydrogen facility, so it should be able to yield a template for design and engineering, procurement, and construction work for other similar facilities, which should, in turn, reduce cost and speed adoption of SOEC hydrogen production, post-processing, and use.
- Solid oxide electrolysis has the potential to be a cost-effective solution to meeting Hydrogen Earthshot goals. INL has unique capability and setup for a successful project. That being said, the main project goal of demonstrating scaled-up SOECs has the potential to become overshadowed by the coach demonstration. The project goals can be stated a bit more clearly, but otherwise, all goals are relevant.
- This project is well organized and should make significant progress on reducing multiple technology/ demonstration barriers.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- The concept will be able to work with dynamic operation and will be at a significant scale of 320 kg per day. The lessons for supporting the grid with very efficient electrolyzer will be key to meeting DOE goals. It was also interesting to see the detailed process model with detailed specifications, which can be put out to bid with high confidence in the economic projections. It would have been very helpful to share how conventional electrolyzers at ~$500–$1,000/kW compare to the current stack cost target and balance-of-plant estimated cost projections. The project also led with $1/kg cost target at megawatt scale, but the number does not mean anything without including an input electricity assumption (e.g., 1 to 3 cents/kWh).
- Having the site construction largely complete and major components procured indicates significant progress less than one year into the project. However, with some design work still ongoing, care needs to be taken not to create situations in which, for example, safety reviews at the advanced design stages result in backtracking or physical rework.
- The project has a very good start. It is exciting to see the arrival and integration of hardware components.
- The project is quite new, so the researchers are still in the planning phase, but the project seems to have good momentum at this stage.

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.

- INL has showed outstanding coordination and collaboration with FuelCell Energy and SARTA and in working with various suppliers. The focus on hydrogen production and commonly used 350 bar fueling of a bus allows the project to focus on the SOEC, which is the highlight. It will be great to explore the comparisons between the hydrogen coach and the electric coach and even explore the range for an extended fuel cell electric bus.
- This project shows excellent coordination with partners on both ends (H_2 production and offtake) and offers opportunities for coordination with additional partners in parallel and the future.

- The presenter mentions that there are two project partners (FuelCell Energy and SARTA) but does not really discuss their roles or how they support the project other than providing pieces of equipment. More detail in this area would be helpful.
- Taking advantage of the SARTA Borrow-A-Bus program is a great idea. Further collaboration could be warranted in a few areas, specifically for data analysis.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- It is somewhat difficult to assess progress to goals without some financial projections around energy input costs needed to reach $1/kg (megawatt scale), or what cost portion the gas processing system will add to some conventional capital cost comparison to competing electrolyzer technologies. SOECs have been speculated on and proposed for years. It is great to finally see this being tested in the real world with buses. The phased approach with on-site testing, followed by integration with the actual bus fleet, will be incredibly relevant to DOE goals and have a very high impact, considering the high probability of success from the incremental testing and integration.
- Both the use of SOECs for hydrogen generation (because of their efficiency and compatibility with thermal sources such as nuclear) and the use of on-site hydrogen production for heavy vehicle fueling have great potential for lowering the cost of hydrogen production and expanding the use of hydrogen in transportation.
- The project seems to be tackling two different areas of demonstration: (1) SOEC hydrogen production and (2) fuel cell bus use in extreme conditions. Both areas will benefit from this project.
- Successful execution of this project would support multiple technology and implementation goals.

Question 5: Proposed future work

This project was rated **3.8** for effective and logical planning.

- The contracts for the hydrogen post-processing system are very important, as is working with vendors early on for fabrication. It is good to see SARTA and other fuel cell vendors being considered for 2023. For 2024, it will be great to see the SOEC gas conditioning system in operation. The key milestone will be to see the full system commissioned with storage, compression, and dispensing in place. It will be great to see end-to-end operation and compare SOEC station operation to efficiency or limits on the conventional bus stations under operation with SARTA or elsewhere. Especially interesting will be how the post-processing system affects efficiency or the overall system cost when projected at scale.
- The work ahead to install, commission, and operate the system is clear. It would be helpful to understand the metrics that will be used to evaluate the project's technical and operational success and to understand the plans and next steps after the demonstration concludes next year. Significant infrastructure installation is taking place. It is unclear what happens after 600 hours of running one coach.
- The timeline seems tight, but if the project can be completed in a reasonable time, this is a good set of tasks.
- The proposed work is very good.

Project strengths:

- This is a great Systems Development and Integration and technology acceleration project because it is creating a very real piece of infrastructure from commercial building blocks that can be shown and demonstrated. Prospective adopters of the technology can see and feel a real installation, which is very helpful. Also, it seems like the project plan and high-level designs can be used as templates for other SOEC hydrogen production/fueling installations.
- The flexibility of the project is a major strength. There are opportunities to test/demonstrate additional electrolyzers, to test additional vehicle types, and to gather data on FCEVs in challenging climate conditions on medium-distance routes.

- The partners from INL, FuelCell Energy, and SARTA are outstanding. Demonstrating SOECs at scale and focusing on just post-processing is an important strength of this project.
- The project tackles a couple areas of interest, and INL seems uniquely suited for this project.

Project weaknesses:

- There are no obvious weaknesses.
- It would be great to see more discussion of how the oxygen could be used in the future as byproduct revenue or incorporation for onsite use. It would also be nice to see some local university engagement as part of workforce development goals. It would also be good to see more techno-economic analysis to highlight where SOEC development is compared to conventional electrolysis, as well as how long it might take to reach commercial deployment as needed by the upcoming hydrogen hub proposals.
- The project presentation is light on details about the collaboration partners and their roles. It seems like this project will be of much value for them in showcasing what can be done. The project should take advantage of that. Part of its appropriate role should be greater experience and familiarity of a large circle of participants, which will help foster more future adoption.
- With a tight timeline, achieving tasks on time may be difficult, especially with a dispensing system installation included in the project.

Recommendations for additions/deletions to project scope:

- The project summary slide mentions an objective to "verify suitability of heavy-duty FCEV to provide backup power," but this objective was not discussed, and it is unclear whether it is being pursued. Perhaps in a two-year project, this should be taken out of the scope, although it is definitely a useful project in the long run and maybe should be looked at as a follow-on project.
- The project should share integrated energy efficiency and bus use with energy used for compression storage and dispensing to compare to other bus station archetypes. Cost and technical comparisons to conventional electrolysis technologies could be added.
- Addition of data analysis by other relevant national laboratories would help increase the success of this project.

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

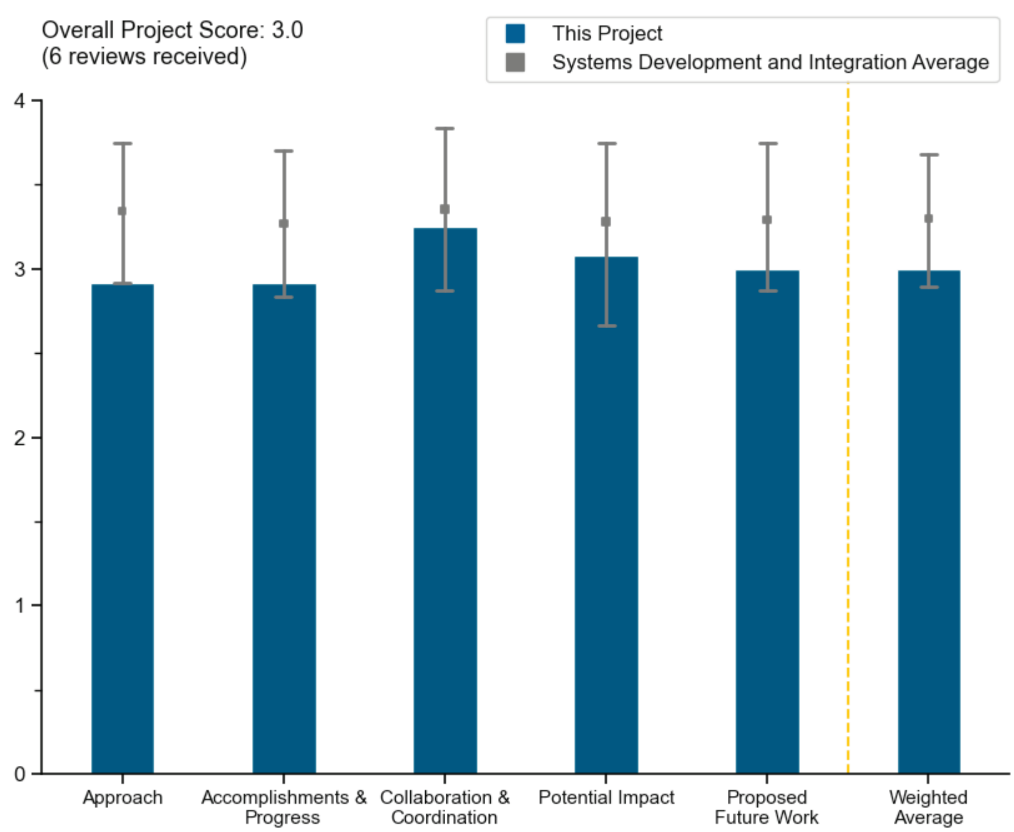
Peter Rupnowski, National Renewable Energy Laboratory

DOE Contract #	WBS 10.1.0.501
Start and End Dates	7/1/2007
Partners/Collaborators	Chemours, 3M, Nel Hydrogen, DeNora, Giner, Fortescue Future Industries, Advent Technologies, Lawrence Berkeley National Laboratory, National Research Council–Canada, Fraunhofer-ISE, University of California, Los Angeles, University of Massachusetts Amherst
Barriers Addressed	• Lack of improved methods of final inspection of membrane electrode assemblies

Project Goal and Brief Summary

The objectives of this project are (1) to understand quality control needs from industry partners and forums, (2) to develop diagnostics by using modeling to guide development and in situ testing to understand the effects of defects, with a focus on heavy-duty fuel cell and low-temperature electrolysis applications, (3) to validate diagnostics in-line, and (4) to transfer technology to industry partners.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration projects.

Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is well defined and leverages both industry and the international community to understand needs. Research is aligned with inputs received from these interactions. Other consortiums are engaged to support research and development (R&D) activities.
- The team presented optical approaches to qualifying defects in the high-speed manufacturing of membrane electrode assemblies (MEAs) for fuel cells and electrolyzers. The great challenge is the strong adsorption of light in the ultraviolet-visible (UV-VIS) range of the optical spectrum by the electrode and support materials. The combined theoretical and experimental studies on the effects of electrode layer variability seems to be thought through better.
- Strengths include the phased approach: understand industry input first, then develop methods. This project is linked to other funding opportunity announcement projects; it addresses major components. It would be good to connect the dots between the requirements from industry (speeds, types of measurements) to the techniques developed, for example, in a table or with green/yellow/red status like the imaging comparison across cameras/exposure times.
- At a high level, the approach involves interacting with industry to determine needs and challenges, but choices about what to work on seem to be at the discretion of the principal investigator, and some of the choices made are surprising. A formalized process to determine industry priorities, such as a request for information, should be considered. The UV-VIS-near-infrared (NIR) spectroscopy work would benefit from an improved approach. Comparing membranes with different thicknesses and different mechanical supports and additives confounds the analysis and prevents meaningful correlation of the results. A better way to do this experiment would be to use a membrane of constant thickness and add controlled amounts of cerium, or other radical scavengers, so that only one variable is being changed at a time.
- The principal quality inspection methods being developed at lab scale do provide relevant data, but they are not considering the speed, accuracy and consistency required for roll-to-roll (R2R) manufacturing.
- This is a project on the use of analytical techniques to measure fuel cell properties and assess fuel cell performance.

Question 2: Accomplishments and progress

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

- The research team has performed the tasks as outlined. The camera system was built; the optical responses of the MEAs were characterized. The optical data, unfortunately, does not provide much information about quality or defect concentrations within the MEAs. The modeling and experimental characterization of layer thickness variability on fuel cell performance has made significantly more progress.
- Accomplishments are well described, and efforts appear to support project goals. Issues identified are either being worked on or fully resolved. The work supports the need for continuous-catalyst-coated membrane (CCM) inspection of R2R-produced parts.
- The project appears to be on track with meeting milestones and clearly presents which measurements were or were not successful.
- The work follows the statement of project objectives and is of high quality.
- Good progress is being made, but it is a little hard to tell how close this is getting to the requirements. The project shows a good mix of methods for point measurements on overall process vs. continuous measurements for defects. The project team should consider how good is good enough, whether the technology is 100x or 2x away from the needed speeds, and whether a solution can be engineered (e.g., perhaps moving the camera in line with the web line and returning to a start point) or if a new invention is needed.
- The accomplishments and progress show some mixed results. Overall, the project does not appear to have yielded many successes or valuable results. The work on chromatic confocal probes looks interesting, but there are no results yet. The optical transmission work shows some preliminary results, but the extremely

long integration times raise questions about the applicability of this approach to high-speed manufacturing. There are no results that can demonstrate or validate the value of this approach yet. The results of the UV-VIS-NIR spectroscopy study are not very meaningful since the test was not designed properly. It is not possible to determine from the results whether the differences in absorption were due to the Ce or due to differences in thickness and reinforcement. Indeed, the comparison with the x-ray fluorescence (XRF) results show that there is little correlation between XRF-measured Ce and UV-VIS-NIR measurements. The XRF measurements show a surprising amount of Ce in the nominally Ce-free NR212, calling into question multiple aspects of the accomplishments and progress in this area. The results of the Lawrence Berkeley National Laboratory (LBNL) modeling on membrane thickness variation match expectations, but these results do not seem to tell us anything new or provide much insight that can be used by industry.

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.

- Cooperative research and development agreements (CRADAs) were executed; this project is also tied into multiple projects. The team is working with multiple competitors in the space, showing the importance of the project to industry.
- The project collaborates with industry, U.S. national laboratories, foreign partner laboratories, and U.S. universities.
- The project showed great use of industry, national labs, and academics.
- The project makes good use of DOE facilities for state-of-the-art results. The model of the CCM is generic and assumes any thickness variation is uniform and consistent, while quality issues typically are defects in material/process quality. A welcome enhancement would be a trilaterally defined set of “acceptable” specifications coming from the performance model, the industrial partners, and the detection limits of the developed test methods that are enhanced with their development.
- The project involves coordination with industry to determine manufacturing R&D needs, but the process of determining prioritized manufacturing R&D areas does not seem to be well defined. Some interaction with LBNL on modeling is included, but the work does not seem particularly relevant to a manufacturing R&D project.

Question 4: Potential impact

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

- The relevance to the Hydrogen Program is very significant. The ability to characterize MEA layer thickness variance is critical for fuel cell and electrolyzer MEA quality control. Developing a greater understanding on how the layer variability affects performance and durability is also of critical importance.
- Further planned development and work represented to date will provide significant value to CCM manufacturers where automated inspection is required to keep pace with production fabrication processes.
- Assuming the developed methods for quality control are implemented in a relevant manufacturing environment, this research can significantly speed up production and avoid rework of stacks.
- Some of the work may be valuable to industry manufacturing efforts, but the lack of a disciplined and documented approach to identifying industry needs makes it difficult to evaluate the relevance and impact. If this project is continued, the project team should rigorously document existing industry needs and then demonstrate that the project approach is actually making progress toward addressing those needs.
- Quality control is absolutely essential to scale-up, which is essential to reaching the cost targets. Inspection can become an enormous bottleneck unless measurement speed meets or exceeds manufacturing speed, and huge amounts of scrap are generated if a process deviation occurs and is not rapidly caught.
- After all this good work, there is not much innovation or prediction of what is needed for a better fuel cell power source.

Question 5: Proposed future work

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

- The current limitations are openly discussed, and the presenter verbally indicated “flash” methods would be developed to increase analysis speed. Planned involvement with industrial partners and suppliers is critical, as their openness on real production issues, compliance with quality standards from the International Organization for Standardization, and a list of “radical scavenger” ingredients to look out for in the membrane will really focus this development on the application at hand.
- Proposed work aims to refine techniques and make correlation between inspection, observation, and in-cell performance. The work will be of great value in understanding defect tolerance and scrap reduction.
- The reviewer did not have time to review future work in detail, but generally, the team has many ideas for moving forward and is continuing to collaborate with industry.
- The continued modeling and experimental studies on how defects affect MEA performance are worthwhile efforts. More focus on optical characterization methods as compared to x-ray and thermal imaging is probably not going to yield much benefit. The strong optical adsorption greatly limits the value of the UV-VIS methods.
- The focus on identifying industry needs is appropriate, but a clearer and more formalized plan is needed.
- The future work is to do more of the same.

Project strengths:

- The modeling and experimental effort that characterizes the effects of variance in the membrane thickness on fuel cell performance is quite valuable. The team recognizes that optical methods do not seem to show much promise as compared to x-ray methods. The membranes are too adsorbing in the optical spectral range. Lithium batteries are inspected using x-ray tomography. The team’s future plans to pursue x-ray methods are highly recommended.
- Engagement with industry is a strength, as is the ability to look separately at catalyst layers, membranes, additives, etc. The project is making progress in distinguishing differences in components more accurately.
- The project has great collaboration with academics, labs, and industry. The research is well-planned. Issue identification and mitigation strategy are project strengths.
- The topic is absolutely relevant to scale production while improving quality.
- The team has extensive interactions with partners and collaborators.
- The team is highly skilled and set up to do the measurements.

Project weaknesses:

- The Coolsnap camera used for imaging may be obsolete. Modern complementary metal oxide semiconductor imagers have better spectral range, faster frame rates, and higher quantum efficiency. Advanced image processing techniques, such as Bayesian inference, may help improve MEA characterization when the signal-to-noise ratio is very low. The penetration depth of UV light may be too low to properly characterize the UV adsorption attributed to Ce. No physical model of the UV adsorption by Ce ions was presented. MEA Ce standards could be made via ion exchange to better calibrate the UV adsorption model.
- The project would benefit from a more focused and disciplined approach. Some of the project activities do not appear to fall within the reasonable scope of an MEA manufacturing R&D project. While the segmented cell and membrane modeling efforts are interesting, they seem surprising focus areas for a manufacturing R&D project. If this project is continued, the Hydrogen and Fuel Cell Technologies Office should provide close oversight of project activities to ensure that they are relevant and useful.
- Many techniques to evaluate the state of the art are reported, but there is no clear path or focus for predicting what changes to the state of the art are needed to improve fuel cell durability and performance.

- Results could be better tied back to where the technology needs to be; significance should be stated on a slide. A dashboard of methods and status could be created showing green/yellow/red or progress toward the goal.
- Single-point measurements may not paint a full picture of CCM quality and would be improved if the scan area could be increased.
- The development is positioned in a lab environment, lacking deep immersion into industrial production requirements.

Recommendations for additions/deletions to project scope:

- Benchmark data on commercially available equipment for quality control (S++, high-resolution bright field, dark field cameras) should be provided. Without disclosing proprietary intellectual property, relevant detectable quality issues should be demonstrated to indeed lead to preliminary failure (this could even be an artificial, self-inflicted defect).
- The efforts to further develop UV-VIS optical methods to quantify MEA defects and layer variability probably should be deleted from the project. The use of modern image-processing techniques applied to high-throughput x-ray characterization should be added to the scope.
- The team should assess results they have generated and give recommendations for improving the state of art to improve fuel cell durability, performance, and alternatives for lowering cost.
- The project should continue to engage with industry on tools of highest need and relevance of outcome and allow for flexibility in the project if a method is not yielding the desired quality/speed/resolution.
- The membrane thickness modeling should be deleted.

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

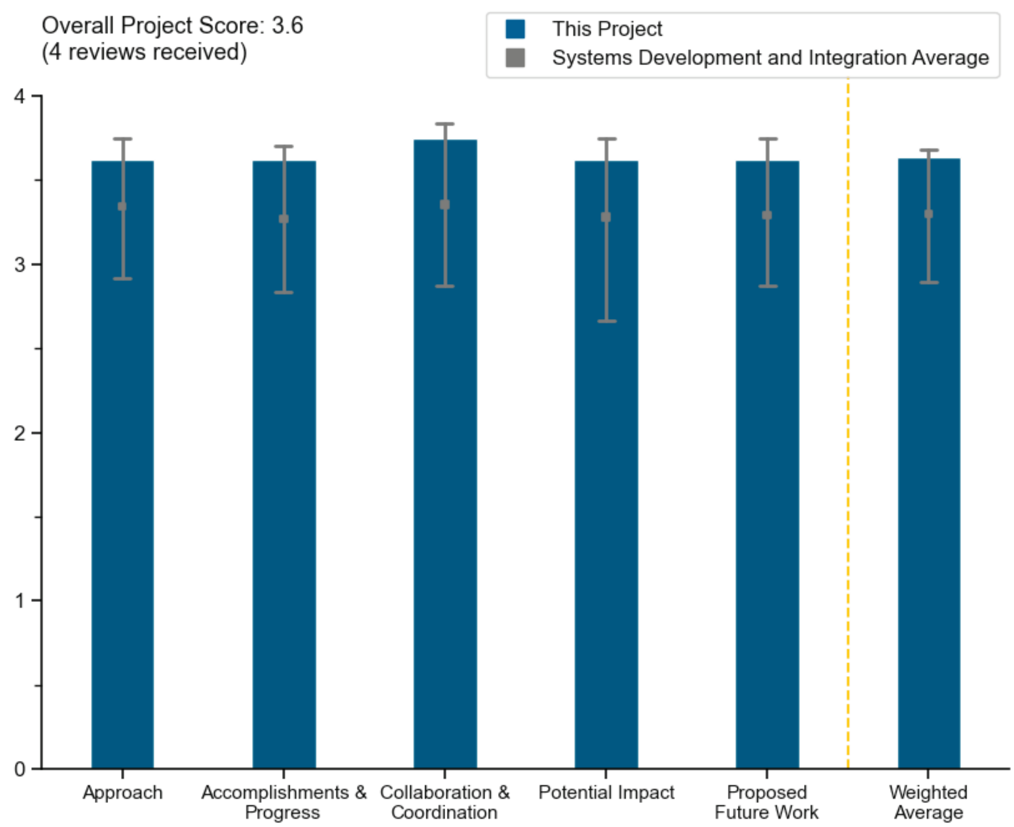
Jason Hanlin, Center for Transportation and the Environment

DOE Contract #	DE-EE0006523/0009
Start and End Dates	7/15/2014–2/28/2024
Partners/Collaborators	California Air Resources Board, South Coast Air Quality Management District, California Energy Commission, Southern California Gas Company, United Parcel Service, Cummins, Universal Engineering Services, University of Texas at Austin – Center for Electromechanics
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 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 medium-duty fuel cell hybrid electric trucks.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration projects.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project has identified (and overcome) challenges directly related not only to the fuel cell application but also to the general issues of repowering existing trucks and providing training/support to get them accepted into regular service. The Phase 1/Phase 2 structure of the project was also a very good approach and certainly helped improve the prospects of completing Phase 2 successfully.
- This project is needed to bring about confidence in hydrogen and fuel cells into this delivery market that needs to be shifted to renewable energy. The approach of the team will bring about this confidence.
- The approach is/was practical and achieved progress, as the number of hurdles that this project encountered is robust.
- The overall objective in the second slide talks about driving range, and in the results, driving range improvements are not seen, although fuel cell power improvements are seen. The Phase 2 vehicle test and evaluation are planned to be completed June 2024. Barriers A & F identified needs that should be addressed completely in Phase 2.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- Getting the vehicles built and delivered and everyone trained was a great accomplishment, given the soft-side challenges in the United Parcel Service (UPS) organization that were described, in addition to the technical challenges. The experience of the trucks in service will be exciting accomplishments for next year.
- While delays were encountered at the beginning of the project, the accomplishments in the last year were very good. Having the first package delivered shows this accomplishment.
- The project substantially increased driving range with a single fueling event.
- Good progress was made on fueling with the following accomplishments: (1) improved the communication protocol with the hydrogen fueling station and (2) created a fuel cell shutoff function as a method of risk mitigation during hydrogen fueling. For the added hydrogen door sensor, the project needs to indicate how data collection on this can improve the fueling scenarios. Clear cost metrics are missing, even though they are mentioned in the objectives. Indirect metrics were given on fuel economy, but the cost category is missing. The accelerated introduction of the technology adoption rate appears mostly due to the fleet partner's internal barriers and being uneducated instead of contractual.

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 partners are appropriate and bring a good deal of value. Many of the contributors will be able to use the project outcome going forward in their businesses. Having National Renewable Energy Laboratory (NREL) as the data analysis team is also a key to project success.
- It sounds like working with UPS has been quite challenging. In addition, the general effort to coordinate with nine project partners was certainly significant. However, the proof is in the results; the trucks are all built and ready to deploy.
- The project included a broad group of partners and peripheral support entities, and completing this project took a community of stakeholders.
- The project was a well-collaborated effort from all parties. The project's prioritization of safety and work is great.

Question 4: Potential impact

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

- A major accomplishment here is getting the people who are going to drive and work on fuel cell electric vehicles in the commercial environment on board and comfortable using new technology.
- A successful project could open the door to this option of renewable energy to delivery trucks.
- Data collection can significantly improve the DOE research, development, and demonstration goals.
- Relevance/potential impact was somewhat diminished by UPS staff turnover and the project timeline. Other similar vehicles have been built in the interim outside this project and have been commissioned for operational use (by other entities not directly engaged).

Question 5: Proposed future work

This project was rated **3.6** for effective and logical planning.

- The reviewer wishes the project team the best of luck in getting the trucks deployed.
- The proposed future work is appropriate for the final project phases.
- More Phase 2 work is expected to be completed on vehicle testing and evaluation. Detail should be provided on what exactly the issue is in "Issue – Utilizing public hydrogen refueling infrastructure prevented a significant number of demonstration days."
- The recommendation is to report only on vehicle test and evaluation results and project management (Tasks 7 and 8) in 2024 and 2025 instead of rehashing all project details again after many years of presenting this project (make reference to previous Annual Merit Review presentations).

Project strengths:

- Commercial fleet operators will be notified to consider zero-emissions vehicle options other than battery-only. The project is targeting a vehicle class that falls outside of many "standard" vehicle classes (last-mile delivery van) and product offerings of large medium- and heavy-duty vehicle original equipment manufacturers. The project is developing a more robust direct current (DC)-to-DC convertor for medium-duty vehicles, a component which is in short supply in the market.
- Dividing the project into a two-phase approach could greatly help with knowing the development issues beforehand. The leadership turnover challenge was resolved well. Hydrogen fueling improvements are seen in the project: the communication protocol and hydrogen door sensor.
- The project is undertaking direct commercial deployment, with the opportunity to acclimate an existing industry to hydrogen/fuel cell technology.
- This project is very relevant to the industry and creates potential to bring about acceptance and adoption of the technology.

Project weaknesses:

- The presenter was pretty direct about the delta cost challenges in retrofitting a diesel delivery van to a fuel cell hybrid powertrain. This is not a weakness of the project per se, but it would be a good area to dig into in detail to see how this challenge could be addressed.
- More metrics should be added in results to quantify the results on the team's data analytics. Mileage improvements should be added. The end goal of Phase 2 data should be added, i.e., what the team is planning to do with this data and whether there is a plan to improve the data gathered.
- Delays to the timeline are the main weakness but are not necessarily unexpected.
- The contractual commitment and timeline have been repeatedly affected by the fleet operator partner's new findings and perspectives.

Recommendations for additions/deletions to project scope:

- It would be helpful to know how the powertrain and drivetrain developed through this project can be integrated into the University of Texas at Austin E-Bus (specifically), to provide (more generally) a second life to small transit buses at the ends of their economical lives, those in need of repowering, or vehicles for college transit operations.
- A total cost of ownership analysis could help the project get a handle on the issue of the cost of retrofitting delivery vans with fuel cell hybrid electric vehicle powertrains.
- This is not necessarily an addition, but the data evaluation at NREL needs to be a major outcome of the project to show feasibility.
- There are no recommendations for additions or deletions to project scope.

Project #TA-017: Innovative Advanced Hydrogen Mobile Fueler

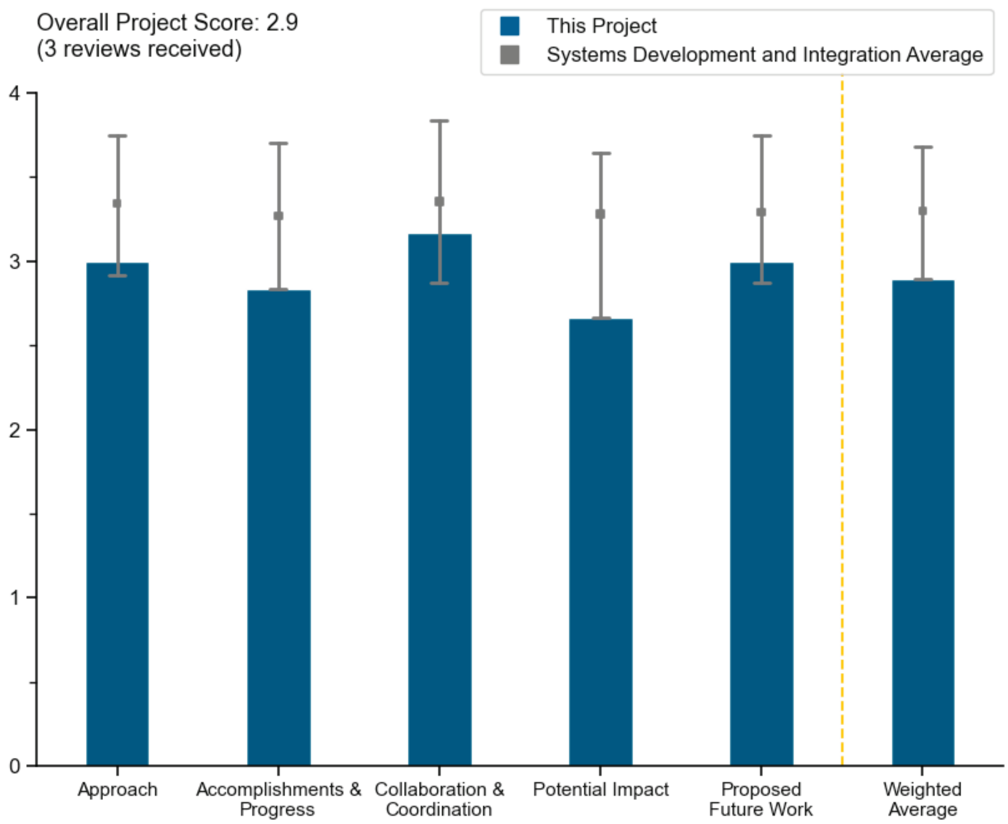
Sara Odom, Electricore Inc.

DOE Contract #	DE-EE0007275
Start and End Dates	7/1/2016–6/30/2023
Partners/Collaborators	Electricore Inc., Air Liquide, HTEC Group, QAI, 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 AHMF will be deployed to support hydrogen stations and vehicles; fueling data will be gathered for analysis by the National Renewable Energy Laboratory's Technology Validation Team. The project's economic findings and market opportunities will be published. To reduce risk, the AHMF 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 Systems Development and Integration 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.

- As this project nears completion, it is clear that the tasks identified by the project worked well to organize the project efforts and matched well with the overall objectives.
- Overall, the project has encountered many hurdles to this point and is finally filling 35 MPa buses. The capacity fueling from buses will be useful but does not offer the complexity of a 70 MPa fueling and somewhat undervalues the work with the high-pressure bank storage U.S. Department of Transportation (DOT) special permit. Lessons were learned on how a mobile refueler could be constructed to meet the heavy-duty truck refueling. Obviously, with the station's downtime learning for light-duty transition to heavy-duty, there is no doubt that mobile refuelers will be needed to support the refueling network expansion.
- Electricore Inc. (Electricore) had a good approach to the work, with some challenges highlighted: expiring permit to use the middle cylinder, consumables of liquid nitrogen (LN2) that may not have been fully tested, and the current use case of a cascade fill with orifice flow control to fill only buses for now. The project clearly has not met targets demonstrating fast fills for 70 MPa to 95% state of charge.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- COVID-19 greatly delayed the project demonstration start, and it is not clear when it will meet 70 MPa full fills at a faster rate. There were some good learnings about shore power and the ability to explore zero-emissions power generation for remote operation. The results of this trailer project showcase the need to have liquid hydrogen mobile fuelers at much higher dispensing capacity and to reduce the challenges of precooling balance-of-plant needs, including size, power, and consumables. The Type 4 high-pressure tank enabled use for 95 MPa on-road transport, which was a good accomplishment, even if it has not been used as much as expected.
- This project has demonstrated solid accomplishments. The three most important are completion/demonstration of the system itself, allowing for validation and data collection; the use of off-the-shelf technology to solve the hydrogen cooling problem in a limited footprint; and advancement of permitting for hydrogen storage and transportation.
- Given the complexity of the schedule delays and other pivots throughout the project, the project made good progress and collected information that will be useful.

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.

- This project engaged appropriate partners well—in particular, component suppliers for the design–build of the unit and permitting, national labs for data analysis and modeling, industry partners for technology and additional support, and government agencies for safety analysis and permitting.
- There was overall good coordination and collaboration across the project. It was good to be proactive with the mobile refueler requirements of the International Code Council (ICC) and National Fire Protection Association (NFPA).
- Electricore had several good collaborations listed. The approach of using existing Air Liquide equipment should have allowed for faster project development. The team was also able to get one of the cascade tanks more rapidly; unfortunately, owing to project delays, the use and life expired before the team was able to test the fueling.

Question 4: Potential impact

This project was rated **2.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The most impactful development following from this project will be the establishment of permitting guidelines for high-pressure mobile hydrogen storage and transport. This provides a path forward for any other entrants into the space.
- These small-capacity trailers may have been useful a few years ago. It is not clear how useful these trailers at 15 kg/day are now or will be in the next few years. Individual components may be of interest, such as low-cost orifice-based fueling (especially maximum flow rates) and in-parallel advanced storage technologies, which might use the LN2 system for early validation at small scale or in limited demonstrations.

Question 5: Proposed future work

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

- With only a month left, it is not clear whether the project will actually be able to reach 70 MPa dispensing at full capacity and reaching 95% state of charge, as stated in the project goals. Three challenges remain for Electricore: achieving faster fueling than orifice-based cascade fills, increasing supply hydrogen capacity, and conducting economic assessment for the total system cost (not dependent on used or donated components). DOE and the community will be excited to see how the mobile refueler can be used beyond 2023.
- This question is not as applicable, as the project is nearing completion, but the stated intent of Air Liquide to continue use/demonstration/data collection using the AHMF is good to see.
- Outside funding/support could be possible for refueling of several different vehicle classes.

Project strengths:

- Despite challenges in supply chains and schedule due to the global pandemic, the project was successfully carried through. Real-world data has been/is being collected in a practical application.
- The project has a strong, motivated team. It is addressing high-capacity fills and is working the difficult DOT Pipeline and Hazardous Material Safety Administration special permit process, as well as implementing codes and standards harmonization across ICC and NFPA requirements.
- The strength of the system was to showcase a standalone 70 MPa fueling system for remote low-capacity operation in a very short timeframe. It is not clear that the team will be able to demonstrate this before the end of the project.

Project weaknesses:

- This project’s weaknesses stem from delays in the project, procurement of parts, and full demonstration of the original project goals. It is not clear how feasible or realistic it is to use the LN2 supply for 70 MPa fueling. At only 20 kg of dispensing capacity, it is not clear that there is much use in allowing longer fueling and simply increasing onboard capacity.
- No 70 MPa fueling was accomplished, which was a main objective of the original project.

Recommendations for additions/deletions to project scope:

- As the project is at end of life, it is not clear that there are any opportunities for additions or deletions to the project scope. A clear summary of total usable capacity and limits of the LN2 system for back-to-back fills at 70 MPa and 35 MPa high-flow fueling would be valuable. The discussion of shore power vs. onboard generator would also be very helpful for planning higher-capacity systems for more clear use scenarios.

Project #TA-018: High-Temperature Electrolysis, Stack, and Systems Testing

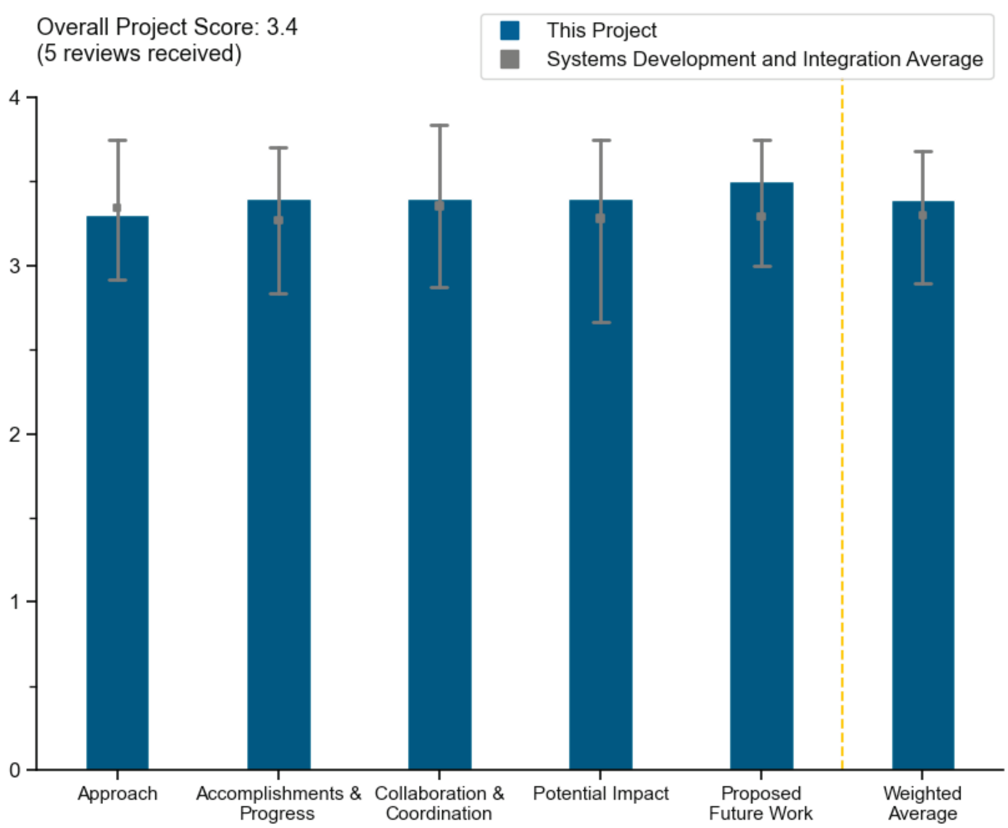
Micah Casteel, Idaho National Laboratory

DOE Contract #	WBS 7.2.9.1
Start and End Dates	9/30/2020
Partners/Collaborators	Strategic Analysis, Inc., Bloom Energy, FuelCell Energy, OxEon, Nexceris, Xcel Energy, Topsoe
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 material 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 to simulate real-world applications, including nuclear-to-hydrogen hybrid energy 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 Systems Development and Integration 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.

- Great progress has been made to provide access to a large stack and system (future) testing platform for third-party stack and system evaluation. Extended operation on 5 kW stacks and a 100 kW system is encouraging.
    - Perhaps it would be beneficial to revise hazard and operability (HAZOP) and plan systems with multiple redundancies (justifiably, as it will cost more) to ensure prolonged and uninterrupted operation (where needed). However, in some cases, interrupted operation might represent supply–demand variability in hydrogen production; thus, many lessons could be extracted from such events. The team has already indicated the need for boiler redundancy.
    - Perhaps it would be beneficial to consider incorporating accelerated tests on stacks/systems to enable predictive degradation analysis. Accelerated tests at stack/system level might look very different when compared to cells and thus might need to be developed separately. It would be very interesting to see plans for accelerated test approaches.
    - With test bends in place, many smaller and start-up companies would see significant benefits with access to Idaho National Laboratory's (INL's) testing capabilities. Perhaps it would be beneficial to understand how larger original equipment manufacturers (OEMs) would gain any technical/efficiency/cost benefits from the third-party validation tests at INL since these OEMs already have test data from internal research and development centers and customer sites.
- INL has established excellent HTE stack testing capabilities and is leveraging those capabilities on this project to support multiple HTE stack and system developers. As INL expands and scales its stack testing capabilities, the researchers are learning valuable lessons and sharing these lessons with the technical community. They are obtaining baseline stack performance and durability data and sharing this information (to the extent allowable) with the community. They are providing DOE with an assessment of where HTE stack technology stands with respect to performance and durability targets. One recommendation is to include a real-time means of assessing stack leakage (perhaps with a tracer gas). Since leaks often manifest as performance improvement or lack of degradation, the true stack degradation that may be happening can be hidden. INL observed this in one of the stack tests.
- The objective of this systems development and integration project is to support industry to enable economical hydrogen production (at $1 per kg H_2 at megawatt scale) using solid oxide electrolysis cell (SOEC) systems. The challenges, barriers, and goals are clearly identified. The proposed technical approaches are reasonable. The work plan is well thought out. It is likely that the team will be able to overcome the critical barriers and achieve project goals.
- The approach to performing the work is excellent. Different approaches may be used for testing stacks/systems from different vendors. However, there is a need to summarize lessons learned indicating what is common and what is different.
- There is a clear need to generate stack test results independently, although INL test stand stability, quality, and capability could skew results.

Question 2: Accomplishments and progress

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

- Good key performance indicator numbers have been reported, for example, 14 tons of hydrogen being produced, stable operation to the point of being perceived as "boring," and test stand issues being resolved. The project displayed clear regard for safety and attention to detail with regard to the continuous HAZOP review.
- INL tested multiple third-party stacks in the past year and increased the size of stacks that were tested. The third-party testing provided to stack developers provides critical feedback and also provides DOE with an assessment of where industry is relative to the stack performance and durability targets.
- The reported performances of the FuelCell Energy stacks and the Bloom Energy stacks are very encouraging. It seems that the project objectives and critical barriers are being adequately addressed. In

addition to the stack voltage and current, it would be helpful to provide some additional information about individual cell performance, such as the current density in A/cm^2 of active electrodes and the cell voltage under various testing conditions.

- Progress has been made toward the project objective. Some metrics need to be developed to measure progress and accomplishments.

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.

- Collaboration and coordination are absolute strengths of this project. INL has established excellent relationships with most (if not all) of the industrial members of the HTE community. Trust is one of the most important components of collaboration, and INL has certainly earned the trust of its partners, who have been willing to send them stacks (and systems) for testing.
- This project involves a large number of partners, including two other national labs, six industrial SOEC developers, and one industrial SOEC user. It seems that the team functions well in performing the planned tasks and achieving several project objectives.
- Although the number of tested partner stacks is limited to FuelCell Energy and Bloom Energy, this project is well connected to related projects and actively engaging third-party stack testing.
- The project has excellent collaboration and coordination with different stack/system developers.

Question 4: Potential impact

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

- There is strong impact on advancing stack suppliers in development who need validation to proceed, but at higher technology readiness levels (e.g., Bloom Energy), there may no longer be a need for DOE to support.
- While good progress has been made in testing several commercial SOEC stacks from FuelCell Energy and Bloom Energy, it would be more impactful if an effective “accelerated” testing protocol/procedure could be developed so that SOEC systems can be reliably evaluated in a much shorter period.
- Demonstration of testing capabilities for different developers helps to advance progress of the technology toward DOE goals/objectives.
- This project is accelerating the development and acceptance of HTE as a highly efficient approach for hydrogen production.

Question 5: Proposed future work

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

- INL’s plans to expand its stack and system testing capabilities in support of industry developers is exactly what industry needs to accelerate development efforts.
- Expanding test capacity, while pushing dynamic operation for high-temperature stacks (a typical weak point) is an extremely valuable way to demonstrate true performance capability.
- The proposed future work seems to be reasonable for addressing the remaining challenges and barriers. It would be more impactful if more efforts could be devoted to “accelerated” testing of commercial systems under a wider range of conditions.
- The proposed future work is effective for making progress toward the project objectives.

Project strengths:

- The project is (1) providing a stack testing service that accelerates industry’s SOEC stack development progress and (2) keeping DOE updated on the technical progress toward meeting HTE stack performance and durability goals. Collaboration is also a project strength.

- INL showed strong expertise and a trusting relationship with partners, thus providing a solid foundation for expanding collaboration and knowledge transfer.
- Excellent progress has been made in testing commercial SOEC systems under typical conditions.
- The project has developed a unique testing capability for large stacks/systems from various developers.

Project weaknesses:

- As SOEC and solid oxide fuel cell (SOFC) product maturity increases over time, together with the level of secrecy in disclosing information, the added value of this testing validation service may become less relevant or just too small.
- Some more analytical analysis to gain more information about the performance of individual cells would be very helpful.
- Clear and well-defined objectives have been lacking in testing done to date.

Recommendations for additions/deletions to project scope:

- Recommendations include anticipating the growth of the SOEC/SOFC market demand and incremental implementation of such products; additional business cases need to be assessed for multiple applications, going beyond continuous operation. Of course, this discussion has to strongly engage all stakeholders.
- A cost study is also included (but subcontracted to an outside firm) in this project. It is unclear how the cost study contributes the stack/system testing effort.
- It would be very helpful to develop an “accelerated” testing procedure of commercial systems under a wider range of conditions.

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

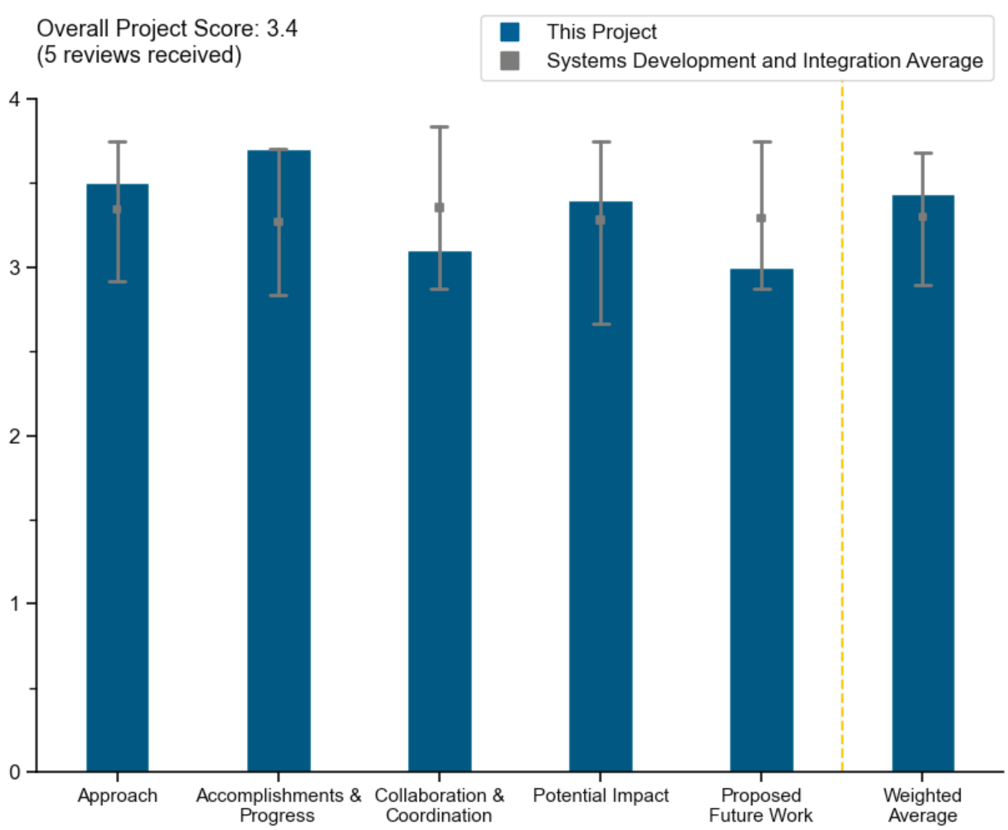
Uuganbayar Otgonbaatar, Exelon Corporation

DOE Contract #	DE-EE0008849
Start and End Dates	10/1/2019–10/1/2023
Partners/Collaborators	Exelon, Idaho National Laboratory, National Renewable Energy Laboratory, Argonne National Laboratory, Nel Hydrogen
Barriers Addressed	Site selection: the criteria for site selection Regulatory: the relevant regulations that affect nuclear hydrogen production Market-related: 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 a Constellation nuclear power plant. A 1 MW proton exchange membrane (PEM) electrolyzer and supporting infrastructure will be installed, providing an economic supply of in-house hydrogen consumption at the plant. Researchers will also simulate the scale-up operation of a larger 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 Systems Development and Integration 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 project has successfully achieved full operation, and it is expected that the final milestone (demonstration of dynamic operation at the site using the front-end controller developed by the National Renewable Energy Laboratory [NREL] and Idaho National Laboratory [INL]) will be achieved (allowing for considerations of cybersecurity, as mentioned during the presentation). The project approach was/is excellent.
- The approach is a combination of installation, demonstration, and analysis work that is critical for enabling nuclear-sourced hydrogen. The key components of the approach include demonstration of dynamic operation and economic hydrogen production. The project is effective in contributing to the demonstration of an economic supply of hydrogen to nuclear facilities for their own hydrogen consumption. The presentation did not provide enough information to determine whether the challenges on site selection and regulatory impacts, presented in the project overview, were answered. While Argonne National Laboratory (ANL) did an impressive market analysis, it misses the mark on capturing and communicating the considerations of a nuclear facility versus placement of electrolyzers at any other cost-competitive location.
- The approach is fine since it should achieve the major goals of this project, which is to demonstrate how a water electrolysis system can be used at a nuclear power plant. It could have been outstanding if more time were allocated to actually collecting data on the electrolyzer system. For example, to date, only steady-state operation has been demonstrated. It would be useful to demonstrate transient operation and determine the response time, and it is not clear if this will be done as part of this project. Since the project is scheduled to end on October 1, 2023, it is unlikely that any extended data on the system (e.g., reliability and decay rate) will be included in this project. This relatively short operational period is a common problem with DOE demonstration programs, which often end shortly after the demo system is commissioned. Extensive testing should be included in the project, and the operational results should be shared with the community.
- This is an excellent project that integrates nuclear power with an electrolyzer for an onsite demonstration. The project also includes some modeling work. The project does not specify how the waste heat would be utilized for the electrolyzer operation to enhance the overall system efficiency. The project does not include measurable milestones such as system efficiency, operating conditions, and duration (i.e., 5,000 hours).
- This is an excellent project that integrate nuclear power with an electrolyzer for an onsite demonstration. The project also includes some modeling work. The project does not specify how the waste heat would be utilized for the electrolyzer operation to enhance the overall system efficiency. The project does not include measurable milestones such as system efficiency, operating conditions, and duration (i.e., 5,000 hours).
- The overall approach here is great, but there is some concern that much of the scope is being executed by national labs, possibly in a very uncoordinated way.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and DOE goals.

- This project is near completion, and no significant challenges were identified. Some technical/equipment issues were reported and appropriately addressed by engineering design efforts. Collectively, the project achieves the DOE goals of research, development, and demonstration for the hydrogen technology; the project also advances the DOE efforts to sustain nuclear power as part of a secure and robust electric power grid.
- This is a meaningful project with many accomplishments. Most strikingly, the 1 MW PEM water electrolysis system has been installed in the nuclear plant for the purpose of integration. This is a first-of-its-kind integration. The project has included some simulation results that are also informative. Milestone 8.0 is for steady electrolyzer operation. It was labeled as "completed," but there was no reported data as of the Annual Merit Review.
- The installation and demonstrations of the system, initially in steady state and now in dynamic operation, are great project progress. The scope of analysis that the ANL team conducted is truly impressive, although details of the analysis were not provided, making it difficult to assess the quality of results.

- The project is nearly complete, having successfully met most milestones and addressed significant questions.
- It is good that the electrolyzer started operating on March 7, 2023. However, it is disappointing that it took more than three years after the project started to achieve this milestone. It does not allow much time to demonstrate the operation of the electrolyzer under various modes and conditions, which is a major lost learning opportunity for the DOE Hydrogen Program.

Question 3: Collaboration and coordination

This project was rated **3.1** for its engagement with and coordination of project partners and interaction with other entities.

- The project team seems to be coordinating well, and the presentation clearly communicated how the project will coordinate with Advanced Research on Integrated Energy Systems (ARIES) and other DOE-funded demonstration projects to address previous reviewer comments.
- The project has a strong team including the Constellation Energy Corporation, INL, NREL, ANL, and Nel Hydrogen. Each participant has unique expertise but is complementary to others.
- Based on the information provided, the collaborative relationship between Exelon/Constellation, Nel Hydrogen, and the DOE labs was good. Very little information was made publicly available during the project performance by any of the participants, making it difficult to conclude anything other than the stated grade.
- Nel Hydrogen's contribution is obvious, and its collaboration with the prime appears to be good. ANL's contributions on hydrogen markets and emissions savings are good, but it is not clear why the Nine Mile Point Generating Station is not included in this analysis. It is surprising that NREL and INL, and not Constellation, were used to develop controllers for this system. In any case, it is not clear if these controllers are good, since no transient testing of the electrolyzer has been done to date.
- It would be preferred to see formal collaboration with the Electric Power Research Institute, Nuclear Energy Institute, etc., or other utilities.

Question 4: Potential impact

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

- Demonstrating the dynamic operation of electrolyzers and performance over time provides critical data that is lacking in the field. Understanding the needs of nuclear facilities and the intersection of hydrogen and nuclear energy is a critical opportunity for low-carbon hydrogen production, and the lessons learned from the project will build confidence.
- This project is highly impactful, as it will set a great example of how to utilize nuclear power to generate green hydrogen. The project execution and results are very encouraging to the hydrogen community.
- This project aligns with Hydrogen and Fuel Cell Technologies Office and H2@Scale goals of demonstrating multiple end uses of hydrogen and the usefulness of the electrolyzer in grid services.
- The project was very successful in producing an integrated demonstration-scale system at a nuclear power plant. Several design and licensing hurdles were overcome to facilitate the installation, which has significantly advanced the potential for future deployment at larger scale. The choice of technology, however, may limit the economic value of any large-scale project as compared to high-temperature solid oxide electrolysis. The efficiency of the high-temperature systems with the availability of thermal energy from a nuclear power plant (with relatively low impact on net generation) will be required to achieve hydrogen production at a competitive cost long-term. This is likely to be the case, considering some forecasts for long-term power demand growth with increasing power prices.
- Demonstrating that a water electrolyzer can enable a nuclear power plant to maintain steady-state operation while delivering varying power output is certainly well aligned with DOE's H2@Scale Program. However, this project has not yet demonstrated that the electrolyzer can do this, since transient operation has not been demonstrated, nor has the project demonstrated electrolyzer operations optimized to maximize the value of electricity and hydrogen production.

Question 5: Proposed future work

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

- This project is nearing completion and has achieved its objectives. The score provided is based on the reported future applications of the hydrogen system, which is outside of the DOE scope. The project team has done an excellent job of providing future advancement of the demonstration system to maximize the long-term economic value of the integrated process.
- Future work beyond operating the electrolyzer is not clear. However, if the Midwest Alliance for Clean Hydrogen (MACH2) Hydrogen Hub is funded by DOE, this should bring many opportunities. This project has also identified and started work with national labs in several areas that could, in themselves, be useful future scopes.
- Constellation has committed to investing $900 million through 2025 for commercial clean hydrogen production using nuclear energy. This includes participation in MACH2. The project needs to produce more electrolyzer operating data in the rest of the project time.
- It is commendable that the project included lessons learned in the future work. The completion of installation and dynamic operation is key for the team to meet project targets. It is not clear whether there are any plans to make the ANL work public, or how that work is being evaluated and compared with other research funded by DOE.
- The proposed future work (on slide 16) is limited to three bullets that all state that additional work may be done, if additional external funding is secured. It is not clear what else, if anything, will be completed during the last few months of this DOE project.

Project strengths:

- This is an excellent project that integrates nuclear power with an electrolyzer for an onsite demonstration. The 1 MW PEM water electrolysis system has been installed in the nuclear plant for the purpose of integration. This is a first-of-its-kind integration project. The project has a strong team. Each participant has unique expertise but is complementary to others. The project execution and results are very encouraging to the hydrogen community. Constellation has committed to invest $900 million through 2025 for commercial clean hydrogen production using nuclear energy.
- This project is very well developed and is focused on the integration of energy processes that have the potential to support and sustain nuclear power while realizing measurable decarbonization of the electric grid. The progression of this overall effort to advance to commercial scale and the application of the produced hydrogen are excellent.
- The project has gained much positive attention from media, funding agencies, and collaborators, which is a great mark of success. The project looks on track to complete all milestones and has done a commendable job responding to past reviewer comments and suggestions.
- It appears that the financial contribution from DOE was <50% ($5.8 million, with a total project budget of >$14 million). This is good for a demonstration project. This project has the potential to successfully demonstrate a useful application of electrolyzers, if transient operations for extended periods are included.
- This project asks questions and starts research in several impactful ways, plus it will have a payback just from the cost of onsite hydrogen.

Project weaknesses:

- This project provided valuable information at a demonstration scale for the installation of a hydrogen production process at a nuclear power plant. However, the low-temperature electrolysis technology has already been tested and validated, and the effort does not advance the PEM process. There was nothing reported on monitoring the dynamic behavior or the long-term reliability of the electrolyzer. The project incurred the cost of integrating the low-temperature system behind the meter. The project would be as successful with the PEM system powered from an onsite grid supply with a meter. It is assumed that the installation behind the meter was done to qualify for the proposed production tax credit. However, the industry should have argued, and still should argue, that clean (nuclear) generation that would otherwise be curtailed and instead is used to produce hydrogen should qualify.

- It was hard to evaluate the analysis value in regard to vetting the feasibility of hydrogen development at nuclear facilities (aside from general end-use evaluation). For example, it is not clear how key decision points are being made, such as using the hydrogen at the plant versus selling it or building storage versus a pipeline. There are gaps on how the project is addressing key research challenges/questions on regulations and generalizability to other nuclear facilities (beyond simply hydrogen price and Hydrogen Delivery Scenario Analysis Model [HDSAM] delivery), which were also highlighted by past reviewers.
- A project budget of >$14 million for just a 1 MW electrolyzer demonstration and some analysis is much more than one would expect. The cost of the 1 MW electrolyzer should be <$3 million. Clarification is needed as to whether the cost of non-reoccurring engineering (i.e., product development work) at Nel Hydrogen is also included here.
- There is nothing really innovative about this demonstration project. It can demonstrate that this obvious use case for an electrolyzer can be realized, if the team does successfully complete some transient operations with the electrolyzer. It would be even better if the project included some extended operational period to demonstrate durability and reliability. If Constellation wants to demonstrate something innovative, then the utility should consider demonstrating that turbine cooling can be done with a hydrogen stream that is recycled using an electrochemical hydrogen pump to purify and compress the hydrogen. This would mitigate hydrogen consumption and emissions.
- The project does not specify how the waste heat would be utilized for the electrolyzer operation to enhance the overall system efficiency. The project does not include measurable milestones such as system efficiency, operating conditions, and duration (i.e., 5,000 hours).
- The weakness is that this project does not really solve any of these scopes that are managed by the national labs; it only opens them up to future work.

Recommendations for additions/deletions to project scope:

- In the long term, it would be desirable to see Constellation include clean hydrogen production with carbon capture for the subsequent production of carbon-neutral, non-electric energy products (syngas, methanol, Fischer–Tropsch fuels, etc.) to assist in decarbonization of other sectors.
- DOE should ask Constellation if the utility is willing to do a no-cost extension of the schedule to include the collection and dissemination of electrolyzer operational results. More extended-operational data of electrolyzers in real-world applications is needed.
- It is recommended that the project revisit the simulation based on the performance observed in the installed dynamic operations. This is (understandably) not included in the scope but should be considered by DOE as a follow-on project.
- The project needs to produce more electrolyzer operating data in the rest of the project time period. The project should specify how waste heat would be utilized for the electrolyzer operation to enhance the overall system efficiency.
- There are no recommendations for changes to project scope.

Project #TA-035: Power Electronics for Electrolyzer Applications to Enable Grid Services

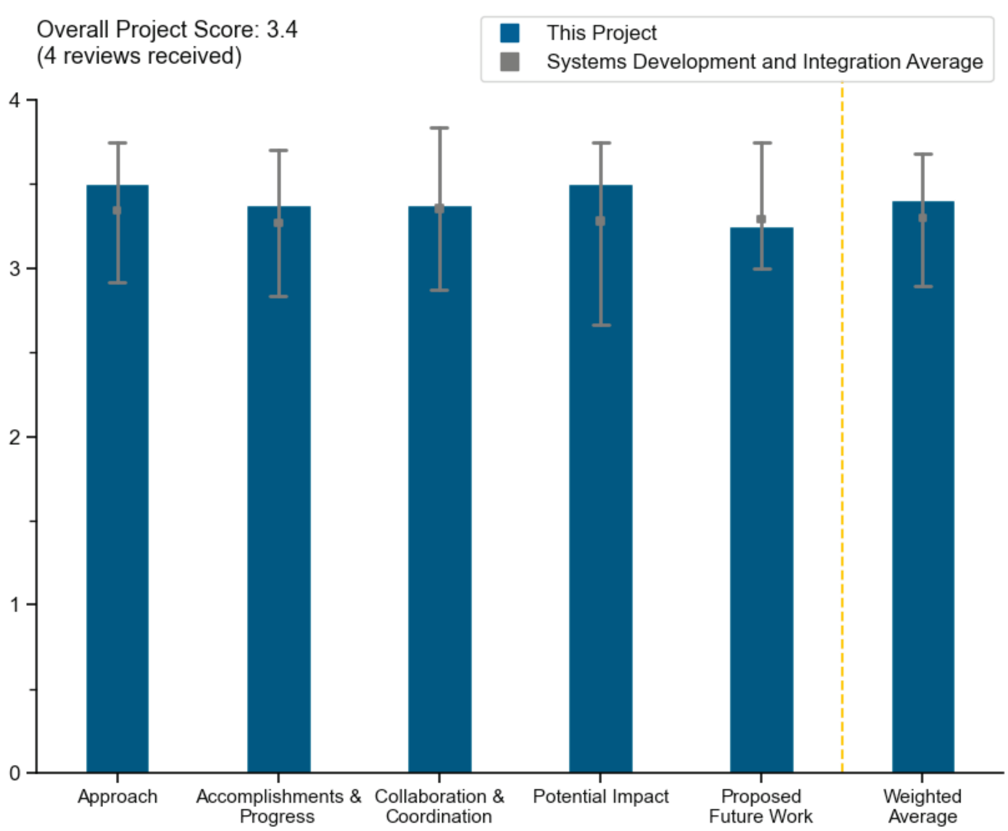
Robert Hovsapian, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.5
Start and End Dates	3/1/2020
Partners/Collaborators	EPC Power Corporation, Nel Hydrogen, Typhoon HIL, General Electric, SunSpec Alliance
Barriers Addressed	• Lack of standardized controls interface for electrolyzer applications in real-world operation as per grid codes and interconnection, interoperability standards, and scalability analysis • Coordinated control of multiple electrolyzers, including interaction with other power electronically interfaced distributed energy resource technologies in hybrid energy systems • 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 Systems Development and Integration 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.

- Great modeling work is proposed to integrate control architecture to maximize electrolyzer integration with renewables.
- Identifying a standardized approach for integrating electrolyzers into the grid is valuable, particularly for communicating grid-relevant signals. To date, most of the project's targeted operations are in response to existing grid conditions, rather than receiving direct signals from the grid. It would be good to include utilities as part of this effort to help guide grid-relevant signals.
- This project will continue in Fiscal Year (FY) 2023 and FY 2024. The team has added additional power converter companies to the project. The team has a well-laid-out plan to continue the research in FY 2023 and FY 2024.
- There is a clear need for this protocol standardization and a demonstration of its functionality.

Question 2: Accomplishments and progress

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

- A framework for testing electrolyzer response in a simulated environment has been created, and results are promising. The slide with data from the 1 MW electrolyzer and 1 MW fuel cell is interesting, but it would be nice to see the demand/output from the electrolyzer/fuel cell in separate plots. There are likely low-load/-output values that need to be maintained for both units, and it would be valuable to understand those interactions—for example, whether the electrolyzer can be turned off completely or whether there is a low-load limit that must be maintained to achieve the expected response times. The same goes for the fuel cell.
- There has been great progress toward project goals. There is a good blend of modeling and verification through real installation of electrolyzer equipment, controls, and storage, which will help to optimize integration of these systems and support broader deployment of technologies.
- Clear results have been achieved in a relevant hardware-in-the-loop (HIL) environment.
- The team has made significant progress on the tasks laid out in the project plan.

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.

- There is great collaboration with industry and the lab. Leaders of respective technologies are pulled in to support and develop both modeling and installed systems to verify the approach.
- NREL has partnered with EPC Power Corporation, Nel Hydrogen, Typhoon HIL, General Electric, and SunSpec Alliance and is in discussions with Semikron Danfoss and Hitachi Energy.
- The partners are actively contributing to create a working system, and more industrial parties are brought into the conversation.
- It is suggested that the project include some utilities in this conversation to gain a better understanding of what control points would be of interest. There are also monitoring data streams that utilities would likely be interested in tracking but not controlling. These could be valuable for consideration as the standard is being developed.

Question 4: Potential impact

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

- The project contributes directly to the Hydrogen and Fuel Cell Technologies Office's "Hydrogen Shot," which seeks to reduce the cost of clean hydrogen to $1 per 1 kilogram in 1 decade ("1 1 1").
- Current electrolyzers have few options for external controls. This is a valuable project in that it provides a framework for future development around the integration of electrolyzers with the grid.

- The impact of this work will further support electrolysis and integration with renewables to optimize installations and create greater value and cost reduction of hydrogen.
- The true value of this project will become apparent once Institute of Electrical and Electronics Engineers (IEEE) standardization has been achieved.

Question 5: Proposed future work

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

- The team has laid out a plan for FY 2023 that is reasonable for the tasks and goals for this project: (1) identify three power conversion and control vendors for different capacities of electrolyzer systems; (2) establish a high-level test plan for integrated testing of electrolyzer and power conversion and control and develop SunSpec Alliance validation and automated testing for identified vendors; and (3) conduct experimental validation using controller HIL.
- Proposed future work will continue the verification of modeling with actual testing of installed equipment. Demonstration work planned with additional direct current (DC) power sources is being considered. The intent is to engage with additional suppliers to get a better survey of stakeholders.
- It is encouraging to see more validation of scalability and modularity of hybrid systems.
- It could be valuable to consider different electrolyzer technologies in the context of response rates, start-up times, minimum loads, etc. Proton exchange membrane (PEM) electrolyzers have different response characteristics and operating envelopes from solid oxide fuel cells or molten salt electrolyzers. If it is not already being considered, a brief comparison might be made between the different electrolyzer technologies and the different integration/control paradigms they might require.

Project strengths:

- This project is valuable in that it provides a potential framework for future electrolyzer integration with the grid in a standardized manner. Following the SunSpec Alliance model is a reasonable starting point.
- The team and collaboration are strong. The project looks to develop predictive models confirmed with testing at scale.
- This project is taking the initiative to solve a pressing issue that can find direct application. There is a clear demand.
- Power electronics are a weak point in integrating hydrogen and fuel cells. This research is necessary for the advancement of the technology.

Project weaknesses:

- Utility perspective is lacking in this project. If these devices are expected to provide grid services, it would be useful to get input from utility operators to provide guidance on what those signals may look like. Evaluating different electrolyzer technologies is also of interest.
- It may be difficult to unite enough stakeholders to gain critical mass for standardization, if matters like reliability, security, and bidirectional communication are not sufficiently addressed.

Recommendations for additions/deletions to project scope:

- It is critical to achieve a stable, decentralized energy network whilst integrating a great variety of sources and sinks. This protocol could play a decisive role by making a very compelling case for its implementation, for example, by also addressing additionality requirements and “certificates of origin” compatibility.
- The project should compare electrolyzer technologies and include utility perspectives on using electrolyzers for grid services.

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

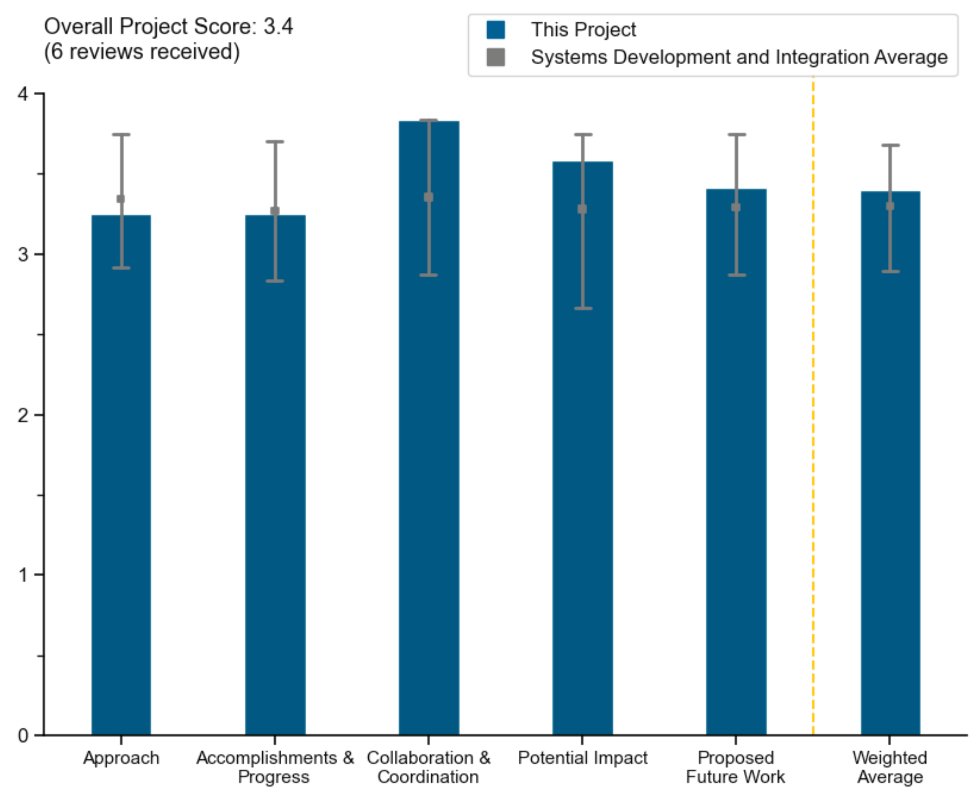
Rich Myhre, Frontier Energy, Inc.

DOE Contract #	DE-EE0008850
Start and End Dates	10/01/2019–7/31/2024
Partners/Collaborators	Air Liquide, CenterPoint Energy, Chart Industries, Chevron, ConocoPhillips, Frontier Energy, GTI Energy, Low-Carbon Resources Initiative, McDermott, Mitsubishi Heavy Industries America, OneH2, ONE Gas, ONEOK, Shell, Southern California Gas Company, Texas Commission on Environmental Quality, Toyota, University of Texas at Austin, Waste Management
Barriers Addressed	• Need to demonstrate hydrogen and fuel cell technologies in complete, integrated systems operating under real-world conditions • High investment risk for developing H_2 delivery infrastructure, given the current absence of demand for H_2 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. 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/Gulf Coast region that leverages existing hydrogen generation, distribution, and infrastructure assets to enable deployment of stationary fuel cell power and hydrogen-fueled vehicles. The plan will summarize opportunities, challenges, and key partners, as well as identify the economic and environmental benefits of at-scale hydrogen deployment for the region.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 constructing a demonstration of mixed-source hydrogen to mixed onsite demand for very relevant hydrogen production and use technologies. A safety analysis is a key component of the project. The project includes an assessment of the hydrogen supply chain in Texas, providing context on variables that drive cost and influence technology deployment. This type of project is highly relevant to DOE H2@Scale. The project is well poised to take a critical look at key barriers to scaling up the use of hydrogen in the Texas region, including validation of hydrogen use for drones and the mixed-source onsite production of hydrogen from natural gas, biogas, and renewable-powered electrolyzers.
- This is a very interesting project that combines multiple resources and technologies with a goal of reducing dispensed costs of low-carbon hydrogen. Overall, the approach seems sound, with a strong project team and a good focus. It would be helpful to see a clearer definition of "least cost" in terms of how capital costs are being treated from an overall cost perspective, and how the underlying solar and wind systems to produce electricity are being included from a cost perspective. It would have been good to hear a little more about how the "hybrid" approach of using solar photovoltaics and simulating wind will be carried out, as well as limitations relative to physically combining these technologies.
- As a sort of predecessor to the upcoming DOE Regional Clean Hydrogen Hubs (H2Hubs), this project will demonstrate several types of production, a fuel cell for stationary power, and fueling for several vehicles, and calculations will be used to look at a larger hydrogen ecosystem. The project will also, to at least an extent, demonstrate the integration of all these production/delivery/use cases to make a functional system that serves all.
- The well-thought-out approach covers most aspects. There needs to be community engagement and outreach. This is an excellent opportunity to gain community buy-in on hydrogen, both locally and nationally. The approach of multiple ways to generate hydrogen, storage, and different types of end users is very good.
- The project has multiple facets, with interesting comparisons between electrolyzer- and SMR-based hydrogen and multiple energy sources. The demonstration should provide data on several use cases of value.
- This project is addressing critical questions but has some gaps. Most notably, the physical demonstration is not clearly linked to the framework/roadmap. The technology selection is not clearly aligned with the framework scope, and there is no apparent connection to scale (i.e., the data center will require vast amounts of hydrogen, and possibly hydrogen storage, not utilizing the SMR). The scope should be reconsidered away from physical deployment toward analysis of well-known technology and reconsidered with the requirement that any physical scope should have a defined purpose and explicit hypothesis that supports the framework.

Question 2: Accomplishments and progress

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

- The project has done a good job adjusting the approach to changes. For example, the team re-negotiated some contracts to get lower prices. The Hydrogen Optimization with Deployment of Infrastructure (HOwDI) model was very useful in developing the plan. The low projected dispensed cost of $3.79/kg H_2 with tax incentives is encouraging. It should be remembered that these are tax credits, so they work only when a taxable profit is made. The site-level and equipment-level hazard analysis looked very complete. It was good to hear that the principal investigator is responding to the hydrogen safety panel recommendations. The cost analysis for pipeline hydrogen delivery is good.
- Significant hardware procurement has been completed; hazard and operability (HAZOP) studies are ongoing. There has been an impressive amount of safety analysis through process hazard analysis and functional hazard assessment with third-party engagement, which changed the layout onsite. Construction has started for pads and interconnects.

- The project has made marked progress toward the installation and operation of the demonstration site, including procurements, safety and hazard analysis, engineering design, and skid analysis. The project also has made substantial progress on the hydrogen region framework and economic model, including near-completion of a five-year report plant.
- All major equipment is ready; much is in place, and the rest is coming. HAZOP studies are complete, based on this replanned layout for greater safety. Site construction and preparation are under way. The project is being used to educate the next set of engineers in the energy area.
- The project is somewhat behind schedule, but recent progress has been good. The project is well targeted toward key DOE goals of validating and proving out low-carbon and renewable hydrogen systems.
- Given the scope as it exists, the milestones and delays this project has accomplished have been reasonable.
- The cost analysis would benefit from doing the analysis for onsite production of hydrogen from water electrolysis.

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 highlighted ongoing work related to H2@Scale in Texas and demonstrates successful communication among an impressive number of companies and institutions. There was not enough information to evaluate the data portal proposed for the 13th quarter, but it could go a long way to further enabling collaboration and dissemination of key results and data.
- The project is sort of inherently high-collaboration. About 20 partners mostly support and consult, with all providing at least perspective and advice and some giving physical goods (e.g., Toyota is providing fuel cell vehicles). Many are poised to implement codes and regulations, build production, use units, etc., so they can make this happen if the economic case emerges.
- This is a large team that seems to have roles well defined. It is missing a community outreach and engagement program, which the university could lead. The partners increasing their cash-in when the firm bids came in high shows that they are committed to this project's success.
- Collaboration is excellent. The only suggestion is to consider adding a hydrogen pipeline operator, such as Air Products, to the project.
- The project has a good team of collaborators, including the University of Texas (UT) partner, who can provide independent analysis and evaluation.
- There is a large number of relevant partners. There is tangible hardware with fuel cell vehicles to make the project accessible to the public. Several partners are listed as "support" with no real details.

Question 4: Potential impact

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

- The project is highly relevant to the H2@Scale objective and addresses the critical gap in demonstrating hydrogen production and delivery and use at scales of ~100 kg/day. The demonstration will provide real-world information on the use of hydrogen in drones, a new application. Finally, the project will support improved estimates of construction, contingency, and finance considerations, despite its being a first-of-a-kind integrated system. These non-technical components of hydrogen projects are poorly understood, and additional information on permitting and risk mitigation will benefit other projects.
- The impact depends on whether an H2Hub is chosen in the Gulf area. If so, then the impact will be largely to advise that hub, as the hub will be a massively larger effort in the same space. Of course, this is in no way the project's fault. However, if by some chance there is no Houston area H2Hub, then this will serve as a rather reduced version of a hub and will show what a hub there might do. The amount of data the project will gather in the time remaining may limit impact. The researchers think they might get good data in the time allowed, but delays in commissioning and integration could easily prevent that. Even with a no-cost extension, the team might not have much replication of data and, thus, no real handle on uncertainty in the values.

- Demonstrations of this type and scale are necessary to gain regional acceptance and show how different use cases work together.
- This is very relevant to the Hydrogen Program for both the Hydrogen and Fuel Cell Technologies Office and the Fossil Energy and Carbon Management Office. The only gap would be a community outreach effort.
- This is a highly relevant project with potential for significant impact.
- The framework is highly impactful. It is less clear that physical deployment is impactful.

Question 5: Proposed future work

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

- The proposed future work to complete the demonstration project and finalize the economic analysis report will bring substantial value to the project and toward overcoming the key barriers listed. It would have been helpful to hear more information on the data portal and the type of information being provided there (and to whom). The end goal is ambitious, and the project does not have that much time remaining; the team will have to focus to stay on task once the demonstration is operational.
- The planned future work is excellent. The cost analysis should include onsite hydrogen generation with no pipeline. It is recommended that the project add a community outreach effort, which could be led by the university partner.
- Future work seems well chosen, based on status and end goal. There is a nice level of detail, so one can be confident the team is doing the right work.
- The plan in the next budget period is to actually operate equipment together. The timeframe for operation may be shorter than planned (12 months originally). The equipment will not be ready until a few months before the end of the project.
- Future work should emphasize the framework and lead to an understanding of how any physical deployments will contribute data to the analysis.
- The remaining project timeline may not be sufficient, given project delays, which is somewhat concerning. It is unclear how much time will be available for data collection, realistically. If more time is needed, it is not clear whether the project team is in a position to continue under a no-cost extension to reach the desired outcomes.

Project strengths:

- The project did a commendable job with a value engineering assessment to lower bids for Phase II and III by 12%. The project shows a clear progression toward (1) being operational, (2) meeting milestones for skid and controls verification, (3) safety and hazard assessment and response, and (4) procurement. The project seems to have an effective method for engaging with multiple team members from industry and academia to inform decision-making.
- This is well-funded by both DOE and industry. The project is making a demonstration facility that demonstrates a variety of different hydrogen generation methods (reforming and electrolysis) with other unit operations. There is strong industry support, with 19 partners. The project is located at a university, which makes it a learning laboratory.
- The project may serve to enhance H2Hubs projects if the learnings are in an easily actionable form by the end of 2023. This is a first attempt at a small-scale ecosystem for hydrogen. The team is willing to adapt when needed (e.g., replanning the UT site based on HAZOP studies and fire review).
- The project is ambitious, combining multiple feedstock/sources and technologies. The project team is strong.
- The project has great collaboration and an impactful framework scope.
- The project addresses multiple elements and includes a strong safety analysis.

Project weaknesses:

- It was unclear from the presentation and submitted information how the demonstration, which uses SMR without carbon capture and sequestration and electrolyzers powered on solar and wind, aligns with and is informed by the scenarios in the Monte Carlo analysis using HOwDI. It is unclear why the demonstration would not be better represented in the economic modeling, or how the variable correlations inform the demonstration. The demonstration is built, and it will have a certain hydrogen production price based on the capital and feedstocks and markup; none of this is properly linked to the information coming from HOwDI. To be clear, the modeling capability of HOwDI is impressive and important as a standalone assessment tool for Texas. Engagement with community members on the framework report was difficult to evaluate.
- Wind energy sources are only being simulated, so this is a good stepping stone but not an actual physical integration. Biogas is being directed rather than physically reformed, so project lessons learned will be somewhat limited as a result, vis-à-vis applications in which biogas would be used directly.
- The project needs to increase the community outreach plans. The educational plans should expand beyond just college-/university-level teaching. The project can make results available for technical schools and unions for hands-on training modules. The project represents a large investment for what could be a very short demonstration unless the project is extended.
- The usefulness of the physical deployments is unclear.
- The project is behind on time and over budget.

Recommendations for additions/deletions to project scope:

- The key data being collected from the demonstration in the subsequent period is not clear. Success is based on driving a hydrogen vehicle around, but more information is needed to evaluate the approach for measuring and monitoring performance (e.g., hydrogen leakage, energy efficiency, cost, feedstock consumption, and community feedback). It is suggested that the project include a summary of findings to support how teams model the scale-up and deployment of similar hydrogen networks.
- The project needs to increase the community outreach plans. The educational plans should expand beyond just college-/university-level teaching. The project can make results available for technical schools and unions for hands-on training modules. The project would benefit from a pipeline.
- If project needs to be extended to demonstrate critical equipment demonstration, incremental funding should be added to accommodate.
- There should be a high point at which the five-year plan for the Port of Houston/Gulf Coast region is ready (December 31, 2023) and can be shared with any Texas-based H2Hub and perhaps with other hydrogen hubs.
- The scope should focus on the framework, not the physical deployments.
- There are no recommendations. Project results are happily anticipated.

Project #TA-039: Solid Oxide Electrolysis System Demonstration

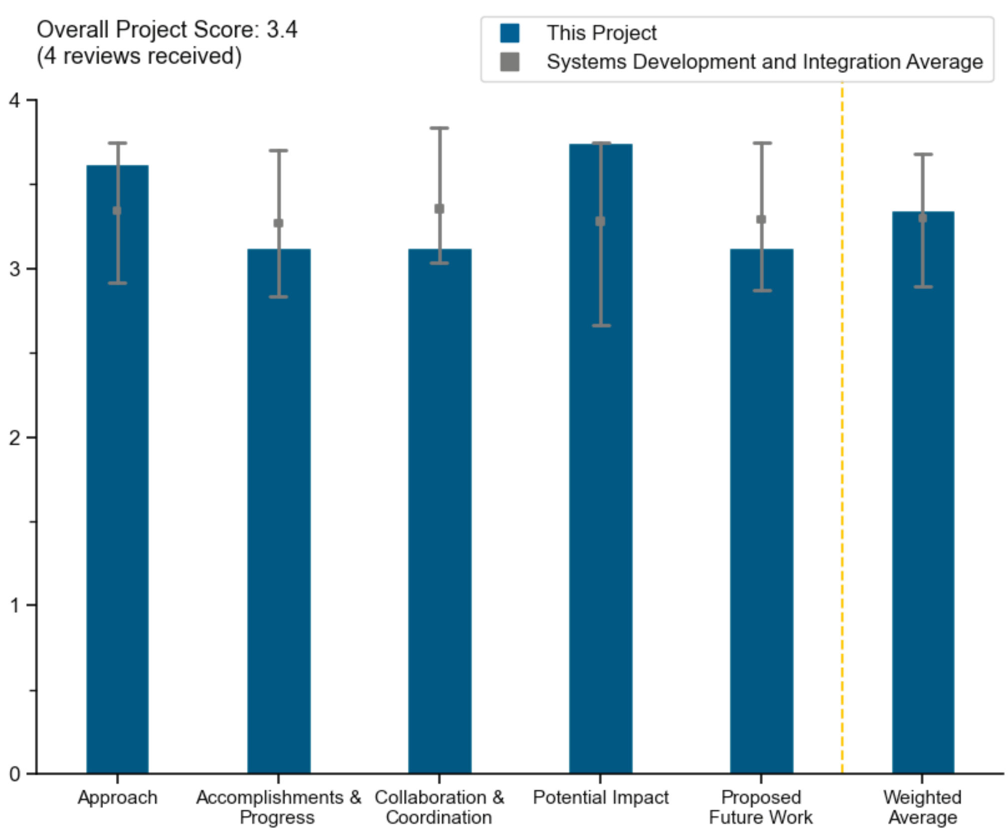
Hossein Ghezel-Ayagh, FuelCell Energy, Inc.

DOE Contract #	DE-EE009290
Start and End Dates	10/1/2020–5/31/2024
Partners/Collaborators	Versa Power Systems, Idaho National Laboratory
Barriers Addressed	• Capital cost • System efficiency and electricity cost • Electricity generation integration

Project Goal and Brief Summary

The project will complete design, engineering, procurement, assembly, integration, and demonstration of a solid oxide steam electrolysis hydrogen generation system. The project will validate the technology's potential as a high-efficiency, low-cost alternative for hydrogen production at nuclear plants. Researchers will design, build, and test a 250 kW (input) steam electrolysis system using hardware-in-the-loop simulation of light water reactor operation. Objectives include validating solid oxide electrolyzer cell (SOEC) technology performance and reliability for steam electrolysis and hydrogen production in a packaged system; developing system operational and control strategies specific to the nuclear industry; demonstrating key features of SOEC electrolysis systems, including high electric efficiency and waste heat utilization, in a 250 kW class unit prototypical of larger-scale systems suitable for integration with nuclear plants; and acquiring the data necessary to valorize the integration of SOEC systems in light water reactor facilities for increasing their operational flexibility and profitability by switching between electricity production and hydrogen generation.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration projects.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach to demonstrating the operational performance of a prototype integrated high-temperature solid oxide electrolysis system with nuclear power is effective and well developed and contributes to overcoming most technological barriers. Accomplishing the demonstration objectives is considered highly feasible. The size of the demonstration is appropriate for the purposes of demonstrating the SOEC technology performance and is accommodated by the Idaho National Laboratory (INL) Energy Systems Laboratory (ESL) facility design. However, the use of the INL ESL facility and the controller hardware at the proposed demonstration scale may not address large-scale plant integration constraints as they relate to electrical loading and variable steam demand from the plant. These physical system limitations may result in a different operational space for the SOEC system when integrated. Regardless, the performance of the SOEC system (e.g., stack efficiency and response characteristics) will be well demonstrated during this project. No detailed information was presented on the large-scale techno-economic assessment (TEA) to follow the demonstration project. Based on similar efforts already completed for an integrated generic high-temperature SOEC system, the TEA results will be weighted based on the application of the high-temperature steam electrolysis (HTSE) system (e.g., dynamic load following vs. baseload operation) and the specific electric grid and market conditions. Analysis of a range of large-scale operating conditions would be advisable. As it relates to the future TEA, the researchers are advised that the reference to nuclear plant "waste heat" is misleading. A nuclear plant considers waste heat to be the heat that must be rejected from the condenser (i.e., Rankine Cycle), which is insufficient to satisfy the requirements of promoting the HTSE process water to steam. Typical condenser discharge is about 125°F at atmospheric pressure. The thermal energy from the nuclear plant needed to produce steam for the HTSE (to achieve maximum overall HTSE efficiency) would be taken from the turbine inlet (high-pressure or low-pressure, depending on design). This will have a corresponding reduction in steam flow to the turbine and a reduction in electrical output. This needs to be factored into the TEA.
- The approach that FuelCell Energy set out to execute in this project is solid, exactly what is required to design and demonstrate a high-temperature electrolysis system that is targeted for use with a nuclear power plant.
- The project objectives were clearly outlined, and the work plan was well thought out for design, fabrication, and testing of a 250 kW SOEC system. It is likely that the project will be able to overcome several critical barriers and achieve project objectives.
- The approach to performing the work is effective, with the focus on designing, building, and evaluating the stack and balance of plant (BOP) before system integration.

Question 2: Accomplishments and progress

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

- Progress on the project is proceeding in accordance with an adjusted schedule, given the noted issues with supply chain and stack production. The FuelCell Energy representative stated that company resources are presently dedicated to increasing stack manufacturing capacity. The added capacity should now facilitate the stack manufacturing with minimal delay. It appears that the manufacturing schedule aligns with the efforts at the INL ESL. The conditions that resulted in the delay were reasonably beyond project control.
- To date, significant progress has been made, and excellent system performances have been demonstrated. For example, the project has successfully demonstrated a 250 kW SOEC, with anticipated performance and reliability for hydrogen production from steam electrolysis in a packaged system. It seems that the project is on track to achieve its goals toward commercialization of the SOEC technology.
- Fabrication of BOP components is complete. The progress of stack fabrication is not clear without detailed information.
- It is a bit disconcerting that all DOE funds have been spent and the stacks for the demonstration system have not been built. The BOP for the system is nearly completed, but one has to wonder if this project will be completed without additional DOE investment.

Question 3: Collaboration and coordination

This project was rated **3.1** for its engagement with and coordination of project partners and interaction with other entities.

- The coordination between FuelCell Energy and INL is excellent. The visitation at the INL facilities confirmed the collaborative efforts to support the FuelCell Energy SOEC demonstration by both participants. This collaboration is fully expected to achieve the end goal of verifying the SOEC stack performance and durability under (simulated) dynamic operation.
- The collaboration and coordination among partners seem to be effective, including testing of an SOEC system at INL.
- FuelCell Energy has an excellent partner in INL for hosting the high-temperature electrolysis system demonstration. FuelCell Energy might have included a nuclear power plant operator as a project partner (or at least collaborated informally) to make sure that the project's demonstration system design had all the appropriate functionality to facilitate future integration with a nuclear power plant. It is questionable to consider Versa Power as a collaborator, given that Versa is 100% owned by FuelCell Energy.
- No information is given regarding collaboration and coordination with vendors/suppliers of key BOP components.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This high-temperature SOEC demonstration project advances technology that is critical to the Hydrogen Program and has the potential to significantly advance progress toward DOE research, development, and demonstration (RD&D) goals and objectives. The economic viability of clean hydrogen production via nuclear power is directly dependent upon improvements in the electrolysis stack efficiency and resulting system total efficiency. This project advances progress toward SOEC technology development and supports the DOE Office of Nuclear Energy objectives to maintain domestic nuclear power as part of a resilient and secure grid. Improvements in stack efficiency will be required to achieve DOE cost goals and to incentivize industry (current fleet) to integrate hydrogen production and will inform advanced reactor development. This project provides verification of the electrolysis technology's performance and eliminates a significant risk for first-time, at-scale plant demonstrations.
- This project, if completed as originally proposed, has significant potential impact. Integration of high-temperature electrolyzers with nuclear power plants is an extremely promising approach for achieving DOE's hydrogen cost targets.
- This development and demonstration project aligns well with the Hydrogen Program and DOE RD&D objectives and has the potential to advance progress toward DOE RD&D goals and objectives.
- Testing and demonstration of a 250 kW solid oxide electrolyzer has the potential to advance the technology and demonstrate progress toward DOE goals and objectives.

Question 5: Proposed future work

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

- The proposed future work is consistent with the described project plan and progresses in a logical manner.
- The proposed future work seems reasonable for addressing the remaining challenges and barriers and for achieving the project objectives.
- FuelCell Energy's proposed future work is fine and includes all that is needed for completing the project as originally planned. The question is whether FuelCell Energy will complete the project without additional financial support from DOE.
- Proposed future work lacks details, especially on timeframes and end dates.

Project strengths:

- The project provides in situ performance demonstration of the SOEC technology, and the results of the dynamic performance testing are directly applicable to larger commercial-scale applications. The performance demonstration de-risks the installation of this technology in nuclear facilities and provides a tested/verified input for the economic analyses of these integrated systems. The project provides an actual demonstration of an integrated system that will assist in the design of interfacing systems for larger-scale applications at nuclear power plants. This again provides an element of risk reduction for the utility. The performance data likewise provides input for the design of integrated energy systems for advanced reactors. The HTSE/SOEC TEA will provide supporting economic bases for integration at existing domestic plants and for advanced reactors. The integrated technology provides options for nuclear plant economic viability that will be required to achieve electric grid (and other sector) decarbonization goals. The collaborative arrangement between FuelCell Energy and INL appears to be excellent and will ensure successful project completion.
- FuelCell Energy has a solid oxide cell and stack technology upon which the prototype electrolysis system is based. FuelCell Energy has a solid system design, and the hardware is ready for stack installation and system testing.
- Demonstration of the SOEC technology at the system level is important to its commercialization.
- The main project strength is the design, fabrication, installation, and operation of a 250 kW electrolyzer.

Project weaknesses:

- It may be useful to evaluate SOEC performance in a wider range of operating conditions to better characterize the behavior of the SOEC system for various applications.
- The project's main weakness is the lack of detailed schedules on various activities in the critical path of the project.
- A project weakness is the budget challenges.
- No weaknesses were identified with respect to the stated project goals.

Recommendations for additions/deletions to project scope:

- The demonstration (analysis) should consider the energy input associated with the steam inlet (INL steam to FuelCell Energy—simulation of nuclear thermal energy) and the associated degradation in electrical output. This should be factored into the overall efficiency. Stack testing, to the extent possible, should account for typical nuclear plant system response in electrical loading, steam supply, temperature variations/transients, and those associated with other interfacing systems. It is suggested that the project include additional scope to assess system response to black-out power conditions, which could be of value for nuclear plants performing failure mode and effects analyses for integrated systems design.
- There are no recommendations for additions/deletions to the current project scope.

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

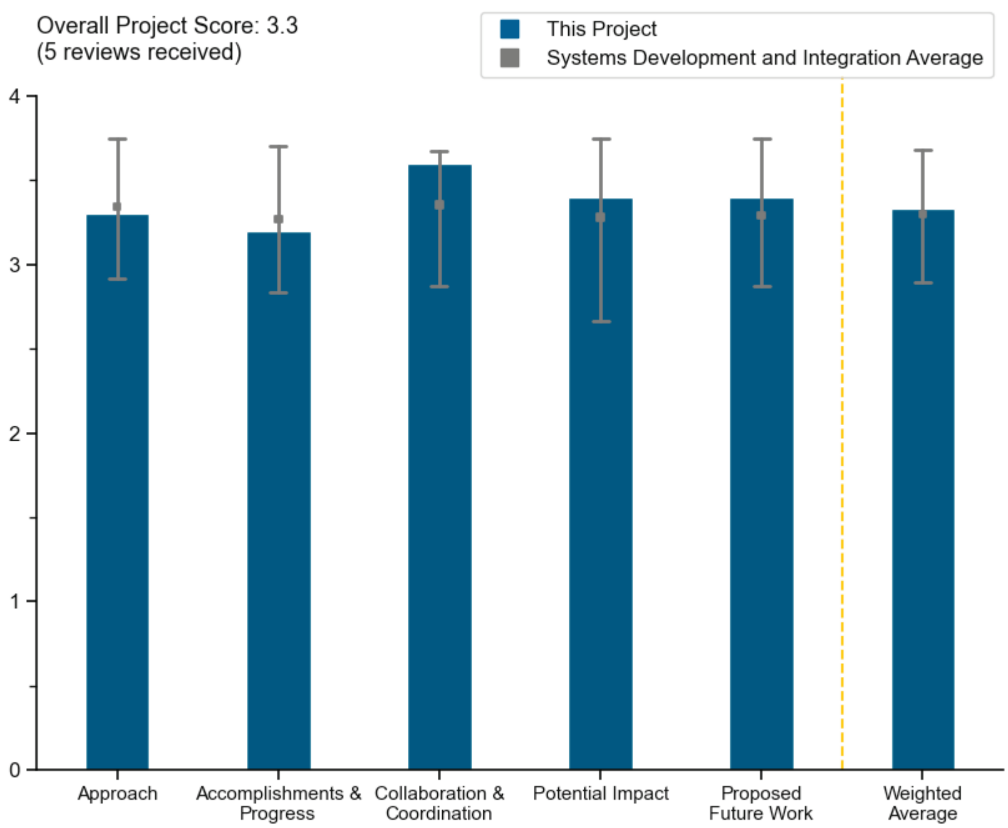
Genevieve Saur, National Renewable Energy Laboratory

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, International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and Association of Hydrogen Supply and Utilization Technology (HySUT), Gas Technology Institute, California Department of Food and Agriculture – Division of Measurement Standards, University of Maryland Center for Risk and Reliability, Air Liquide, Air Products, California State University, Los Angeles, Equilon Enterprises LLC, First Element Fuel, H2 Frontier, ITM Power, Iwatani Corporation, Linde plc, Messer, Proton OnSite/Nel ASA, Shell, Stratos Fuel
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 for status, benchmarking, technology readiness, value proposition, and research needs. 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 reliability, fuel economy, range, and driver behavior.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 National Renewable Energy Laboratory's (NREL's) approach to evaluating work is outstanding. The team is objective, thorough, and comprehensive in collecting data from new refueling stations. This is critical to meeting DOE targets for infrastructure cost and ultimately the cost of hydrogen to customers even beyond light-duty fueling stations. The objectives are directly aligned with DOE needs and include the critical feedback from end users and stakeholders.
- Overall, the project has a great approach to capturing data and presents it with no direct correlation to a data provider. Since the project will be developing composite data products (CDPs) for heavy-duty refueling stations, now is the time for involved stakeholders to possibly fix some of the issues on the reporting requirements, especially as pertains to maintenance and safety events. Reliability data will be critical with the data. The project should also evaluate needs now to be ready for station evolution—for example, if bi-directional communication gets implemented.
- The project has an established, optimized, and proven data collection and management process (>12 years). It is unclear how, outside of government entities and academia, the vast and growing number of data parameters collected continues to provide value toward overcoming barriers for industry (per impact stated on slide 2).
- The detailed data product/CDP process has been developed into an effective tool for aggregating and sharing data. It does still have the downside risk that the private companies that provide the data will not necessarily provide all the data that might be needed to get a complete picture of station operation.
- The project's overall approach looks fine. Quality of the analysis will always depend on quality of the supplied data, which will be variable across station providers.

Question 2: Accomplishments and progress

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

- The project is doing an excellent review of the total number of vehicles on the road and highlighting the increased throughput from liquid hydrogen stations. This is critical data to be shared with DOE and stakeholders in parallel programs and efforts where high-throughput hydrogen will require liquid storage and eventually dispensing. NREL is also making this data available to the public through the CDPs. All these items contribute to DOE goals to reduce the cost of deployment. Costs are increasing, but that should not reflect on NREL's project efforts. The utilization is increasing, and the capacity at stations is increasing. DOE needs this data to plan for the next steps in hydrogen for transportation. The stations can double their average throughput with increased demand. The data on impurities by production type is also important for sharing with stakeholders and to improve quality assurance across the industry.
- Many of the accomplishments discussed (more stations, more fuel dispensed, lower cost) are noteworthy but not necessarily results of this project, per se. The accomplishments of daily station profiles, hydrogen quality reporting, and component reliability (assuming good data on this can be had from the station operators) are accomplishments of this project and very valuable to the industry.
- The project has good analysis and distribution of the aggregated analysis products.
- The project has good accomplishments highlighting the increasing utilization of the stations in California.
- It is unclear whether hydrogen fuel demand increase is an accomplishment for this specific project. The project does not indicate a root cause follow-up on why the data shows the reported accomplishments (for example, the data does not give insight into why fueling times are shorter and why there is an increase of demand at certain stations).

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.

- Having all the station operators participate is a major accomplishment (admittedly driven by requirements of the California Energy Commission funding). It would be helpful to understand that the project is getting uniform/consistent data from each operator. One notable bit of information that would be very helpful for codes and standards development (and increased customer satisfaction) would be data on what the ending state of charge (SOC) of all fills is, as there are reports of problems with stations stopping fills prematurely because of how SAE J2601 defines the required pressure ramp rate, but it is difficult as an industry to quantify that problem at this point.
- There is excellent collaboration with station owners, funders, and providers. This can be seen in the level of detail about the stations and various challenges from impurities to throughput. NREL is also open to working with heavy-duty station operators, which will be key for DOE, as the Hydrogen Program has shifted to fuel cell targets for larger fuel cells in transportation than those used in cars, as seen over the last decade.
- Collaboration is appropriately broad and coordinated.
- Collaboration is a strength for this project.
- Many, if not all, parties operating hydrogen fueling stations report data to NREL because of contractual obligations.

Question 4: Potential impact

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

- This trailing data is important for DOE to alter research, development, and demonstration (RD&D) and to focus on next steps for the Hydrogen Program, especially for the shift from gaseous-based stations to liquid-based stations. This may eventually lead to liquid dispensing and is a key aspect of DOE's RD&D roadmap.
- There is no substitute for having good data. The data products have been developed and matured. Hopefully, as the number of stations continues to expand, the project can add some additional targeted data (such as end-of-fill SOC).
- Current analysis and reporting provide a useful set of outputs for those working in the space. The development of data around reliability should have a similar impact.
- Station data collection that can help identify trends and RD&D needs will have a high impact.
- The project provides fueling station data to DOE. However, it is unclear how this translates directly to setting and achieving DOE RD&D objectives, particularly translation of light-duty retail station data to future new medium- and heavy-duty fueling stations. It is not clear how the data collected provides insight, other than to station operators, for improvement of station components and/or development efforts for next-generation station technology.

Question 5: Proposed future work

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

- The proposal to expand data collection and analysis to maintenance/reliability sounds good. It does seem that this type of information would be helpful in planning station uptime, and possibly in station design (selection of components), in the future.
- Transition to heavy-duty trucks is an obvious future direction. Keeping the light-duty station data is also important to capture data related to larger-capacity liquid hydrogen stations. The project needs to look outside of California to capture data as much as possible, although this is more difficult to implement.
- The future work proposals, as outlined, all appear valuable and aligned with the reviewer questions and comments. It would be good to understand the planned/expected funding picture a bit better. This project has been going on for 12 years. It is not clear whether the project is open-ended or whether the team has to

reapply at some point (and if the latter, whether the team would ask for something different). One slide says that the DOE contribution for 2022 was $200. Perhaps that is a typo.

- The online maintenance tool will be important to keeping costs down and highlighting problematic suppliers. The community is looking forward to more data on medium- and heavy-duty station reporting, especially as the cost of hydrogen is expected to come down, thanks to higher throughput. There may be challenges with higher flow rates and larger-capacity cooling systems.
- The project could consider reducing the number of data parameters collected. The project could consider the conventional fuel industry key performance indicators (KPIs) for fueling stations.

Project strengths:

- The project has had a strong track record over many years of creating the go-to source of summary data about the performance of overall U.S. hydrogen station system performance. The project should continue making sure that the industry knows where to look for all the published data.
- NREL's strength is the open nature of CDPs and operators' willingness to share the data because it is anonymized. This is a unique capability in the world. Most critical data shared also includes impurities, and measurement technologies are used for quality assurance at the fueling stations. The project has a large number of data providers, and long-term data collection allows for observation of trends.
- The project delivers analysis in both public and private forms, serving both the data suppliers (and so incentivizing them to collaborate, hopefully) and the public consumers of the information.
- The project has a large number of data providers. Long-term data collection allows for observation of trends.

Project weaknesses:

- The project has limited weaknesses. Most issues are outside of NREL's control, such as sharing actionable data and good-quality data sets. Sometimes data is missing or partners are not able to comply with obligations or requests.
- The project has a large number of parameters for which data is collected. It is unclear how data is used for station component development and improvement that (eventually) increases station availability. This is a rapidly developing technology area, with shifts that are difficult to capture in data collection and that create difficulty for observing actual trends for hardware/software components.
- The major weakness, as acknowledged by the project, is that access to data is not guaranteed, and a (possibly) increasing fraction of operating stations may opt out/age out of reporting.
- The project is only going to be as strong as the data that comes from the station operators. It is unclear if the project is actively updating the data requirements associated with new funding.

Recommendations for additions/deletions to project scope:

- The project could reduce the number of parameters after assessing what the conventional fuel industry collects data for (i.e., KPIs). The project could include root cause follow-up for data patterns recorded by, for example, looking at time-stamped data and comparing this to fueling station availability and issues reported on fuel cell electric vehicle driver social media groups. When reporting on data from stations, the project could distinguish between stations with different numbers of fueling positions (of particular interest for medium-/heavy-duty hydrogen stations).
- If the project is connected to H2-041, perhaps that project's work could inform and support what data could be requested in the future and what analysis would be helpful.
- Additional funding or scope should be included for heavy-duty and medium-duty stations where equipment may not be ready for metering at the much faster flow rates.

Project #TA-043: Solid Oxide Electrolysis Cell Stack Development and Manufacturing

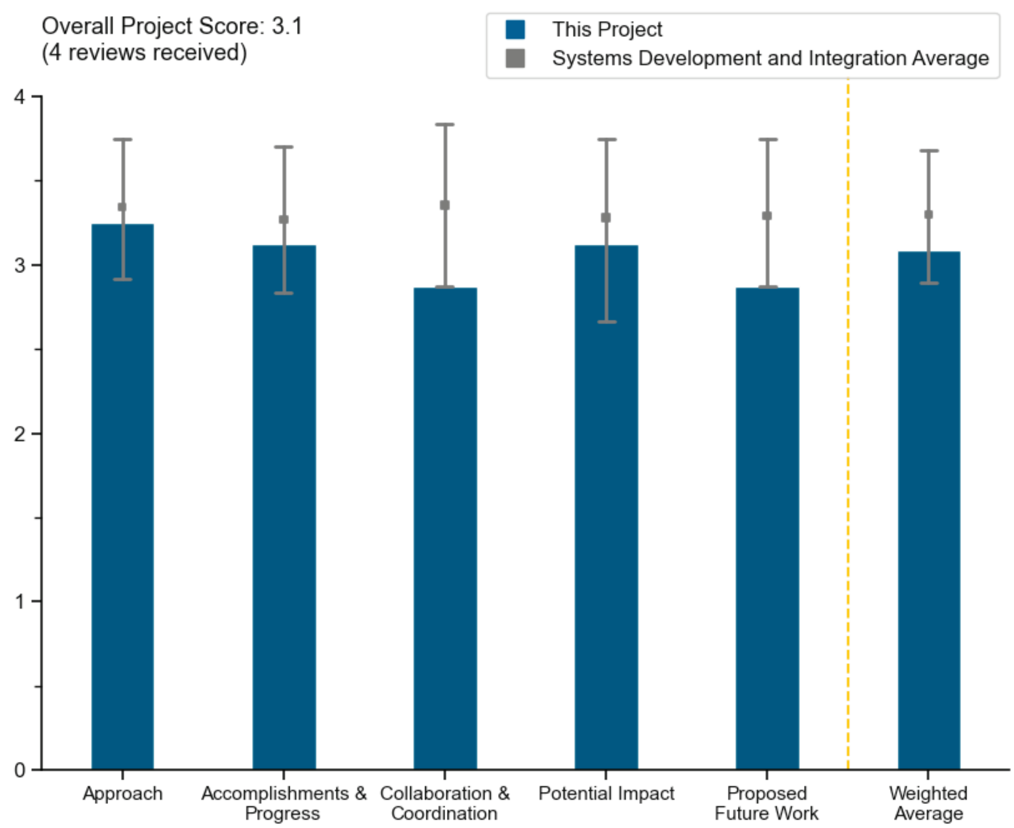
Olga Marina, Pacific Northwest National Laboratory

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

Project Goal and Brief Summary

Pacific Northwest National Laboratory (PNNL) and Idaho National Laboratory (INL) are collaborating to perform research and development to reduce the cost of high-temperature electrolyzer operation and improve stack durability and efficiency, thus reducing hydrogen cost and increasing hydrogen production. The project team will also initiate stack and related component degradation studies using a baseline stack, develop in operando health monitoring equipment for stacks, develop a predictive stack digital twin, and perform post-stack-test characterization analysis for solid oxide electrolysis cell (SOEC) original equipment manufacturers.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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.

- This presentation shows excellent progress toward reproducibility in cell manufacturing and testing via developed fabrication and testing procedures. The team has put major effort into eliminating any cell non-flatness challenges and successfully measured short stacks (1.3 kW, 4,300 cm^2 cells) with promising current density, and the team is on track testing the larger stack (5 kW) and achieving the set goals. Successful thermal cycles were also demonstrated. Electrochemical impedance spectroscopy (EIS)/ distribution of relaxation times (DRT) analysis incorporation is extremely encouraging to separate ohmic and polarization losses in stacks. The following comments are suggestions to further improve on the scale-up and validation processes:
    - Since all stacks will be tested at INL, considering how stack fabrication reproducibility will be ensured would be valuable. Identifying gaps in reproducibility is rather challenging unless the stacks are tested in-house. The approach to ensure reproducibility of cells involves measuring multiple ~1 kW stacks, but scaling up to 4x5 more cell layers in a single stack may introduce more variation, making it challenging to ensure reproducible cell fabrication, stacking, sealing, and conditioning. INL can follow the same testing procedures for each stack, but clarification is needed as to how this information will identify the root cause between performance variation of different stacks. Drafting a clear plan to address such scaling/manufacturing challenges would be valuable.
    - Working with larger industrial partners on quality assurance (QA)/quality control (QC) cell and stack fabrication or consultants coming from the large fuel cell/electrolyzer industry is worth considering. While major original equipment manufacturers will not share proprietary information, the major lessons they have learned could benefit PNNL in allowing smaller startups to follow their examples in fabricating and testing cells and stacks. For instance, Cummins Inc. is funded by DOE to assemble an automated manufacturing line with many stages of QA and QC. This could potentially serve as a good example to tighten cell and stack specifications.
    - Investigating accelerated stack tests (beyond single-cell tests) in order to effectively simulate long-term operation would be valuable. Further expanding on the matrix structure, including more on/off cycles, would be valuable.
- The main objectives of this project are to improve SOEC stack durability and efficiency, increase hydrogen production rate, and reduce hydrogen production cost. The challenges and barriers are clearly identified. Proper technical approaches for achieving the objectives are outlined, and the work plan is well organized. Overcoming the critical barriers and achieving project goals is likely.
- The approaches being pursued are all important to the development and manufacturing of high-temperature electrolysis stacks. The value provided by stand-alone development of new cell and stack designs is not clear without an industry partner to take the technology further.
- The project shows a proactive approach to improving material and interface issues, as well as solving practical problems to secure good test data for deep analysis. The queries and issues coming from the industrial stakeholders, however, have not been elucidated clearly.

Question 2: Accomplishments and progress

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

- Operating a short stack for hundreds of hours generated significant data for building and validating models, as well as validation of practical improvements to the system. The project goals are very ambitious, and the achieved results provide a firm basis upon which to expand. The goal of the project is to help industry recognize issues quickly, fix them accordingly, and bring their improved stack products to market quicker, providing a toolbox rather than constructing its own PNNL stack prototype.
- PNNL’s work on post-mortem characterization of tested stacks provided by industry is extremely valuable, as PNNL possesses characterization and analysis capabilities to which most industrial stack developers and manufacturers do not have access. PNNL’s development of techniques for measuring impedance in stacks under load could be valuable in developing a real-time understanding of stack degradation. Predictive

models established for glass sealing, temperature distributions, and thermo-mechanical stress–strain relationships can also provide value to stack developers. While operating a stack at target density of 1 A/cm^2 was successful, the stack degraded rapidly (to ~0.7 A/cm^2) under that condition.

- Several areas have shown excellent progress, including fabrication of single cells, cell stacks, multi-physical modeling, and electrochemical testing of cells and stacks.

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.

- As indicated by the presenter, larger players in this high-temperature field should be more involved in defining issues to be solved and identifying the scope of the potential solution. The test station with a large-active-area short-stack test enables statistical analysis of cell-to-cell behavior and distinguishes material degradation, which could be transferable to commercial platforms.
- The principal investigator was able to collaborate with INL and industrial partners in identifying issues critical to manufacturing, understanding the mechanism of degradation, optimizing operating conditions, and developing micro-/nano-structure to enhance performance and durability.
- PNNL's support of stack developers by providing post-test characterization of stacks is exemplary.

Question 4: Potential impact

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

- Solving durability issues with material solutions and understanding practical problems are key to delivering long-lifetime operation. The health monitoring, in combination with digital twin modeling, can guide the operational strategy, provided it can be connected to single cells in a commercial stack.
- The project will provide excellent support to the DOE Hydrogen Program to achieve the Hydrogen Earthshot's $1/kg H_2 target.
- The stack characterization support provided and stack development tools established on this project are all important to the solid oxide community, but they seemed to be only a small fraction of the work performed.
- However, without a development/commercialization partner, much of PNNL's work performed to develop large-area-electrode-supported stacks may have limited impact.

Question 5: Proposed future work

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

- Problem-solving is necessary to secure stable stack operation, but introducing stamped metal components into a prototype stack design may create more issues, without contributing to a more attractive cell design that will interest industry. Key is that potential issues (such as shorting) are characterized and recognized early, so mitigation in the stack assembly process or in operation can be implemented in industry on proprietary stacks.
- The remaining challenges and technical barriers are clearly identified, and a suitable future work plan is outlined.
- PNNL is planning to continue the stack development work and build a 5 kW stack for demonstration testing at INL. Focusing on the core stack technology (sealing, current collection, shorting, etc.) that is making it difficult to build taller stacks might be better. Fixing these issues likely will improve performance and reduce degradation that is being observed in the stacks. Once these issues are resolved, building and demonstrating taller stacks might be warranted.

Project strengths:

- The wide scope of this project covers material, design, process, and modeling topics to resolve issues, with attention to details and input of data.

- The project centers around some important development at the single-cell and cell-stack level to support university researchers and industrial SOEC developers.
- A project strength is providing stack characterization support to industry and establishing stack development tools.

Project weaknesses:

- Developing an advanced prototype design seems to become the goal in itself, while this endeavor should carry commercial product development in its wake.
- The project is developing stack technology without a commercial partner to take it forward.

Recommendations for additions/deletions to project scope:

- The project should deliver workable solutions to problems known in industry, as well as methods to recognize these, as a key performance indicator to monitor project progress. Proposed advanced component developments may over-complicate any proprietary stack design that already has established production processes, causing more issues.
- The project should focus on improving performance and reducing degradation by addressing core stack technology issues (sealing, current collection, shorting, etc.) that have been encountered. The team might consider a smaller stack demonstration at INL so that more project resources can be devoted to the above.

Project #TA-044: System Demonstration for Supplying Clean, Reliable, and Affordable Electric Power to Data Centers Using Hydrogen Fuel

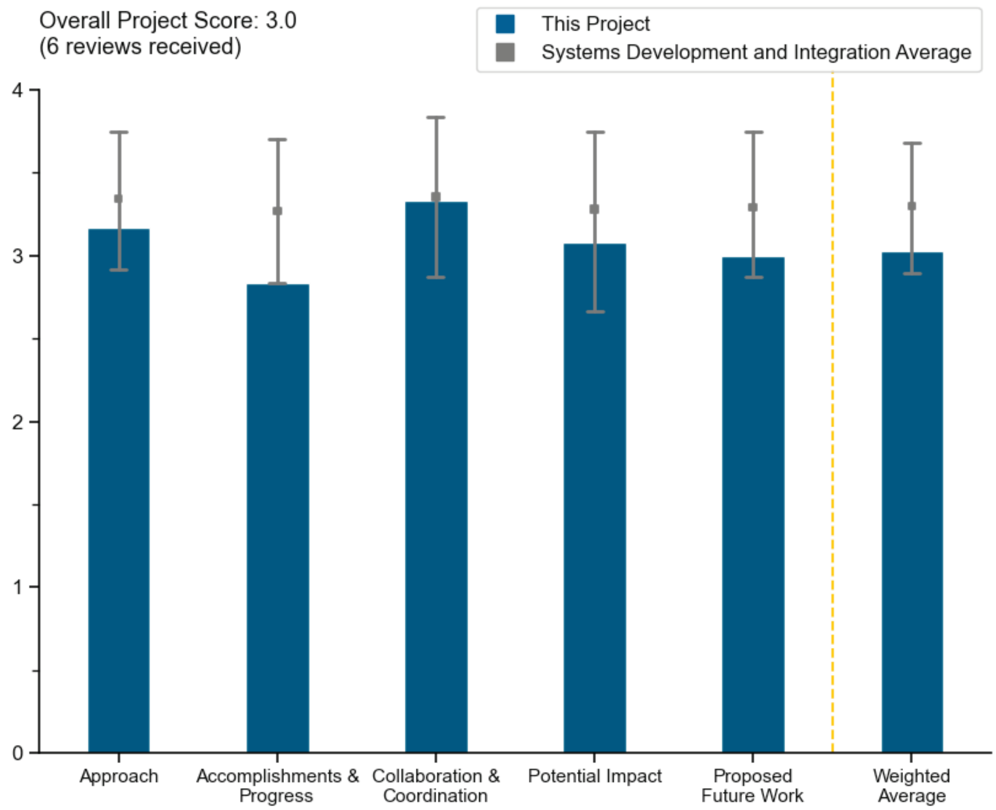
Paul Wang, Caterpillar Inc.

DOE Contract #	DE-EE0009252
Start and End Dates	10/1/2020–3/31/2024
Partners/Collaborators	National Renewable Energy Laboratory, Microsoft Corporation, McKinstry, Ballard Power, Linde plc
Barriers Addressed	• Scaling of proton exchange membrane fuel cells (multi-megawatt-scale) for data centers • Hydrogen sourcing, logistics, and environmental impacts • Performance and control for fast response and grid support • Liability coverage for large-scale hydrogen projects

Project Goal and Brief Summary

This project aims to conduct a first-of-its-kind demonstration of hydrogen-fueled backup power for a data center. The project team will scale a proton exchange membrane fuel cell (PEMFC) to megawatt scale. Performance targets include a full load rating of 1.5 MW and 48 hours of liquid hydrogen storage. All aspects of the complete power delivery system will be addressed, including (but not limited to) hydrogen production and delivery, site layout design, safety planning, component sizing, controls development, and permitting. The equipment will be installed, tested, and debugged, and data will be collected. Project completion will entail system decommissioning. This project supports the DOE goal of reducing greenhouse gas (GHG) emissions by heightening the viability and expanding the capabilities of a green fuel source, namely hydrogen.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 is addressing what appears to be a viable near-term market for hydrogen energy storage. Critical control systems and power electronics are being addressed, as are hazards and siting requirements. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model provides conservative estimates of GHG savings, and savings are likely to be higher. The GREET model uses averages of published data for the grid that is already a few years old. The majority of new power added to the grid is renewable, and old fossil plants are being decommissioned. Likewise, GREET uses data for truck delivery, using data from current fleets (diesel), while future delivery fleets for hydrogen trucks are likely to be hydrogen-fueled. By the time fuel cell backup power generators are deployed, the grid and truck fleets will be greener than the GREET dataset indicates, and GHG savings will be greater than indicated. It is not clear how the project will determine system reliability, which is key for the backup power application.
- Installation and commissioning are planned for Fiscal Year (FY) 2023. Testing and debugging will also be performed. FY 2024 will be for data analysis and report writing. The plan is reasonable and can be accomplished.
- This is a straightforward project for demonstrating a stationary fuel cell for data center backup. The project seems to be doing well in overcoming some challenges, including identifying a new demonstration site. There is concern about the project timeline and how little time (one month) has been set aside for data collection and report writing at the end of the project. Ideally, there would be a somewhat longer period for data collection and analysis, and ideally testing during warmer/colder months, but it seems this is not possible with the project scope and budget.

- The approach involves making controllers and a system integration of fuel cell and battery components supplied by others. This is the first PEMFC development for a data center to date.
- The scope is clear: to implement PEMFC backup power, including batteries, at scale significant enough to be viable and transferable.
- Unfortunately, this project will not accomplish much as it is currently designed. The principal investigator states that the 1.5 MW PEMFC will not actually be connected to the data center. Instead, the electrical power will be sent to an onsite load bank. Additionally, the fuel cell will operate for only two months (slide 18). One can demonstrate that the PEMFC works at the factory, which one assumes has already been done for more than two months of operation. One can do a paper study and simulations to determine the appropriate size of the fuel cell system and hydrogen storage for this application. If the PEMFC system has never been operated with liquid hydrogen, then this will actually be a first-of-a-kind demonstration. It may also help Caterpillar get familiar with fuel cells. It is unclear what Microsoft really gains from this at all. Ideally, the PEMFC should be wired in parallel with the current power backup system (i.e., diesel gensets), which enables the PEMFC system to respond first, and if it does not (or it stops running), then the gensets activate.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- This project is well targeted toward DOE goals of validating fuel cell systems for various applications; data center backup is an interesting one. This project seems to be focused entirely on technical aspects, without much, if any, economic analysis, so there is a bit of a weakness in terms of addressing a larger suite of objectives and goals for DOE. However, the project appears to be on track, given a few challenges, including the demonstration site.
- The planning phase has been concluded successfully, awaiting successful factory acceptance testing of the fuel cell stacks. Their integration in the system will a be critical step to surmount, particularly when now operating at altitude.
- Validation testing on the fuel cell inverter has been accomplished. The team has laid out the plan building toward the demonstration. Site preparation has begun.
- There has been good progress, though with some delays due to supply chain issues. Fuel cell systems are in factory testing and expected to be shipped in July.
- There is a good deal of hardware in place, but the fuel cell from Ballard Power (Ballard) is late, so there has been no test of the system.
- It is unfortunate that it takes almost three years to install a fuel cell and battery energy storage system (BESS) in a behind-the-meter application. Since both the fuel cell and the batteries are containerized systems, one would expect the site design and prep work to be relatively straightforward. There is very little time allotted for the actual demonstration of the PEMFC system (two months), which is a major lost learning opportunity for the DOE Hydrogen Program. A major goal of doing a demonstration project should be to obtain real-world data.

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.

- This is a good project team that brings the technology provider/integrator with a major fuel cell manufacturer and the site host. Perhaps the project could be strengthened some with more of a third-party project evaluator, but this would appear to be challenging given the scope and timing, as the data collection and report writing phase is very compressed.
- The project team has industry leaders as partners in the project (e.g., Caterpillar, Ballard, National Renewable Energy Laboratory [NREL], McKinstry, and Linde).
- The project has managed to deal with changes in the backup power location, thanks to the competence of partners and frequent mutual interaction.

- The team is skilled and in good contact. The team is capitalizing on DOE inputs and resources.
- There is good collaboration amongst partners to date.
- It is not clear why NREL is the partner, rather than Argonne National Laboratory (ANL), since NREL's key contribution is using ANL's GREET model to assess GHG impact. Linde's and Ballard's contributions here are obvious and are good choices. It is not clear why a "supply of deionized water for fuel cell" is needed. The presenter was asked and did not know. Perhaps Ballard's PEMFC is not capable of operating in water balance.

Question 4: Potential impact

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

- This is an important demonstration of hydrogen fuel cells and hydrogen storage operating as long-term energy storage/backup power. The project addresses an application in which reliability is essential and any outage is extremely expensive.
- This project can demonstrate the potential advantage of a PEMFC system as power backup, enabling fast start-up and dynamic operation, and generate data that allows further optimization between battery pack size and PEMFC power delivery capacity.
- Demonstration of showcasing the 1.5 backup genset will help push fuel cell adoption across the country.
- Success will provide practical knowledge of fuel cell technology. The short data collection period is a bit of a concern. Hopefully, it will be sufficient to generate key project findings and outcomes. As the project team has gone to all the trouble to install the system, it would be ideal to be able to test it over a wider time period, especially given the new project site, which has very disparate climate conditions throughout the year.
- The project, as it is currently designed, will have minimal impact. Additionally, it is not clear why a PEMFC and BESS system was selected for this data center application. Something like a redox flow battery (RFB) could be used as a long-duration energy storage solution. An RFB and BESS could enable black-start capability and could be used to reduce the data center's electricity costs as well—by cycling every day (i.e., to charge the RFB when electricity prices are low and discharge when they are high)—or to enable increased usage of onsite renewable power. The system that is (sort of) being demonstrated here is capable of doing nothing more than replacing diesel gensets.

Question 5: Proposed future work

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

- The project is entering its last year, and the remaining workplan seems reasonable.
- Demonstration of the unit is planned for this year.
- The fuel cell is being installed in the summer of 2023. The system should be testable, so next year should be boom or bust.
- Building and Testing will be the most critical phase of the project—but potentially the most time-consuming if risk mitigation is not considered sufficiently.
- Tests will be done with simulated power demands. It would be a better demonstration if the fuel cell test period was extended for longer time and actually powered the data center through outages or simulated outages.
- What is proposed is essentially just a two-month demonstration of the system, which will not even be connected to the data center. It is unclear what will be learned, other than that the PEMFC can operate on liquid hydrogen for this period. This project could potentially be far more valuable if the demonstration period is extended and the system is actually connected to the data center.

Project strengths:

- This is an interesting application for a fuel cell backup system. It is relatively novel compared to other systems such as a solid oxide fuel cell that typically operates continuously on natural gas. The partnership between the technology integrator and a major site host company is a strength, suggesting possible future commercial adoption.

- The project partners combine strong expertise in coherent fields. Upon successful delivery, multiple systems of similar configuration could be implemented elsewhere, making this a transferable blueprint.
- The project has a strong team with good engineering skills, and it uses well-established technology.
- A highly experienced provider of assured power systems (i.e., Caterpillar) is getting some experience with PEMFC systems.
- This project demonstration could help advance the commercialization of fuel cells.
- This is a good team of partners.

Project weaknesses:

- The very short data collection period is a bit concerning, but given the backup nature of the project use case, it may generate an appropriate amount of data. Some consideration of economics would be helpful. It is not clear whether any of that will be included. Clearly, a diesel generator backup would be less expensive (and in some jurisdictions will probably not be allowed in the future), but in a state like Wyoming (without strong air quality policies), it is unclear why a company would choose a much more expensive proton-exchange-membrane-based solution. Some consideration of this would be beneficial. Clarification is needed on what exactly the value proposition is for different parts of the country.
- This is not a very good application for a PEMFC and BESS system since it is simply a diesel genset replacement. A project budget of $12.5 million is much more than one would expect for just a 1 MW fuel cell demonstration and some analysis. The cost of a hydrogen-fueled 1 MW PEMFC system should be <$2 million. It is unclear if the cost of non-recurring engineering (i.e., product development work) at Ballard was also included here.
- The go/no-go decision follows the factory acceptance test of the stacks, and while the team is likely to pass, there is still a large risk of significant delay occurring with the actual system installation and commissioning on site.
- The scheduled test period in which the fuel cell will be running is quite short (~ one month).
- Component selection could have been better.

Recommendations for additions/deletions to project scope:

- To validate this application more fully, it is suggested that the project include a possible no-cost extension with data collection during both warmer and (especially) very cold periods to make sure the system can start up properly.
- The project team should consider extending the demonstration period and connecting the system to the data center. In any case, the team is asked to ensure that the PEMFC system is used by another DOE project after the decommissioning (e.g., at NREL's Flat Iron site or some other site).
- The detailed hazard and operability study and risk analysis, including the operational strategy, could be reviewed more thoroughly in advance of the system sight acceptance test.
- The project needs to assess cost to justify replacing internal combustion engine generators.
- The time period for the demonstration should be extended.

Project #TA-045: Waterfront Maritime Hydrogen Demonstration Project

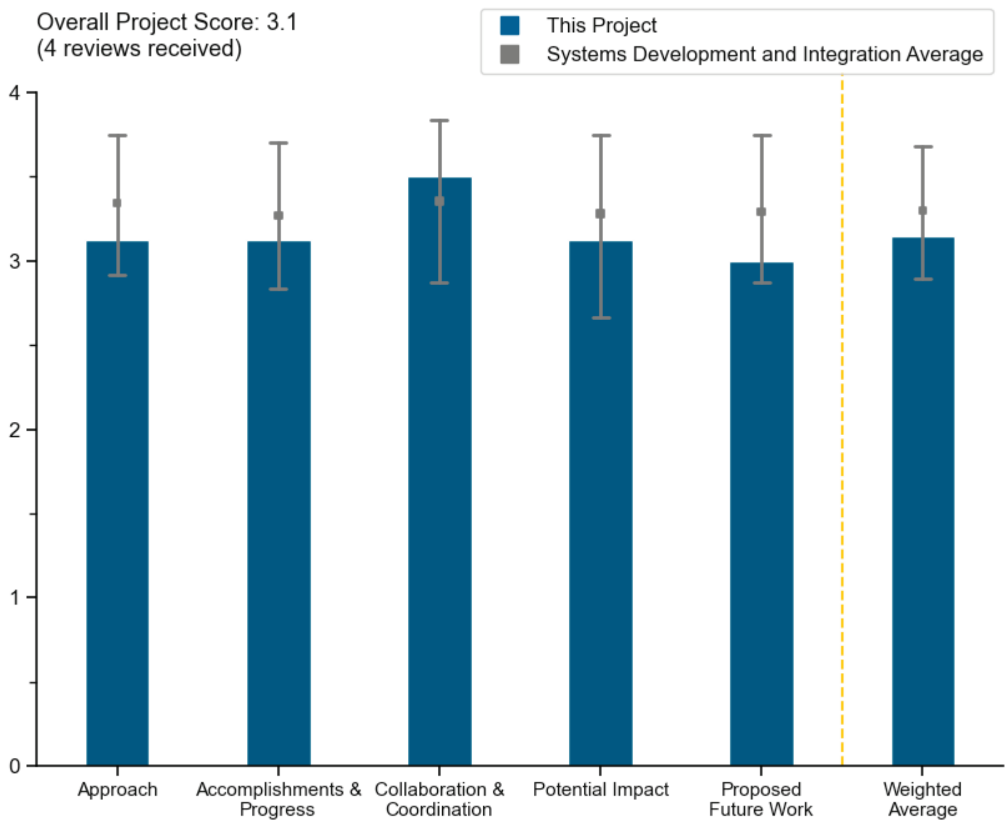
Narendra Pal, Hornblower Group

DOE Contract #	DE-EE0009251
Start and End Dates	10/1/2021–6/30/2025
Partners/Collaborators	Sandia National Laboratories, Port of San Francisco, Air Liquide, Bayotech, Inc., Nel Hydrogen US, Glosten, Moffett Nichol
Barriers Addressed	• Renewable hydrogen refueling infrastructure • Safety, codes and standards • Refueling protocol for vessel to vessel, vessel to land, and land to vessel • Techno-economic analysis data

Project Goal and Brief Summary

This project will establish a hydrogen production and distribution facility onboard a barge at the San Francisco Waterfront. The facility will be used to refuel hydrogen vessels with renewable hydrogen and recharge the batteries of diesel–electric hybrid vessels. This renewable hydrogen infrastructure will also support a land-based hydrogen network, creating an ecosystem of zero-emission mobility and resilience. This project will establish robust science-based protocols, procedures, operating parameters, and attendant training materials for the safe and routine generation and storage of electrolyzed hydrogen, creating a blueprint for optimally designing such a hydrogen barge and showcasing how the infrastructure can be replicated at other ports and similar locations across the United States. In addition, the demonstration will stimulate increased demand for hydrogen; advance the development of safety, codes, and standards for barge-based hydrogen technology; and promote the development of a hydrogen customer base along the San Francisco Waterfront, in the city of San Francisco, and in the greater Bay Area.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 overall plan looks good. The project is engaging partners in technology and permitting/codes in a novel application.
- The principal investigator (PI) and team have been working to develop pier-side infrastructure and develop fueling procedures at these locations. The team developed a piping and instrumentation diagram and drawings of the needed infrastructure and used simulations to understand refueling. The team has also assembled a test platform to test the refueling approach. The researchers worked with an existing code (National Fire Protection Association [NFPA] 2) and the U.S. Coast Guard to consider safety. The team did not perform a system hazards analysis and does not appear to have a plan to provide their insight/ experience to others (e.g., whether the steps they took are sufficient to prevent accidents and ensure safety in the marine environment for others generally). System interfaces can be challenging to safety, and a strong safety culture is essential.
- The H_2 storage on the barge and current barge design seem to limit the system to fueling vessels with ~250 bar H_2 storage. A design that would enable filling both 350 bar and 700 bar H_2 storage would provide flexibility for future designs and vessels for which more H_2 storage is needed and would provide some insurance against becoming obsolete if high-pressure systems become the norm. Many trucks are now being designed with 700 bar tanks.
- The first two technical goals seem to be the main focus and are well thought out. The last three goals seem to be expected outcomes from a successful project rather than goals.

Question 2: Accomplishments and progress

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

- The PI and team list four barriers: (1) developing a refueling infrastructure, (2) safety, codes, and standards, (3) refueling protocols, and (4) techno-economic analysis data. It appears that the project will have contributed meaningfully to demonstrating a refueling infrastructure and provide refueling protocols. The PI and team used an existing safety code and worked with the U.S. Coast Guard to address the state barrier, but it is unclear whether the effort is in this regard is really overcoming a barrier or sidestepping it (perhaps safety should not really ever be thought of, or described as, a barrier). It would be really helpful if the team could provide insight to others on what should be done to institute safety by design (some of this may be in a future milestone for the equipment, but the system as a whole should be analyzed). The work on the refueling protocols and refueling infrastructure appears to be innovative, if the team can secure an electrolyzer.
- There is good progress on process simulation for developing a refueling protocol.
- The planning and technical aspects of the project look to be on track to meet the timeline.
- Implementation of the fuel cell sub-system should be re-evaluated, given possible problems with the expected unit coming out of extended downtime.

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.

- Multiple collaborations are evident (e.g., with the U.S. Coast Guard, American Bureau of Shipping, Air Liquide, etc. on the refueling protocol). Collaboration will be key to the success of this project.
- Extensive collaboration and coordination were designed into the effort. The PI showed an organization chart and arranged the work with team leads from multiple institutions.
- Many different parties/stakeholders have been engaged, each with clear responsibilities and/or contributions.
- The project team has a good set of collaborators with the experience needed to meet the technical project goals.

Question 4: Potential impact

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

- Creating/updating codes and protocols for H_2 fueling and infrastructure for portside operations/bunkering may be one of the most significant impacts, as it would extend beyond this specific project, easing the way for any future projects (DOE-sponsored or other). Data collection during operations will likely also be very useful.
- This project will serve as an introduction to having hydrogen fueling available for marine applications at a port and can pave the way for easier adoption.
- The PI indicates that the team created a blueprint for designing an H_2 production barge and worked through local regulatory approval. The researchers are trying to generate procedures for transfer, but that step remains incomplete. They indicate that another impact was to promote the development of a hydrogen ecosystem in the Bay Area. They did attend some conferences, but one would imagine that more would be needed to really develop an ecosystem. Attending conferences or meetings alone does not develop an ecosystem, leaving this aspect of impact indeterminate.
- The project would have higher impact if the barge could fill 350 and 700 bar storage tanks.

Question 5: Proposed future work

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

- The proposed upcoming work looks good.

- It appears that there is significant risk that the future work will not be accomplished because of inflationary pressures and because the electrolyzer is not in place. There is still regulatory risk, given that the U.S. Coast Guard has not approved the design basis. These risks are concerning.
- The schedule for future work seems appropriate. It appears the increased costs and lead times were identified as issues, but a path forward to address these issues was not identified.
- With the delay, using the fuel cell for providing electrical power as initially planned appears risky.

Project strengths:

- This project breaks new ground in extending H_2 production and delivery to a port/maritime environment and building up a basis in code/compliance. It appears the technical risks are well managed, as the system will integrate existing technologies for production and storage.
- The overall project strengths include the strength of the collaborators, the intent to work with the U.S. Coast Guard, and the modular refueling station. The initial drawings are compelling. The location of the barge site appears to be a plus.
- The technical aspects of this project are very good, and it appears that the team is knowledgeable in the needed areas to make it come together. Bringing a technology that is not commonly used to a well-established industry is not a small feat.
- The barge refueling concept has the advantages of a mobile refueler.

Project weaknesses:

- The justification for the fuel cell module should be expanded/clarified. From the materials, it was not clear what the benefits of including this would be, especially if a new unit is required (at ~$3 million additional cost, per the presentation). Clarification is needed on whether green power charging via shore connection satisfies the desired battery electric vehicle charging. It is not clear whether the fuel cell is needed to increase the peak power available for charging.
- The project does not appear to be developing safety, codes, and standards for refueling maritime hydrogen vessels, despite its being a stated project goal. There does not appear to be a plan to make that happen within the time remaining. It also appears that the team may not be able to complete the work within the agreed-upon budget, which is concerning. The plans for advancing an ecosystem appear to be limited to only meetings without other intentional contributions.
- Weaknesses include limitations with H_2 storage pressure and lack of ability to fill 700 bar storage tanks.
- Some of the non-technical goals identified either need to have planned tasks to show a path for achievement or should be changed to be potential outcomes instead.

Recommendations for additions/deletions to project scope:

- It was suggested that this technology would help to improve air quality in the port area, but it is not clear what the primary drivers of emissions are in a typical port or what it would take to make a real impact. It was suggested that a unit such as this could be moved from one port to another for “emergency support.” The unit seems to require significant shore power connections. It is unclear in what scenarios that would be available and whether the H_2 barge would be needed.
- Some project scope may need to be deleted, perhaps along with some funds, because it is not clear that the team has the ability to develop a safety code or standard (much less codes and standards) within the schedule.
- Storage pressure should be increased, and/or the capability to fill 700 bar tanks should be added.
- Additional funding was identified as a need and should be addressed.

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

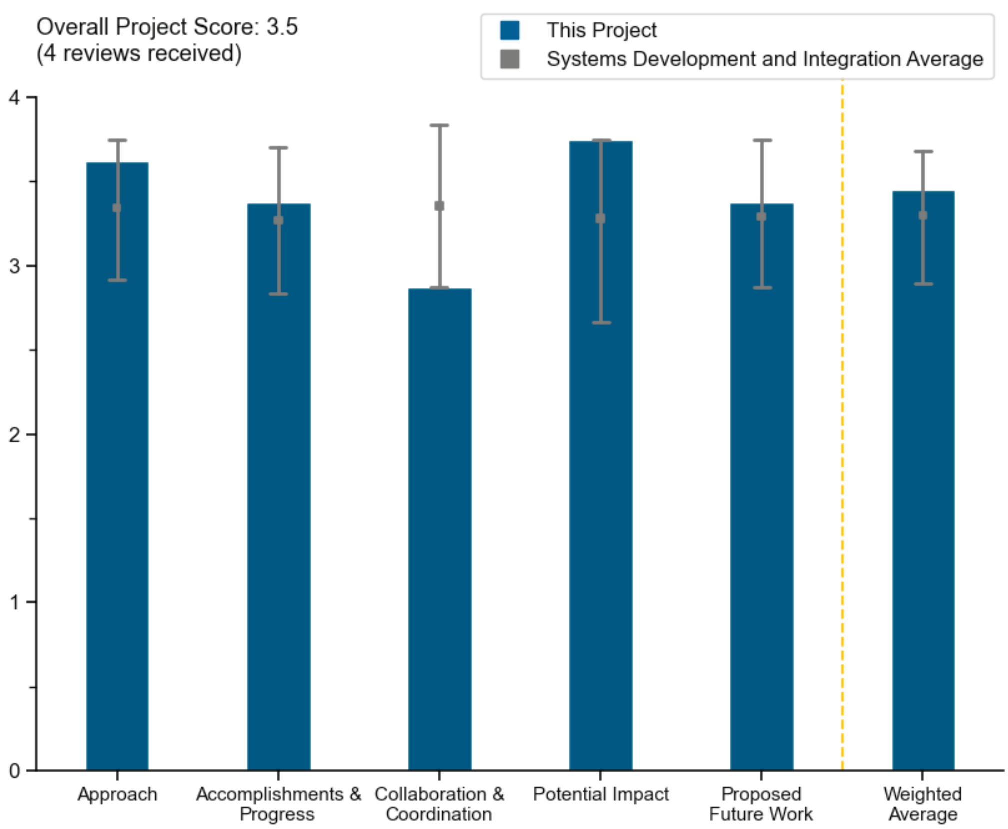
Daniel Leighton, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.9
Start and End Dates	5/6/2020–9/30/2022
Partners/Collaborators	Nel Hydrogen, Toyota North America
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 provide a testbed 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 Systems Development and Integration projects.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Highly relevant to DOE H2@Scale, the project is well poised to take a critical look at key barriers to scaling up the use of hydrogen through demonstration and analysis of integrated production, connectivity, and use of technologies at megawatt hydrogen production scales. The project takes an exciting approach by developing a "core" technology demonstration, supportive infrastructure, and space for testbeds for emerging technologies that require demonstration at the megawatt scale, which may otherwise be challenging because of the high costs of approximate technologies (hydrogen production, water delivery, power delivery, etc.). Redundancy in the system is not clear, which may be a source of risk for companies and project teams considering the campus.
- It seems that industry could do these demonstrations. In some conversations that this reviewer has had, industry seemed interested in doing this type of demonstration and making their facilities available to others (including competitors) to try their technologies in the industry setup. The goals of demonstrating the power to hydrogen to storage and back seem similar, maybe even duplicative of other work, such as the Constellation (NE-002), Energy Harbor (NE-001), and Frontier Energy Inc. (TA-037) demonstrations. It seems that these projects could be made to be flexible, similar to what is being done at ARIES. The approach seems to be good for the stated targets. The project reported only the Hydrogen and Fuel Cell Technologies Office funds. ARIES is being supported by many DOE offices. The presentation really should have listed all of the DOE funds that have been and are being used to develop this portion of the ARIES facility. This is especially relevant since the presenters said that the electrolysis portion is being connected to other areas (wind, solar, and grid—and claiming to leverage those investments). The project is limited to one type of hydrogen generation: low-temperature electrolysis. The project lists no partners, which was surprising, given the industry interest in this area. The project would have benefited from an industrial advisory board.
- The project allows testing and integration of megawatt-scale renewable energy with a megawatt-scale electrolyzer, 20 MWh of hydrogen energy storage, and a megawatt-scale fuel cell at one site. Flexibility and ability to reconfigure to test different assets are important.
- This project represents an "execution" project that represents critical infrastructure for the national hydrogen roadmap.

Question 2: Accomplishments and progress

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

- The project is currently building out the demonstration system. The integration of renewables, microgrid, compression, storage, and power generation appears to be well done. The research being done is not clear. It seems that the project involves building and operating systems. It is not clear whether loads will be simulated and whether validating some of the models for using hydrogen for long-duration energy storage will work with grid modernization. The lack of potable water is a concern but can be remedied. It would be beneficial for the team to reclaim the water generated from the project fuel cell for use in the electrolyzer, but this could result in concerns over the warrantees and/or agreements the project has in place with the electrolyzer original equipment manufacturers (OEMs).
- The scope of work is unclear, including equipment delivery, site build, and safety evaluations—aligning with the $0 DOE funding for Fiscal Year 2023. The project seems on track to be ready for operation and for accepting projects from other institutes, suggesting excellent progress.
- The infrastructure has been built and commissioned, equipment delivered, and sub-systems integrated.
- Safety evaluations have been completed.
- This project is almost complete and has met its goals of getting installed and commissioned. The project has successfully determined the next steps and will have a long line of users.

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.

- There are collaborations with Toyota, Nel Hydrogen, General Electric, and the Electric Power Research Institute (EPRI). Now that the system infrastructure is in place, collaborations will increase as the facility is used to test equipment from commercial entities.
- There seems to be industry interest. A major value would be collaboration with other DOE offices, such as the Wind Energy Technologies Office, Solar Energy Technologies Office, and Office of Electricity (for grid modernization). This was not addressed, other than the presenter saying the team is talking with those offices, and seems to be a gap. It is not clear whether the project is collaborating with any other national laboratory, which would be beneficial. Industry support seems to be in leasing equipment, but an industry advisory board was not mentioned.
- As noted in response to reviewers from the 2021 Annual Merit Review, the project is an installation project and does not include research. However, the presentation provided little to no information on how funded projects will be managed, particularly how data and privacy issues will be handled, and how multiple projects reliant on the same infrastructure will be coordinated to ensure adequate provision of utilities essential to the success of funded projects.
- Collaboration with OEMs is critical to getting the systems installed. However, future engagement should focus on and prioritize utility collaborations in the future.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The potential impact of the project is outstanding, as made evident by the number of cooperative research and development agreements (CRADAs) seeking use of the new campus for demonstrations. The 1 MW >50 kg scale is important, as it is large but not too large for prototyping emerging projects, such as novel uses of hydrogen or novel hydrogen storage.
- The project is developing a facility for industry to come and try out technology, with the future being dependent on industry paying to use it. With the hydrogen hubs and other demonstration projects, it seems that industry has the opportunity to do this themselves.
- The facility will allow for testing at commercial scales. The facility is important for conducting third-party validation of commercial products, testing integration of systems, and validating efficiency and performance.
- This is highly impactful infrastructure. There is extremely high interest in utilizing this facility, and it is suggested that DOE replicate it in every region.

Question 5: Proposed future work

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

- The proposed future work will fulfill the ultimate purpose of the installation project, introducing a critical new campus capability for DOE to test and demonstrate hydrogen production, storage, and fuel cell performance.
- This project is coming to a close, but the team has identified users and initial projects.
- Future work involves multiple CRADAs with industry.
- The project did not have a plan for how to work with other DOE offices, which seems to be a gap. More details on future funding to continue the development and the use of the site would be useful.

Project strengths:

- The project creates a capability that will support research and demonstrations critical to the lift-off of hydrogen through the inclusion of water, power, storage, production, and end use of hydrogen. The hybrid controller will provide not only a means of data collection but a means of monitoring.

- The project is well funded and has a good deal of stakeholder interest. The site has plenty of space to grow and has the potential for integration with other assets such as wind and solar.
- Strengths include flexibility and availability of all the components to demonstrate renewable energy production, energy conversion to chemical energy, long-term energy storage, and conversion from chemical to electrical energy.
- The work is very important, and the project has a good design for integration and future flexibility.

Project weaknesses:

- The project did not provide details on the approach used to handle wastewater from the deionized system. The project did not provide a baseline for projected costs, land use, energy, and utility needs or compare it with the ultimate cost and lessons learned during the course of the installation project. No details were provided on the power electronics and the potential need for refurbishment of purchased equipment necessary to stay "up to date" with developments in the hydrogen sector. For example, there was no explanation of how the coupling of the electrolyzers with wind and solar was determined.
- The lack of potable water is a concern. The continued support of the site was not well defined. This could be because those potential projects are considered business-sensitive and NREL could not release the information.
- It is hard to envision or build to every conceivable scenario. However, one weakness is that this facility does not include integration with a water/pipeline network to get a fuller picture of energy–water infrastructure.

Recommendations for additions/deletions to project scope:

- The team should discuss how they will work with other offices and how they can make the site available to other stakeholders, including other national laboratories, for use. The capability seems to be stovepiped, and while the presenter said the technology can be integrated with other assets at ARIES, it is not clear that such integration is being done. Further clarification is needed on asset integration and whether the assets will be tied into other grid modernization work. The team should consider a stakeholder advisory board.
- The team should work with EPRI to get expansions and replications funded under the Low-Carbon Resources Initiative.
- A hydrogen liquefaction capability and liquid hydrogen storage are recommended.
- A summary report of construction and installation cost and lessons learned would be valuable.

Project #TA-052: Solid Oxide Electrolysis Cells Integrated with Direct Reduced Iron Plants for Producing Green Steel

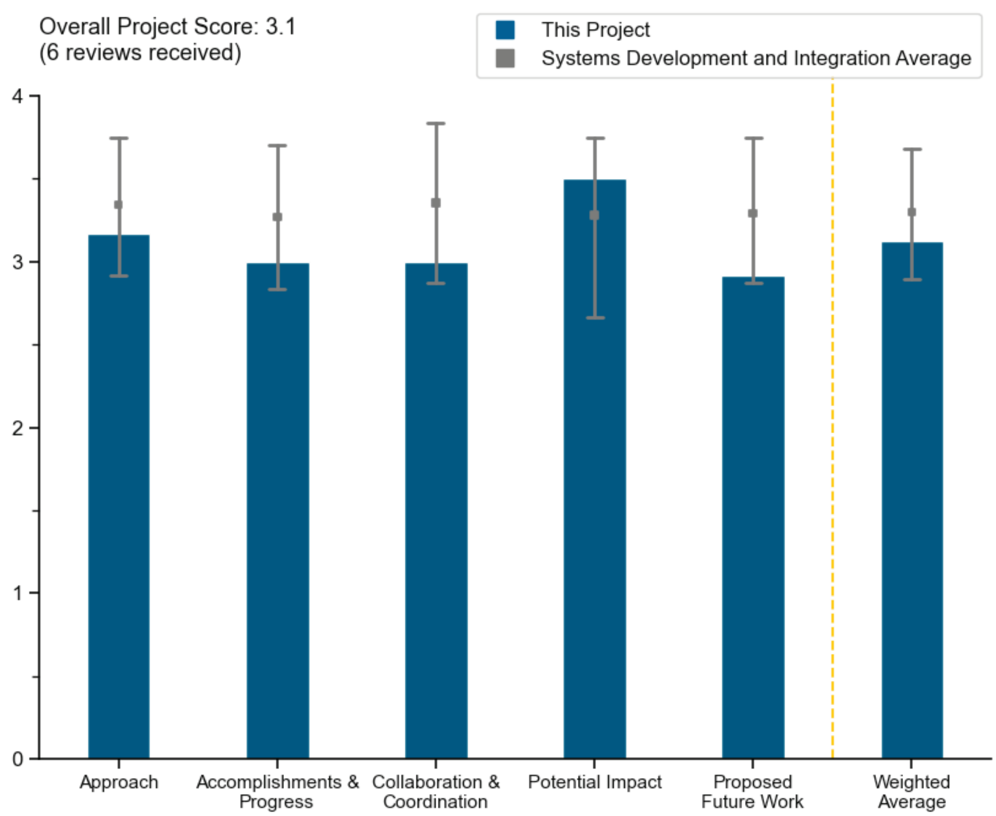
Jack Brouwer, University of California, Irvine

DOE Contract #	DE-EE0009249
Start and End Dates	3/10/2021–9/10/2024
Partners/Collaborators	FuelCell Energy, Versa Power Systems, Hatch Associates Consultants, Inc., Politecnico di Milano, Laboratorio Energia Ambiente Placenza, Southern California Gas Company
Barriers Addressed	• Capital costs • System efficiency and electricity cost • Renewable electricity generation integration

Project Goal and Brief Summary

The main goal of the project is to show the technical and—at scale—the economic feasibility of the thermal and process integration between a solid oxide electrolysis cell (SOEC) module and a direct reduced iron (DRI) furnace, paving the way for production of green steel. The SOEC system will be designed to produce enough hydrogen (>10 kg/day H_2) to supply a shaft furnace of an equivalent size of one ton per week of DRI product. The best-performing configuration will be scaled up via a feasibility design at a production capacity of 2 Mton/year of DRI. The project comprises the following phases: plant conceptualization and thermodynamic analysis, SOEC module sizing and nominal load design, testing in relevant conditions for DRI operation, design and commissioning of a DRI simulator, and techno-economic assessment of a full-scale system. The proposed hydrogen direct reduction system has the potential to reduce specific energy consumption up to 35% compared to conventional DRI and ensure the product specifications of a conventional DRI plant (metallization 96%).

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 objective of this system development and integration project is to validate the feasibility of integrating an SOEC system with a DRI plant for producing green steel. The challenges and barriers are clearly identified. The theoretical analyses and the proposed technical approaches are scientifically sound and convincing. The work plan is well-thought-out. It is likely that the team will be able to overcome the critical barriers and achieve project goals.
- The approach of this project involves several work packages on concept design, analysis, modeling, and experimental work. The approach is very effective for addressing the project objectives.
- The approach to the work is outstanding. The work packages made sense individually and as a whole.
- SOEC integration with a heat and steam source is very attractive because of the high efficiency. It is great to see some efforts on this front through both modeling and potential real prototype system deployment. Perhaps the team would consider the following comments/suggestions as ways to further strengthen modeling and experimental approaches:
    - The iron and steel market is large, but clear distinction should be made between virgin/recycled steel and respective market sizes since recycled steel does not require DRI.
    - Stack efficiency is attractive, but the stack efficiency will be dependent on actual system operating parameters, which can only be determined through a detailed system design. It would be beneficial to incorporate system efficiency beyond the SOEC stack and include the entire balance of system/balance of plant needed to run the plant.
    - For additional funding, the team should be seeking industrial advisors to further strengthen the case and demonstrate early adoption of SOEC in the steel production market.
    - The team should create a clear plan for sulfur removal prior to steam injection into the stack.
    - There was a statement during the presentation that "electricity costs will be lowered," but the utilities and independent power producers are the ones controlling the costs. Deploying more renewables does not correlate to direct lower costs of electricity. The team should consider variable electricity costs depending on location and use ranges to conduct sensitivity analysis.
    - It would be beneficial to explain the electricity costs assumed for system modeling and the impact on the system efficiency if the DRI operation is variable such that the system cannot operate at target conditions. Detailed sensitivity analysis should be performed to truly understand optimal operating conditions and barriers.
    - It would be beneficial to provide a detailed sensitivity analysis for stack current density. The proposed stacks are running at moderately low current density of 0.5 A/cm^2, but FuelCell Energy stacks are capable of much more, according to recent presentations. It would be beneficial to demonstrate change in current density with increase in pressure when compared to atmospheric conditions to better understand efficiency improvements. Incorporating such sensitivity analysis into detailed plant design would be beneficial.
- The operation of the SOEC is certainly a critical item, but the project, as defined, has a much bigger scope. Other critical components that need attention include:
    - Evaluating a DRI shaft furnace using 100% hydrogen. It will behave much differently from an H_2/CO reduction gas. More effort needs to be spent on understanding the difference. This difference can greatly change the entire operating system.
    - Recovering heat and cleaning the exhaust gas for use. Much of the waste heat in steel mills is not recovered because it is extremely dirty. Future effort to find a filter is planned, but it will not be a small undertaking.
    - Investigating the longevity (i.e., mean time between failures) of the SOEC, material breakdown, and corrosion of extended high-temperature operation. If the SOEC is not a high-reliability item, it should be designed with many modules that are individually easily replaceable while the plant stays on line. Alternatively, a buffer needs to be built into the system that would allow the SOEC to be down for maintenance without taking down the remainder of the plant.

- Designing or explaining the system for heating the reducing gas while simultaneously removing CO_2, O_2, etc. It is not a simple system, and the process heater used at the Nucor DRI plant in Los Angeles has had many failures that have taken the plant down many times.
- Removing impurities, especially H_2S, in the tail gas. There needs to be a system for removing those impurities while still recovering the waste heat.

- The presentation lists capital costs, system efficiency, electricity costs, and integration with renewables as barriers. The principal investigator's (PI's) work contributes significantly to the first two of these. The arguments that somehow electricity costs will come down with additional renewables is uncertain. Once these electrical sources are priced onto the grid, they are sold at what the market will sustain (the gap is the profit margin or funding for the utility operator). The fact that the actual power output from renewable sources is substantially less than nameplate also leads to some questions regarding the long-term cost of renewables when incentives are retired. The project's integration with renewables thus far does not appear to be developed, other than indicating that this is a source of electricity. The assumption appears to be that the renewables provide steady electricity, which may not correspond to reality (a fine assumption if purchasing electricity solely off the grid, but then the first-pass benefit of renewable cost reductions vanishes).
  - Impurities were raised during the question portion of the review; this is a key question because the difference between first-pass design and final industrial design is often driven by the impurities and understanding where they go in the process. The PI and team would do well to focus more on the impurities in their process design to prevent costly redesign efforts upon implementation. The predictions of meeting cost or energy per mass may depend strongly on how impurities are handled.

Question 2: Accomplishments and progress

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

- The team has indicated progress against two of the barriers. The strongest progress is the finding of 8.07 GJ/ton, which almost (but not quite) meets the 8 GJ/ton objective (there are still questions about impurities and water handling that may yet be influential). Additional progress is anticipated in future budget years. The PI and team are to be complimented for incorporating safety early in the design process by including a hazard and operability study.
- According to the technical accomplishments presented in the meeting, the team has demonstrated excellent progress toward the project objectives through measurable performance indicators. It seems that the project is on track to achieve its goals.
- Good progress has been made on the work overall, especially on the simulation side. The project had some initial delays and is behind schedule. The reviewer is confident that the work can be done within the extension granted.
- Excellent progress has been made in the design and analysis areas. Progress in solid oxide fuel cell testing is somewhat limited.
- The project goals could have been presented more clearly to assess progress.

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 PI has arranged to work with a number of partners or collaborators who serve in project-specific roles or as advisors. Some of these collaborators are prepared to move this project to the next stage. The specific inclusion of industrial partners is compelling.
- There are seven partners involved in this project. The role of each partner was not clearly presented, but it seems that the team functions well in performing various tasks and achieving some of the project objectives.
- Collaboration and coordination with other institutions/organizations is excellent.

- The work presented does show that the PI has established collaboration with most or all partners. Most likely owing to the limited time of the presentation, it was not very clear how engaged the partners really are. For example, slide 6 shows a desired DRI carbon between 0.3% and 0.8%; most of the industrial partners would recognize that the desired value is higher. Also, some of the gas compositions used for inlet of simulations seem a little off.
- It is not clear from the presentation that there is collaboration, other than having a large number of advisors on the board. The project seems to have concentrated on the SOEC, which is a major component of the system, but nobody has looked closely at other components of the system. The advisors have a good deal of experience in these areas, and this presentation does not demonstrate the advisors have been involved. In addition, there are no operational DRI shaft furnaces that use 100% hydrogen. They would operate differently from the standard shaft furnace. The modeled shaft furnace with CO and H_2 is set up to produce typical top gas, but it does not appear as though the DRI furnace modeling using 100% was reviewed by advisor partners.

Question 4: Potential impact

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

- The project describes very well the market and potential of this integration between SOEC and direct reduction. If feasible, combining the two technologies will have a tremendous impact on the energy requirements to make steel by avoiding quenching–reheating cycles currently used with all technologies. This will be a game changer in energy demand—and thus in CO_2 and other emissions.
- Integrating an SOEC using waste heat to create hydrogen and targeting the iron reduction process are hitting a major target for reducing CO_2 emissions.
- The PI and team indicate that reducing CO_2 usage in the production of iron and steel is important to administration goals of reducing CO_2 generally. It is good that the project team recognizes that some carbon is essential to the production of steel, such that all carbon cannot be removed from these processes. Identifying pathways to reduce the cost to or below 8 GJ/ton bodes well for significant potential impact, recognizing that additional refinements may be needed, given that water treatment was not considered.
- This demonstration of an SOEC integrated with a DRI plant represents an interesting and important application of SOEC technology. This is well aligned with the Hydrogen Program and DOE research, development, and demonstration (RD&D) objectives. Thus, the success of this demonstration project has the potential to advance progress toward DOE RD&D goals and objectives.
- This project will contribute to the assessment and possible demonstration of the use of solid oxide electrolyzers integrated with DRI plants for clean steel production.

Question 5: Proposed future work

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

- The PI and team have a clear list of steps they will take to complete design and thermal integration. These steps build on the work completed through the current budget period. These future steps will contribute toward two of the barriers indicated. The PI and team do not appear to have a plan to integrate renewables other than from a grid source. This may be advantageous because the folks operating the grid then have to address problems with intermittency, but it does leave the PI without a compelling argument for decreasing cost due to the integration of renewables. It is unclear that integration with renewables should mean simply plugging into the grid and then operating at steady state.
- The proposed work as described is adequate, considering this is only the first review. There is much to be done on the stack side. The modeling of the DRI reactor could be improved, but overall, the accuracy of the model is not critical to the success of this project. Addressing potential issues such as contamination (e.g., particulates or chemical, like sulfur) is a much higher priority.
- The proposed future work is logical and reasonable for addressing the remaining challenges and barriers. However, it seems that many difficult tasks to achieve the project goals are still ahead.
- Perhaps there is a more detailed plan, beyond what was presented. A DRI pilot plant is a huge undertaking, and planning is not apparent in this presentation. There are many components that need to be designed/

detailed. This presentation does not list all the major sections, let alone how it plans to design or procure them. From this presentation, the project seems to lack detailed planning.

- Proposed future work lacks detailed schedules, especially completion dates.

Project strengths:

- First and foremost, this project is attempting to advance the understanding of integrating two technologies to improve the efficiency of ironmaking. If successful, this will be a game changer. The approach chosen is very sound. The PI's approach of simulating the direct reduction furnace, rather than attempting to make DRI, is commended. This is a much better approach and will avoid the many distractions of operating a small DRI pilot plant.
- A project strength is the thermal integration and the use of SOEC hydrogen direct reduction. The range of collaborators, from academic to industrial partners, is also a strength. The consideration of safety in the design phases is also a strength.
- The use of SOEC using clean waste heat is a good way to create hydrogen. The use of hydrogen to reduce iron ore will make the biggest impact in reducing CO_2 emissions in the steelmaking process.
- This demonstration project represents a unique opportunity for SOEC technology.
- The project's main strength is the design, analysis, and modeling of systems that integrate solid oxide electrolyzers with DRI plants.

Project weaknesses:

- The reviewer is not certain that a DRI shaft furnace reactor has been operationally demonstrated with 100% hydrogen reducing gas anywhere in the world. Without CO, the system will be fully endothermic. It will also have a H_2O/H_2 equilibrium reaction line that decreases as the operating temperature drops, which will slow or stop the reaction. The modeling of the shaft furnace is very complicated and will likely not operate the same way as the standard CO/H_2 furnaces. The presentation makes it appear that the shaft furnace has been modeled as a simplified block; in reality, the whole system is very complicated and completely different. In addition, the pellets contain sulfide impurities FeS and SO_2. The hydrogen picks up a percentage of the sulfide in the form of H_2S. When the tail gas from the shaft furnace is reused, these sulfides will need to be removed to prevent damaging the SOEC, or the SOEC will need to be hardened against sulfide corrosion. Other impurities such as phosphides and chlorides exist in the DRI, and trace amounts may come out in the top gas.
- The project weaknesses include the limited integration of renewables and the assumption that somehow electricity prices from renewables will go down when the system is connected to the grid.
- While some interesting progress has been made, it seems that many difficult tasks are yet to be performed.
- The main weakness of the project is an unbalanced focus on experimental work (stack testing and operation under relevant conditions).

Recommendations for additions/deletions to project scope:

- The following bullets discuss recommendations:
  - High-temperature fuel cells are generally known to have longevity issues, material failures, and corrosion due to the high temperatures. It may be useful to put effort toward determining life of the fuel cells (including long-term testing) or defining acceptable mean time between failures, as well as showing data or testing to show the fuel cells will meet life expectancy.
  - The team should consult with Midrex and/or Tenova on modeling the shaft furnace using 100% hydrogen.
  - Co-electrolysis should be used to reduce CO_2 to CO. The CO can be used in the DRI furnace to mimic existing technology. The new technology to demonstrate is the SOEC making hydrogen using waste heat from the DRI furnace. The suggestion is to keep it simple to provide a higher probability of success for the project.

  - The Nucor DRI plant in Los Angeles has been plagued by breakdown issues. A "lessons learned" is available and should be reviewed. It is believed that 90% of the failures occurred in material-handling equipment and the process gas heater. The material-handling equipment failures are likely scale-up issues, but the reducing gas heating system is something that should be looked at closely during the next stage.
  - It is recognized the recirculation gas needs to be cleaned, but no method of cleaning was suggested. Dirty gas is what prevents the steel industry from using waste heat in general.
  - The project should look into the impacts of carrying impurities such as sulfides, chlorides, and phosphides from the DRI back to the SOEC, with sulfides in the form of H_2S as a very high probability, as well as trace amounts of the other two impurities. The team should look into removing these impurities at high temperature or finding some way to recover and reuse the waste heat and clean the gas at low temperature.
- Since the PI and team have limited consideration of renewables directly, perhaps it would be better to delete this aspect from the scope so that the team can continue to focus on aspects of the work where they really excel. The PI and team are also encouraged to take additional steps to incorporate safety by design in their approaches to both steady operations and start-up.
- The project should proceed with the work as described; no changes are needed.

Project #TA-053: Grid-Interactive Steelmaking with Hydrogen (GISH)

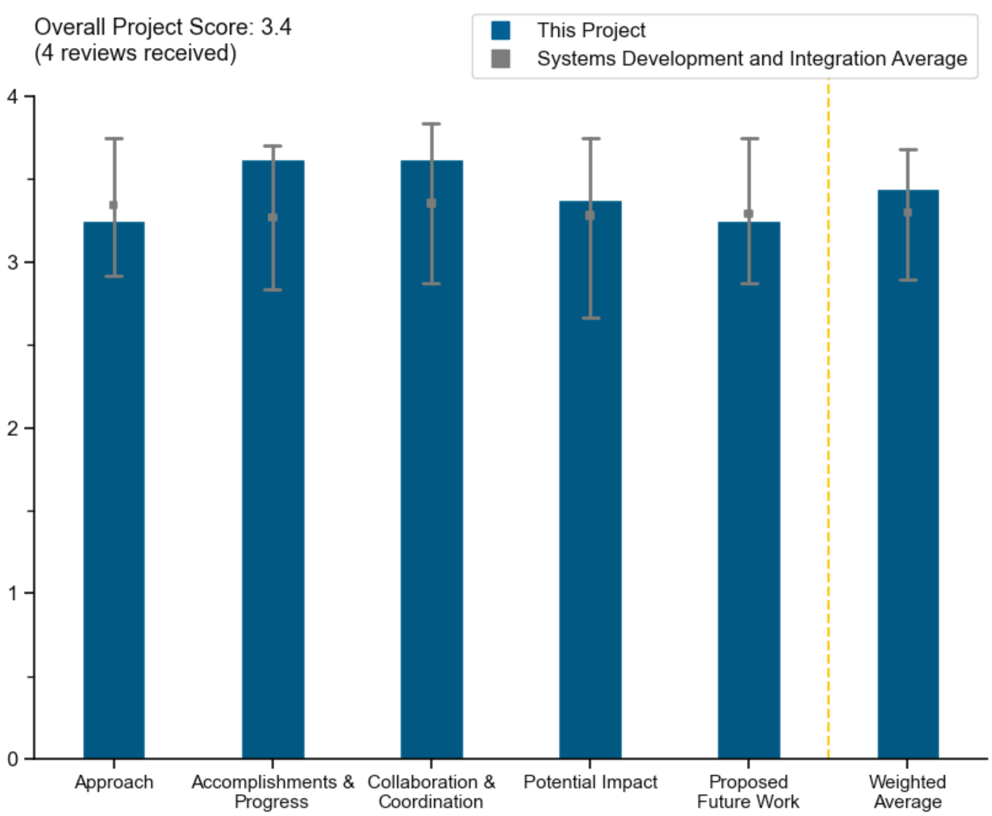
Ronald O'Malley, Missouri University of Science and Technology

DOE Contract #	DE-EE0009250
Start and End Dates	10/1/2020–4/30/2024
Partners/Collaborators	Arizona State University, National Renewable Energy Laboratory, Danieli USA, Cleveland Cliffs, Nucor, Steel Dynamics, Gerdau, Linde plc, Air Liquide
Barriers Addressed	• Rising materials and manpower costs • Materials and construction delays • Gas preheater design start-up issues • Hydrogen safety approvals

Project Goal and Brief Summary

This project aims to de-risk industrial investment in infrastructure for hydrogen-based direct reduction of iron and steelmaking in an electric arc furnace (EAF) by closing critical knowledge gaps in the current research, development, and deployment landscape. The project includes four main activities: (1) documenting the effects of mixed hydrogen and natural gas reduction kinetics for iron oxide and use of plasma to enhance reduction rates; (2) modeling scale-up of an innovative direct reduction pilot reactor to production scale, capturing the characteristics of the materials flow and the thermal profile; (3) developing models for EAF operation with variable carbon-based and carbon-free feedstocks; and (4) conducting a techno-economic assessment (TEA) to quantify the economic opportunity of the project steelmaking process. These efforts have the potential to incentivize the use of clean hydrogen in one of the nation's most CO_2-emissions-intensive industries, expanding hydrogen demand and thereby decreasing costs.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 principal investigator (PI) and team are pursuing two key objectives: (1) to develop a scalable model for mixed hydrogen/natural gas reduction and (2) to demonstrate feasibility of carbon-free direct reduced iron (DRI) processability in the EAF. The scalable model includes both mathematical modeling and physical experiments at pilot scale. These pilot-scale experiments are important because they advance the field with actual data and test assumptions. Two campaigns were completed, and the preheater was re-positioned as a result.
    - The barriers that the team addressed appear to be project barriers instead of barriers to the field. Safety should not be seen as a barrier. The PI and team are to be complimented for engaging the hydrogen safety panel early and on continued engagement.
- This is a good approach to a wide, complex problem. The project attempts to address many of the aspects related to ironmaking with hydrogen, including reduction and melting. This is a big task. The work has been broken down into reasonable work packages performed by different entities.
- This type of project is highly relevant to DOE H2@Scale. The project is well poised to take a critical look at key barriers to scaling up the use of hydrogen in steel, including validation of steel product quality, design and optimization of DRI and EAF based on hydrogen and natural gas feedstock provision, and correlation to pellet characteristics. The project takes an excellent approach that combines process modeling, kinetic modeling, lab-scale and pilot-scale experiments and product characterization, and industrial feedback. However, there was no coordination with other relevant efforts funded by DOE.
- The project has been designed in step-wise fashion, from analytical modeling to laboratory bench test, to pilot plant and comparing data, and then to field trials. There are many variables on a full EAF, and it is difficult to interpret the field trial data to determine success. The bench test reactors will be able to control the variables to better compare and confirm analytical models. All of this is good. The projects do not address the largest barrier to high hydrogen DRI adoption, which is the high cost of using DRI due to more slag, higher yield loss, extra heating, etc., whether it is hydrogen-reduced or not.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- The team has made outstanding progress on several challenging key milestones, including safety and go/no-go targets, despite material cost and delivery delay barriers. Key accomplishments include pilot reactor continuous operation, improved performance of H_2 preheating, 5% agreement of the reactor model and the pilot, initial results of a combined TEA and life cycle assessment (LCA), and new insights on energy consumption and safety.
- The PI and team have a solid plan that lays out specific accomplishments. The pilot-scale work is impressive and an important step in advancing from model to production. The combination of pilot-scale experiments and modeling is compelling. The approach allows for a more sophisticated advance toward scale-up by using process modeling rather than simple correlations that often use diameter as the primary basis.
- Multiple milestones have been set up to show progress. There seems to be excellent project management of these milestones. The past few years have been plagued with delivery issues, and the teams appear to be reacting to them as best as can be expected.
- Accomplishments to date have been very good, considering the global situation and the amount of work to be done. For example, getting the hydrogen safety review done and signed off is very commendable, as this is not a minor task. Having been able to perform two test campaigns in this timeframe is also noted.

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 work presented clearly demonstrates good collaboration and synchronization between some of the engaged parties. Slide 17 delineated the roles of the various entities, which was appreciated. There are many parties involved in this project (including competitors), and getting them to collaborate on this project is remarkable.
- The PI and team have a well-structured collaboration, with each team member sustaining particular responsibilities. The team includes industrial partners, including steel producers and gas suppliers, from each of the major aspects of the project.
- The collaboration between partners is clear cut and readily apparent. Multiple partners have been assigned portions of the project and are making progress on their specified goals.
- It is not clear how the partners collaborate with each other, but it does seem that there is adequate data-sharing and communication, at least on the melting experiments and kinetic modeling tasks. Clarification is needed on how the National Renewable Energy Laboratory (NREL) TEA/LCA modeling team is coordinating with the experimentalists to update and validate system-level process design and simulations. It is unclear who developed the reactor model and COMSOL models and how they are being integrated into facility-scale process designs and models for the TEA. Involvement of students, particularly underrepresented students, was not clearly described, making it hard to evaluate the diversity, equity, and inclusion aspects of the project. The approach for data exchange and coordination between team members was not clearly described.

Question 4: Potential impact

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

- The impact of hydrogen in ironmaking is immense—this is potentially the first new way to make steel since the iron age began. The project was rated in the context of other existing work on hydrogen reduction and melting. There are other institutions, especially in Europe, working on similar topics. The impact of each individual project will be somewhat difficult to evaluate, but all are very valuable, both on their own and in collaboration with one another. This is a big task.
- The project is relevant to DOE goals for deep decarbonization. The pilot-scale work adds significant impact.
- The approach and progress made are outstanding and directly address the barriers noted in the project overview.
- The largest amount of CO_2 produced in the steelmaking process is reducing iron ore to iron. Using hydrogen to reduce the iron ore can significantly reduce the CO_2 emissions in the steelmaking process. This project targets DRI pellet reduction of iron ore and is therefore well aligned with the DOE targets. The goals involve attempting to establish the usefulness of the carbon content in the pellets. The project is establishing the melting point of the pellets versus carbon content. There are other considerations to establish an optimum amount of carbon in the pellets for the overall benefit of the full load. This presentation has created a predictive model for melting point versus carbon but does not appear to address carbon optimization. The target metallization that plasma can be expected to produce is >89%, yet the industry consistently produces DRI at 92% to 96% metallization. This would appear to be a negative toward the plasma reduction. Some of the main barriers for steel mills using large percentages of DRI are cost related to gangue and yield loss to the slag when using DRI, and this presentation does not appear to address those barriers.

Question 5: Proposed future work

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

- The PI indicates four barriers: (1) rising costs, (2) construction delays, (3) gas preheater designs, and (4) hydrogen safety approvals. These barriers are project-specific and not necessarily the more global barriers. More globally, the PI and team appear to be tackling barriers to hydrogen/natural gas reduction and a carbon-free DRI process. In both senses, the future work outlined is appropriate and relevant.

- The proposed future work is aligned with the goals as defined. The plant trials are useful but will require a large number of heats to see a trend in data to determine success.
- The presenter notes the budget and timeline have been reworked. Clarification is needed as to whether April 30, 2024, is the new or old end date. If it is the new deadline, that is less than a year to complete a very large set of remaining tasks. The team will need to be very focused and coordinated to complete the scope of work.

Project strengths:

- This project targets the use of hydrogen in reducing iron ore. This is the highest CO_2 generation portion of the steelmaking process and can have a large impact on CO_2 generation in the steelmaking process. The project seems to be well organized in what it is going to do; project management is readily apparent. The project appears to be shared between partners, and roles are well defined. A number of the project objectives are of great interest to the industry.
- A wealth of experimental data is being generated, as well as knowledge gained from feedback from industry partners. Having data on the kinetics of reduction would go a long way toward addressing key process modeling and simulation uncertainties for the DRI. Similarly, linking DRI and EAF operation to feedstock, byproduct, and product properties is critical data to validate process models ultimately used to predict necessary hydrogen prices for industry lift-off.
- Strengths include the topic of ironmaking with hydrogen, the approach chosen by the project leads, and the different work packages that lead to building and (safely) operating a hydrogen furnace.
- The strengths of the project are the pilot-scale work that couples with modeling, the strong project team, the steady leadership of the PI, and the early engagement of safety expertise.

Project weaknesses:

- The various objectives do not appear to be tied together well. One objective is to model hydrogen/natural gas kinetics for reducing iron, with emphasis on high hydrogen. Another objective appears to try to overcome the weakness of carbonless reduction by modeling carbon content of DRI versus melting temperatures. Another objective uses plasma to reduce DRI. A fourth objective uses a TEA, but it is not clear which of the objectives will be used—whether all at one shot or each objective with an individual TEA. Any one of the projects could stand on its own, but as a group, they are hard to tie together. In addition, the major cost of using DRI is the additional cost related to the gangue. More slag is required to balance out the gangue, more heat is required to heat the additional slag, and yield loss occurs due to greater FeO lost to the additional slag. These listed cost issues are not part of this project, and as such, the TEA of using DRI is not truly complete.
- It is difficult to evaluate how industry partners are engaged and their level of participation. The presentation did not discuss translation of industry knowledge and experimental data to bound parameters used in mathematical modeling and process modeling software (such as ASPEN). Clarification is needed as to whether NREL developed its own DRI and EAF models for the TEA or is leveraging models developed in other funded projects. Integration of the hydrogen delivery system to the DRI and steel facility was not described, making it difficult to know whether the project will provide insights for hydrogen production delivery and storage. Overall, the presentation did not include enough background information or context for preliminary results to be translated into guidance for future research and development, particularly on the key sensitivities affecting decision-making.
- The overall project weakness is that the barriers to the field that this project overcomes were not clearly articulated. Perhaps it is the inclusion of plasma that makes the project truly unique, as others have been working on DRI-based plant design. However, the advancement to pilot scale is compelling.

Recommendations for additions/deletions to project scope:

- The TEA predicts a steel product cost of $583/t levelized cost of steel for 30% H_2 usage, while the Lawrence Berkeley National Laboratory team presented $584/t for 100% H_2 usage from the lab call project on hydrogen storage for steel facilities. Adding a cross-project comparison to ensure updated system-level design assumptions across DOE-funded projects would be an impactful way to guide LCA and TEA in this sector. Additional work to summarize key findings into guidance on pilot- and facility-scale design and CO/H_2 ratios would be beneficial. Much of the cost is due to feedstock. Perhaps there are opportunities to lower this cost—or perhaps it would be helpful to know how pretreatment of pellets affects DRI and EAF design considerations and performance.
- There are multiple cost barriers to using DRI in an EAF. Some consideration/acknowledgement should be given to what those other costs are and how hydrogen reduction may affect those other costs.

Project #TA-056: Ultra-Efficient Long-Haul Hydrogen Fuel Cell Tractor

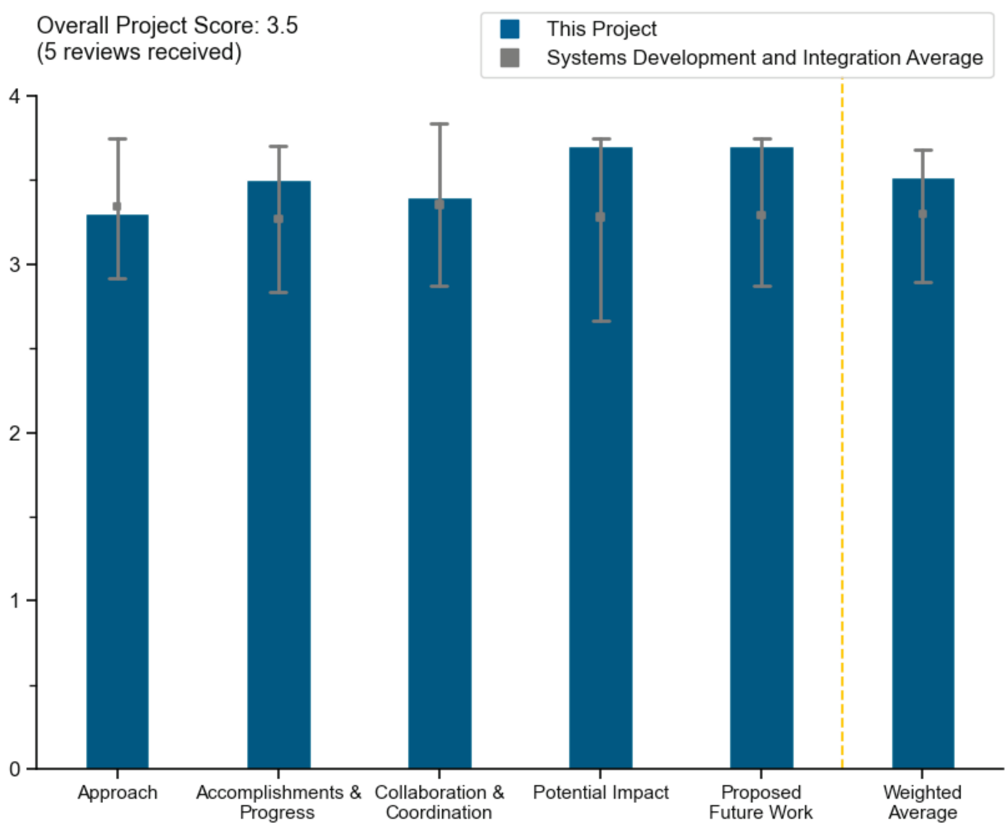
Darek Villeneuve, Daimler Trucks North America

DOE Contract #	DE-EE0009860
Start and End Dates	5/1/2022–4/30/2027
Partners/Collaborators	Linde plc, Michelin, MAHLE Behr, MAHLE Filter Systems, Auburn University, Oregon State University, Oak Ridge National Laboratory, National Renewable Energy Laboratory, Argonne National Laboratory, Schneider National, Walmart
Barriers Addressed	• Vehicle performance • Reduced carbon intensity of fuels • Maximized freight system performance

Project Goal and Brief Summary

Daimler Truck aims to demonstrate a substantial reduction (75% or greater) in greenhouse gas emissions and local pollutants from truck transportation while remaining economically viable and scalable. The project involves developing, building, and testing a Class 8 hydrogen fuel cell truck with specific targets for vehicle performance (6.0 miles/kg hydrogen over long-haul drive cycles, 600-mile range, equivalent payload to baseline diesel tractor–trailer, and analytical pathways to a 25,000-hour lifetime), carbon intensity reduction in fuel production, and maximized freight system efficiency. The project will address the challenge of decarbonizing heavy-duty transport and enabling hydrogen applications at scale. Accomplishments include defining the main design path, developing powertrain concepts, improving tire performance, and establishing a hydrogen supply plan, with future work focused on optimization, validation, and demonstration.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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.

- Daimler Truck has a clear approach to the work. The project's simulation of the fuel cell electric vehicle powertrain prior to build, including the safety plan, is quite difficult. The go/no-go decision is logical. The 700 bar tanks will de-risk the first demonstration and validate the simulations. The power battery also makes sense, but more details would be helpful. The potential to test liquid hydrogen (LH2) tanks is very exciting.
- The project is broken into budget periods with clear deliverables for each one and a go/no-go assessment at the end of each period. The B-sample initial vehicle build supports this very well by getting initial data/ results into the project at an earlier stage than would be possible with a single vehicle design.
- Barriers such as packaging, powertrain configuration, and market acceptance are well identified and addressed, but cooling and durability barriers are identified but not completely addressed. The assumption is that the project plans to address the barriers in coming years. The project should provide more details on cooling optimization. For example, the presenter mentioned that the minimum area of cooling system was to be determined. High-level details on the thermal circuit are needed.
- The approach involves building a beta truck and analyzing it and testing it, then designing the final truck and building it and validating it. The targets are best-in-class total cost of ownership (TCO), Baker-grade climb, and 11-hour run time at 65+ mph. However, the project does not provide a great deal of detail on how the approach will be implemented.
- The project has a solid approach, with a diverse and capable team.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The vehicle packaging looks straightforward and is sufficient for modeling before doing the full truck build. The selection for specialized tires, including steer tire optimization, is interesting. The development of simulations and full high desert proving ground inspires confidence that the hardware will work and move the field closer to commercialization. Thermal management was partially explained and looks useful. The Portland route and reference to past SuperTruck projects appear logical and look like good progress toward DOE goals. Just one or two pages of accomplishments would not show much effort, but the full overview of routes to cooling optimization and efficiency based on real-world routes all show significant groundwork for a successful project. The final review of initial safety work hits all the right areas, from the safety plan, to safety upgrades for facilities, to on-vehicle best practices for safety management.
- The project reports one budget period and 18% total complete. From the presentation, it appears that the groundwork is well laid to build the B-sample vehicle and start to validate the model results this year. Cycles of optimization in Budget Period 2 appear to be a key element.
- The project chose tires and provided a good rationale. The project also chose truck capabilities. The fuel cell will be 300 kW, and the battery is 100 kWh and 450 kW peak. Otherwise, the actual progress was only very generally described. The selection of the fuel cell and battery were drawn out only through questions. The need to protect proprietary information is understood, but this presentation was vague well beyond those of others in the industry.
- In powertrain optimization, the project mentioned increasing efficiency by operating at reduced power. It is not clear which driving scenarios are taken into consideration. It is not clear what Route 1 and Route 2 in the graphs are. It is not clear how 20% efficiency is achieved in Route 1 as compared to Route 2, which is 8%. It is unclear how reduced cooling is achieved. The project could consider making more progress on safety in coming years, as this is the top-priority topic. Design review at 30% is good progress, considering a start date of May 2022.
- The project is in early stages, but the plan seems to track closely with DOE goals and objectives.

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.

- There is great integration of partners. Michelin provided good input on steer tires. MAHLE worked on critical aspects of cooling and drivetrain needs. It was good to see analytics from the National Renewable Energy Laboratory and Oak Ridge National Laboratory, as well as workforce development through work with Oregon State University. The project is going beyond analysis with benchmarking parts with analysis partners. The work with Argonne National Laboratory (ANL) highlights the development of power batteries and cycles required for a successful fuel cell truck TCO. Finally, Linde will provide a compressed gas fueling trailer for testing.
- The work with Michelin on tires was the collaboration that was really discussed in detail in the presentation. It would be helpful to highlight modeling and analysis work. Much of this work was done with collaboration partners (national laboratories and universities), and this work can have a broad impact in supporting industry work on freight transportation. Those collaborations are listed in the summary slide but were not highlighted during the presentation.
- The project team is comprehensive and comprises leaders from industry, government, and academia.
- The project has good collaboration with partner participation that is well-coordinated.
- The project's partners include a truck maker and a truck buyer. It seems like they are probably offering valuable perspective, but it is not clear yet.

Question 4: Potential impact

This project was rated **3.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- A successful demonstration will really prove the capability toward fuel cells for heavy-duty long-haul trucking. The LH2 storage aspect for later in the project will be critical to working toward parity with diesel trucks at nearly 2,000 miles of range. The level of technical effort, engineering, and comprehensive partner engagement show that this effort will have a very high chance for success and will be incredibly relevant to DOE decarbonization goals and the use of hydrogen trucking.
- Assuming it achieves the stated targets, this project's impact will be great. A 600-mile range Class 8 truck with 6 miles per kilogram and diesel-equivalent performance would enable the heavy-duty market if the price is suitable. This is a market that would otherwise be hard to decarbonize.
- Reducing greenhouse gas and emissions in freight transport by 75% is an extremely important goal for the industry. If this can be done with TCO parity, it will have dramatic impact.
- The project supports good progress on LH2 in the future and also plans to study market strategy, TCO, and infrastructure.
- The project is very relevant to energy storage, including the use of LH2.

Question 5: Proposed future work

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

- The technical practicality of vehicle fueling with sub-cooled LH2 is not a sure thing, so the reviewer will watch this project over the next couple of years to see if it can be achieved. Hopefully, this area can be highlighted in future project updates. It would be pragmatic to have a backup plan so that unforeseen issues/delays do not delay the rest of the project. That said, the project plan over the next four budget periods appears to be well developed and sound.
- The future work to finalize the packaging is key to the final sizing of components. Cooling is an important challenge for these large 300 kW fuel cells with limited airflow. Durability is a key for these million-mile truck challenges, and the drive-cycle hybridization with the power-focused battery is critical. The close work with ANL will be important to showing market viability and the need for low-cost infrastructure.
- The project's progression to LH2 is really interesting and should offer many lessons learned to DOE collaborators.

- The remaining challenges are clearly defined with good planning. This is well done, with praise to the project team.
- The project offers very high-level future work only, essentially building, testing, and then redesigning for the final design.

Project strengths:

- The main strengths of this project are the background knowledge of Daimler with Freightliner, in-house proof testing of components, and the long history with compressed hydrogen and recent research and development (R&D) efforts with cryogenic storage.
- The project team is evaluating many things in a holistic approach. The project is very sound, and the reviewer looks forward to the results of the next phase.
- The project has a well-developed execution plan, and it appears that resources are in place to run the plan successfully.
- Powertrain optimization is a project strength. A more critical strength is achieving >600-mile range on a single fill-up.
- The project has a strong team with excellent, high-level goals.

Project weaknesses:

- It would be helpful to see more details about the output metrics that are expected of the B-sample phases and how they will work as input to the final demonstrator phase. Also, while the end-goal metrics (fuel consumption, range, payload, TCO, durability) are stated at a high level, it would be helpful to understand how the project will define success or next steps at the end of the project, as the results of those metrics will likely fall along a range and not all be 100%.
- The project has almost no data on methods or progress (aside from excellent readout on tires), so it is very hard to say whether needed progress is being made.
- Subcooled LH2 is a new technology, so there could be unknowns and unforeseen challenges. The project's safety needs more attention.
- It is not clear that targeting a 600-mile range offers a viable alternative for diesel Class 8 trucks.
- The project has no weaknesses at this time.

Recommendations for additions/deletions to project scope:

- Tire designs and compounds are important in electrified platforms, but perhaps this effort could track closer to DOE hydrogen goals by allocating tire R&D money to fuel cell systems. It is suggested that the project study sleeper cab noise, harshness, and vibration characteristics of the fuel-cell-powered system against traditional diesel powertrains.
- As much as feasible, it would be good to have a pathway to LH2 storage demonstration within this project. The infrastructure will be a lower cost and enable further flexibility in fuel cell cooling with a longer range.
- No changes are recommended. The scope is appropriate for the goals stated.
- There are no recommendations for additions or deletions to project scope.

Project #TA-057: High-Efficiency Fuel Cell Application for Medium-Duty Truck Vocations

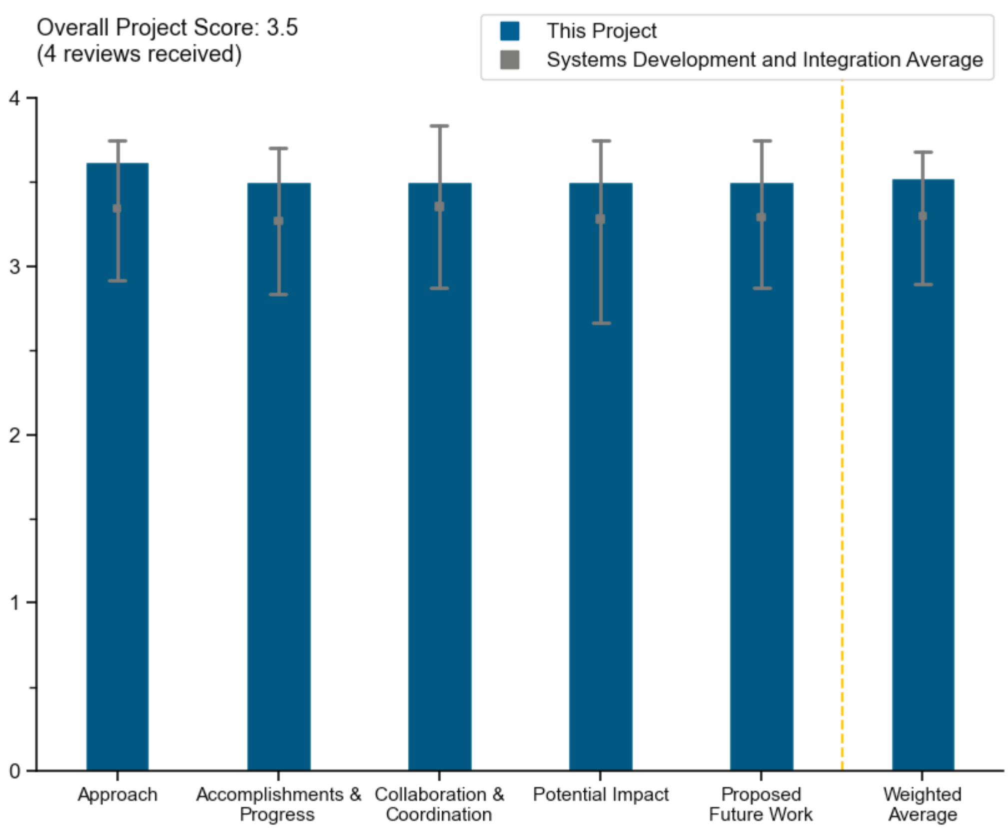
Stan Bower, Ford Motor Company

DOE Contract #	DE-EE0009858
Start and End Dates	3/1/2022–12/31/2026
Partners/Collaborators	FEV Group, National Renewable Energy Laboratory, Consumers Energy, Ferguson, Southern California Gas Company
Barriers Addressed	• Hydrogen infrastructure and cost • Commercial vehicle lifetime durability • Capability in extreme cold environments

Project Goal and Brief Summary

Ford Motor Company (Ford) is leading development of a zero-emission vehicle fuel cell propulsion system for Ford Super Duty® Chassis Cab vocation applications. Researchers will use modeling and simulation to design the technology, then construct the components and integrate them into pilot vehicles. The vehicles will be deployed to three fleet customers, who will demonstrate the technology in real-world environments. Using pilot data, the project team will evaluate fuel cell durability, usage, efficiency, refueling, and operating costs. In addition, researchers will conduct greenhouse gas (GHG) and environmental impact studies, as well as a full total cost of ownership comparative analysis against existing drivetrains.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration projects.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project is looking at efficiency, operating cost, and GHG impact relative to internal combustion engine (ICE) versions. There is a balance between the fuel cell following load and the battery following load and the fuel cell servicing the battery, but mostly the battery takes the transients and the fuel cell keeps it charged. The project has high power chemistry.
- The phased project plan has clear deliverables and metrics for each phase, with logical transitions between the phases. Also, the team earns kudos for clearly stating the go/no-go criteria for each phase.
- There is a sound plan and approach to project execution. It is early in the project, but the team seems to be technically capable of delivering as promised.
- It is not clear what the major contributor to 75% tank-to-wheel efficiency improvement was, and the project is asked to provide more details on overcoming the challenge on extreme cold weather operation. Details are needed on fuel cell, battery, and propulsion system operating strategies.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The project has specced out a 140 kW continuous power stack with a 350 kW peak, 800 V battery pack with 40 kWh capacity to help in towing. Three Type IV tanks hold 21.5 kg at 700 bar and 300+ miles with the same towing and same or better performance. The project has two substacks that share many gas conditioning parts to save cost. The project discovered that the worst case for fuel cell electric vehicles (FCEVs) can be different from ICE vehicles.
- On the performance attribute analysis, it is not clear exactly how the FCEV is providing better range than the 7.3 L gasoline engine. The project a has a detailed evaluation of the fuel cell thermal management system.
- The project is reported to have completed key milestones related to battery and thermal designs as evidence of being on track at this time.
- The project nests well with DOE goals to reduce GHG emissions without compromising vehicle performance.

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.

- Collaboration with fleet users and their assessment of the vehicles' performance will be especially important and is a unique aspect of this project. The next reports should focus on what data and evaluations will be gathered from the users and how those results will be used both before and after the end of the project.
- The project is smart to partner with a utility company. The use case is appealing. Ford could consider taking fabrication of fuel cells in-house in lieu of FCEVs.
- The project has good collaboration with partners that participate and are well-coordinated.
- The project has customers and subcontractors as collaborators, but it is not clear how much the customers are contributing to this project.

Question 4: Potential impact

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

- Adoption of FCEVs in this vehicle class will be a critical component of transitioning transportation away from fossil fuel. Many vehicles of this type are owned and used by "friendly" organizations (municipalities, utilities) that can collaborate on centralized, lower-cost fueling solutions, thus reducing one of the stated project barriers, which is a big opportunity for the project.

- Medium-duty has not gotten as much attention as heavy-duty but is an area where a large number of vehicles are sold and used. These hydrogen vehicles can provide the 24/7 requirements under which these classes of truck may be required to operate. These are all enablers for takeoff of a medium-duty hydrogen truck market.
- The project's potential impact is good, and most aspects align with the Hydrogen Program and DOE research, development, and demonstration objectives.
- The project is very relevant to hydrogen's use as an energy carrier.

Question 5: Proposed future work

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

- The proposed future work seems appropriate for the task at hand. More detail would have been nice, but there is enough detail provided to say the plans are appropriate and well-timed.
- The project structure has logical phases and steps with clear exit criteria and input expected from one stage to the next.
- The project seems to have a solid plan with achievable and meaningful go/no-go stage gates.
- More details on the safety plan could be provided.

Project strengths:

- The project presents as well planned, with appropriate resources engaged to execute. The project is targeted at moving FCEV technology into a key segment of the transportation industry.
- The project has a good engineering process on systems engineering development from vehicle- to component-level development.
- The project is conducting fantastic work. The reviewer is looking forward to the next phase of the project.
- The project has a strong team, a worthy target vehicle, and good partners.

Project weaknesses:

- The project has no obvious weaknesses. It would have been good to learn more about battery chemistry (rather than the answer given in questions, "energy power blend," which is as much about architecture as chemistry per se) so the cold start and life properties could be evaluated.
- It is not clear from the proposed future work slide that the vehicle configurations and usages for the fleet deployments are fully developed (last line on the slide). It would be helpful by the next review at least to highlight the process for figuring out those points and to show the status. For example, power takeoff usage in a boom truck could have significant power consumption and therefore significant impact on some of the project metrics. Snowplowing brings its own unique set of usage profiles and challenges.
- The project should look into electrification of the work truck's traditional hydraulic implements (e.g., booms and lifts) for increased efficiency and reduced system complexity.
- The project needs to show more key performance indicators.

Recommendations for additions/deletions to project scope:

- There are no recommendations for scope changes. This is a good project, and the reviewer is anxious to see future updates.
- There are no recommendations for additions or deletions to project scope.

Project #TA-058: Freight Emissions Reduction via Medium-Duty Battery Electric and Hydrogen Fuel Cell Trucks with Green Hydrogen Production via a New Electrolyzer Design and Electrical Utility Grid Coupling

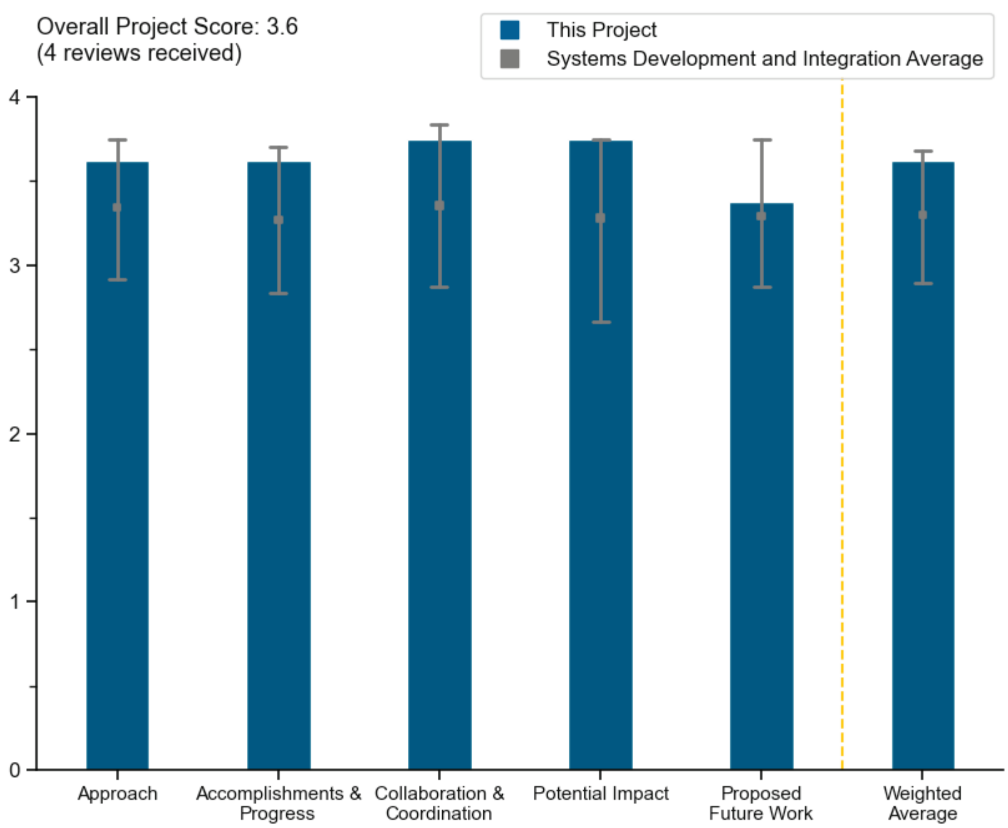
Jacob Lozier, General Motors LLC

DOE Contract #	DE-EE0009859
Start and End Dates	7/1/2022–6/30/2027
Partners/Collaborators	Argonne National Laboratory, Nel Hydrogen, Southern Company, Metro Delivery
Barriers Addressed	• Hydrogen fuel cost • Vehicle heavy-duty fuel cell system durability

Project Goal and Brief Summary

The project aims to showcase a significant reduction of 75% in greenhouse gas emissions while maintaining a competitive total cost of ownership compared to internal combustion engine vehicles in medium-duty (MD) trucks. The project's focus includes modeling, data analysis, and simulation of MD trucks to improve propulsion system performance and durability. The work also involves demonstrating advanced fuel cell and battery electric propulsion systems, establishing a hydrogen-centric microgrid for hydrogen fuel, and conducting equity analyses of the impact of zero-emission trucks on underserved communities. The project seeks to develop a low-cost electrolyzer and create an economically viable pathway for deploying charging and hydrogen-filling infrastructure at scale.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration projects.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach makes sense. The comprehensive integration of the grid and renewable power sources with hydrogen production, fuel-cell-powered trucks, and battery electric vehicle (BEV) trucks is valuable for several reasons. Among them, the work will highlight the role hydrogen can play in balancing temporal mismatches between the availability of renewables and energy demand for transportation. The project will also be an opportunity to understand the relative strengths and weaknesses of MD trucks powered by hydrogen fuel cell and battery electric drivetrains in a real-world operational setting. Southern Company and Metro Delivery will find that the hydrogen fuel cell trucks work best in some situations and the BEV trucks work well in others. Including both drivetrain technologies may reveal the preferred fleet composition (fractions that are hydrogen-fuel-cell-powered and BEVs) for Southern Company and Metro Delivery, which would be a useful starting point as other companies explore the use of both technologies. Using power consumption data from an existing MD truck fleet is the logical starting point, and the use of simulation tools such as Autonomie for estimating fuel cell state of health degradation as a function of the anticipated power consumption profile is a good first stab at assessing the adequacy of fuel cells in this application. The real-world data should then confirm that and results from the rest of the simulation/modeling work going into the system sizing and integration analysis.
- The approach to performing work is well-thought-out and organized. The work is sequential and systematic, encompassing many organizations and following a logical flow. The project team has defined the problem well and set up a project to baseline and analyze data to ensure the project meets or exceeds predicted performance.
- The project has a strong approach that shows the team's expertise and knowledge in developing full-scale hydrogen-fuel-cell-powered systems.
- The project does cover some aspects of overcoming barriers, but it is not clear what measures are completed and what is planned. It would be helpful if the project could pinpoint barriers addressing points.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- Although it is early in the project, the goals outlined will track well with DOE goals. System demonstrations look to be relevant to workloads from real-world use.
- Accomplishments to date are as expected, based on the start date of the effort. Baselining has begun, which will set the bar for how much improvement this project delivers.
- General Motors (GM) seems to be moving forward at a reasonable pace.
- The mechanism preventing membrane and electrode damage factor is not evident.

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 collaboration with two companies that use the MD trucks on a regular basis, a national laboratory that has expertise in vehicle modeling and simulation, and an industry leader in electrolysis position the project for success. The collaboration between GM (expertise in BEV charging), Nel Hydrogen (expertise in electrolyzers), and Southern Company (expertise in electrical infrastructure) is a logical division of labor for the development of the microgrid that plays to each of the contributors' strengths.
- The project has exceptional collaboration and partnering. Working with well-established entities provides high potential for a successful outcome. The project has helped establish a new working relationship between two major companies, one of which is investing in new production capabilities near the lead performer, thus reaffirming the deep collaboration fostered through this effort.

- The project has close, appropriate collaboration with other institutions. The partners are full participants and are well coordinated.
- The project has a strong, collaborative team with plenty of experience.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project has specific targets and high-level goals derived from the DOE targets. The project strives to answer questions on efficiency and applicability of fuel cell technology at a fleet level. Performance over baseline incumbent technology is extremely important for understanding what gaps still exist, how those gaps can be closed, and what additional work needs to get done.
- The project is well aligned with the Hydrogen Program goals. If successful, it should help pave the way for greater adoption of hydrogen-fuel-cell-powered MD trucks, which seems like a good target, given that such fleets can rely on central refueling/recharging infrastructure.
- The project is a great opportunity to showcase the next generation of GM's fuel cell technology. The lessons learned should be applicable to most ground systems using hydrogen fuel cells for power.
- The project has excellent impact since electrolyzer development is involved.

Question 5: Proposed future work

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

- The proposed future work is a logical extension of the current state of the project and, when complete, will carry the project closer to its goals. It would be helpful to understand in greater detail how the team plans to exploit the new electric vehicle powertrains to improve other aspects of these vehicles, for example, by electrifying auxiliary systems that are currently hydraulic. Perhaps such efforts are anticipated after 2024, when the early demonstration trucks will have been built.
- This reviewer is looking forward to seeing the technology in service.
- Future work is in line with continuing the progress set forth from the project objectives.
- The project needs to capture key performance indicators on the target or end goal for future work.

Project strengths:

- The project connects to real-world data for initial sizing and state of health modeling. The project is collaborating with companies that will use the trucks in real-world conditions. There is collaboration with organizations that have expertise in technology areas critical to the success of this project.
- Hydrogen export is a key project strength for the proposed systems. This could have a positive impact on future decisions made by fleet managers when considering investing in alternative fuels for individual duty cycles.
- The project has great partnership and a very large scope of work aimed at answering fundamental questions about performance and cost versus the current technology.
- Strengths include a detailed engineering process and an advanced fuel cell system.

Project weaknesses:

- It is good to see a focus on durability for this set of systems (this is not a weakness). Total cost of ownership will be a strong argument for or against this technology, and system downtime will be a critical factor influencing fleet managers.
- The project has a lack of scale. The scale of the current effort makes sense and is a logical first step. However, it will not reveal potential problems such as refueling/recharging bottlenecks associated with a fleet of vehicles that are all used on the same schedule. Building a larger number of trucks that more closely represent the way Southern Company or Metro Delivery would use a fleet of entirely hydrogen fuel cell vehicles and BEVs would reveal such infrastructure constraints, if they existed.

- Prototype fuel cells are being used in commercial fleet assets, which increases risk, both in performance and maintenance.
- The project's novel approach in durability tests needs better review for covering edge cases.

Recommendations for additions/deletions to project scope:

- The project could assess changes in driving/use patterns with the hydrogen fuel cell and BEV trucks compared to the existing diesel trucks. With the new capabilities and limitations (e.g., BEV range), it will be useful to understand how the trucks are used differently from the existing fleet vehicles.
- There are no recommendations for additions or deletions to project scope.

Project #TA-059: Medium-Duty Vehicle Total Cost of Ownership and Target Development

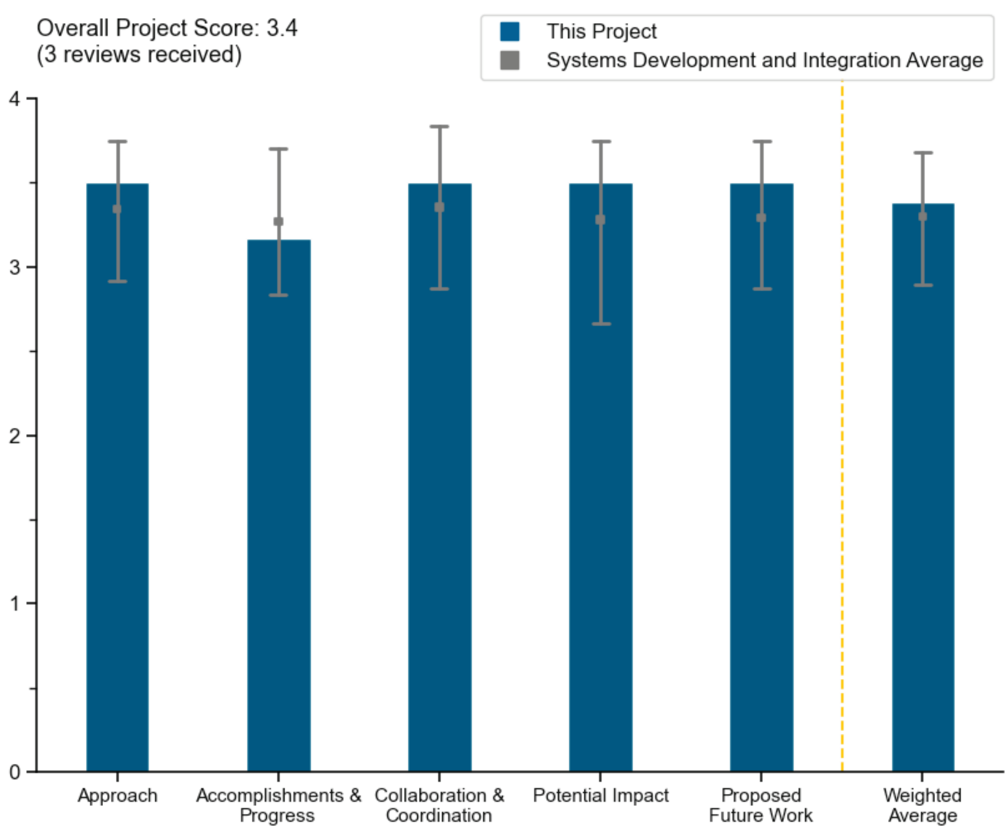
Ram Vijayagopal, Argonne National Laboratory

DOE Contract #	WBS 9.3.0.6
Start and End Dates	9/1/2021–8/31/2023
Partners/Collaborators	National Renewable Energy Laboratory, 21CTP, Strategic Analysis Inc.
Barriers Addressed	• Future market behavior • Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools

Project Goal and Brief Summary

The project's objective is to support the development of fuel cell electric trucks (FCETs) for medium-duty (MD) applications by evaluating their real-world performance and total cost of ownership (TCO). The project aims to identify the applications where FCETs have the most impact, quantify their energy consumption and cost compared to conventional diesel trucks, and determine the cost and efficiency targets needed for FCETs to achieve cost parity with competing technologies. The project involves conducting vehicle simulations, analyzing data from industry sources, and considering inputs from the Hydrogen and Fuel Cell Technologies Office (HFTO) and other stakeholders to inform target-setting and technology development activities. The analysis demonstrates that FCETs have the potential to be a viable solution for longer-range MD applications in the future, and they can provide a lower TCO compared to both diesel trucks and battery electric trucks, depending on the vehicle's range and operational requirements.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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.

- Argonne National Laboratory's (ANL's) approach to performing the work is outstanding. The project has a methodical evaluation of stakeholders and component suppliers. The vehicle performance is critical to projecting TCO and total energy consumed. Evaluating MD trucks is not straightforward and requires extensive review of real-world requirements and usage to have good results in modeling the performance. The real value is in comparing two types of powertrains between fuel cell hybrid and fuel cell dominant, which will depend on cost projections for batteries, fuel cells, and hydrogen storage.
- Generally, the project is well targeted. These are key questions to address for development of the medium- and heavy-duty (MD/HD) vehicle market. The scope is perhaps a bit broad, with the various vehicle types, but it is interesting to see how the different vehicle types may have different TCOs based on duty cycle, etc.
- Vast amounts of data from a variety of related topic areas add to the strength of outcomes in the context of this being a new area of development and availability of operational data. Preliminary TCO values are likely not the only parameters for the choice of battery electric vs. fuel cell electric, or a mix thereof. Particularly in the commercial application setting (versus commuting and travel in passenger vehicles), equipment functionality can be expected to play a major role as well.

Question 2: Accomplishments and progress

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

- ANL has made excellent progress toward project objectives and DOE goals. The vehicle sizing and component requirements span a very large range, from Class 3 to Class 8 refuse trucks. The target of 45 mph may be too fast or two slow for some class vehicles within the seven applications.
- This is the project's first time reporting. It is valuable that a broad input approach was taken in a context where very limited operational data is available for the targeted MD/HD vehicle market to verify how accurate the modeling effort is.
- Progress so far is good. Final project results are eagerly anticipated.

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 range of collaboration between the 21st Century Truck Partnership (21CTP) and component suppliers is outstanding. The team has considered real-time feedback from stakeholders to adjust targets and to modify the modeling capabilities.
- It would be helpful to make references to DOE Vehicle Technologies Office (VTO) projects in the presentation to show the link to peer reviewers and audience members (as well as industry stakeholders reading reported outcomes). VTO is working on some of this. The project is missing MD/HD compressed natural gas vehicle information as an additional/supplemental benchmark to diesel. It would be helpful to have truck fleet operator input.
- There is some collaboration, but the work is pretty confined to ANL.

Question 4: Potential impact

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

- ANL has showed an excellent comparison to batteries and fuel cells to help steer DOE investment priorities and to educate industries that are preparing for the transition to electrification and zero-emission trucks. The problem of optimization and limits of different technologies is very complicated in considering the true cost of electricity, delivered hydrogen, and cost curves as they begin to level out this decade. A key result is that, for a 270+-mile range, a fuel cell vehicle may be more economical, depending on the cost of hydrogen, electricity, and total miles per year. Hydrogen pricing has a big impact on the range, increasing to over 500 miles at $8/kg, showcasing how important it is to reduce the cost of hydrogen for Hydrogen Program goals.

- This is the first TCO project performed by a (more) neutral stakeholder. TCO provides valuable insights when it comes to cost/mile analysis of goods moved and, for example, the potential cost increase of consumer goods in the long term. When comparing vehicle technologies based on range and cost, assessment for battery electric (and fuel cell electric) needs to include weight and sizing limitations (slides 15 and 16).
- This is an analysis project that can speak to TCO, but it likely will not have much broader market impact in terms of technology validation.

Question 5: Proposed future work

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

- The listed future work items are very relevant: the role of degradation in TCO, future drive scenarios with more automated logistics management, and the use of FCETs in future freight movement technologies. There are more results and data from MD fleets, with increased information on real-world results from fuel cell performance and cost, as well as the emerging learnings from different storage technologies.
- The focus appears to be strongly on the vehicle side of the equation. Functionality of evaluated technologies appears not to be considered.
- There is a strength in terms of understanding durability requirements and cost implications for different vocations.

Project strengths:

- ANL's project strength is the clear results from fuel cost and how different technologies may be compared. The model's flexibility to enable many different inputs is also a highlight.
- The project is conducting an overdue and much-needed assessment. The broad approach and inclusion of data sources are also strengths.
- TCO analysis coupled with detailed technology assessment is a strength, along with assessment of several vehicle types with their unique requirements.

Project weaknesses:

- There are no particular weaknesses here.
- The scope does not include an assessment of the fueling infrastructure factor (at scale, not infrastructure scattered here and there for both FCET and battery electric truck technology options). Availability of operational data from MD/HD truck fleets is very limited. Functionality of assessed technology options in a commercial setting appears to be factor that is currently not included.
- The sheer quantity of drivetrains, technology offers, and pricing leads to a dilution of the message and how to interpret results. It would be helpful to focus more on real-world use cases to clearly show what technologies and which use case scenarios are most likely to need one technology over another.

Recommendations for additions/deletions to project scope:

- The project should evaluate whether 100,000 units/year is the appropriate production volume for all the vehicle classes/categories included in this assessment because several of these vehicle classes have a lower realistic production volume (for example, transit buses see approximately one-tenth of this number annually). The "functionality in commercial application" factor should be included.
- The project should provide clear use cases when more data is available from the MD hydrogen fuel cell truck use: storage technology options, hydrogen pricing, and updated fuel cell technology options.
- Perhaps some consideration for climate and gradeability, if possible, could be included.

Project #TA-060: Offshore Wind to Hydrogen – Modeling, Analysis, Testing, and International Collaboration Work

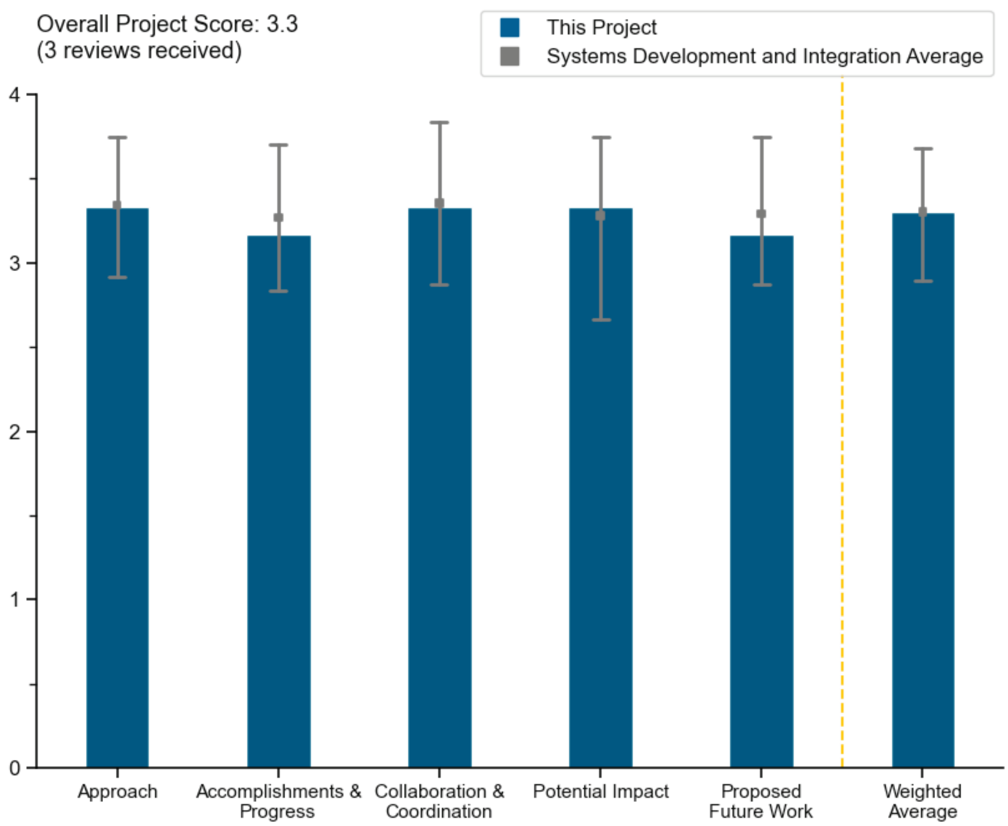
Genevieve Saur, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.15
Start and End Dates	1/1/2022
Partners/Collaborators	Netherlands Organization for Applied Scientific Research (TNO), Giner, Inc., GE Research, HYGRO, Plug Power Inc.
Barriers Addressed	• Renewable electricity generation integration • Capital cost • Footprint, size, and weight • Operations and maintenance • Control and safety

Project Goal and Brief Summary

A key barrier to industry adoption of hydrogen production using renewable energy sources is the uncertainty that the approach is economically viable. This project aims to better understand the economic viability of multiple system-level concepts to produce hydrogen from offshore wind, as well as test/validate control systems, in addition to electrolyzer performance under specific conditions for hydrogen production using electricity from offshore wind.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration projects.

Question 1: Approach to performing the work

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

- The approach is reasonable and sound. The project employs a combined approach of modeling, experimental demonstration in NREL's test facility, and international collaboration, which is very good. Additionally, the approach of examining three specific techno-economic analysis (TEA) case studies to cover the main configurational options is a very good choice.
- The project aims to better understand integration of control systems and electrolysis with offshore wind. Optimizing the systems will help researchers to gain a better understanding of the most effective control schemes, and the modeling work is well supported with real tests.
- The comparison of three different strategies for offshore wind power to hydrogen is interesting and relevant. Although the direct electrolysis of ocean water is unlikely, it could be an interesting side case, as there are somewhat promising research efforts in this area. It would be interesting to better understand why project partner TNO Norway (Toegepast Natuurwetenschappelijk Onderzoek) is involved, as the labs have good TEA capabilities. Presumably, TNO has some additional insights around offshore wind concepts.

Question 2: Accomplishments and progress

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

- So far, only modeling and preparation for the experimental portions of the project have been reported on. Capital cost results have been completed but not yet released. A top-level comparison between general TNO and NREL assumptions regarding specific cases has been made and is considered a worthwhile activity.
- Significant progress has been made in understanding cost-effectiveness in multiple scenarios and regions. Initial outputs have shown configurations that produce economic value through TEA. A test is needed for confirmation.
- The project is in the early stages, with no results presented. The reviewer is looking forward to the project outcomes.

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.

- Teaming with TNO is a solid choice. Partnering with Giner, Inc., General Electric (GE), and Plug Power Inc. for electrolyzer and wind turbine expertise significantly strengthens the project.
- There is very good collaboration between lab and industry. Outreach to the international community to look at regional impacts on the models provides significant value.
- The international exchange with TNO is interesting, and it is good to see there might be some good exchange of information with the European Union.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Off-shore wind represents a significant opportunity for low-cost renewable hydrogen. As there are no current offshore wind/electrolysis demonstrations, yet there is fundamental uncertainty regarding optimal configuration, this project is relevant and has high potential to aid understanding.
- This is a very interesting question to investigate. All sources for low-carbon hydrogen that can be brought to bear will be needed. The project is taking a likely avenue to relatively low-cost hydrogen, if carefully combined with electricity production and under the right conditions.
- Success here should provide greater insight into how system integration can be optimized for cost, resulting in broader deployment of the technology.

Question 5: Proposed future work

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

- The main future work task is conducting and analyzing the experimental results and is a high-value activity. The joint NREL–TNO paper is also a high-value activity.
- Proposed future work will continue to address issues identified and confirm the modeling with actual testing of the integrated systems.
- There are no real issues here. The project plan seems reasonable.

Project strengths:

- Teaming with TNO is a substantial strength. Combined modeling and testing in the NREL testbed is a strength. Evaluating multiple TEA case studies (in collaboration with TNO) is a strength. The list of key insights, options for reducing costs and uncertainty, and recommendations for improving the TEA are excellent.
- The project is researching a very interesting question, and the three production strategies seem well conceived.
- The project has strong collaboration with industry partners and the international community.

Project weaknesses:

- There could be a more explicit statement of the parameter that will be assessed (and modeled) as part of the experimental project, for instance, how response time is being measured (what the measurement is, exactly) and polarization curves. There should be more discussion of stack and system volume and whether it fits on an offshore platform.
- Overall project goals are a little unclear. Clarification is needed on the final objective functions/decision variables. The project seems focused mostly on operating expenses with some capital expense considerations but is pretty confined.

Recommendations for additions/deletions to project scope:

- Further analysis should be added to gauge whether the volume (and required stack power density) of the electrolysis system fits on an offshore platform. Low-cost, undersea hydrogen storage at a 40 m depth (to offset some of the pressure load [~bar] and reduce storage cost) is a good idea. Matching stack pressure to the storage depth is worth considering. Slide 22 refers to stating the cost estimation uncertainty for systems that do not yet exist, which is a worthy effort.
- The project should look at the internal rate of return for an offshore wind project and then see how the three hydrogen strategies impact that (positively or negatively) depending on the assumptions. The researchers should use "electricity only" as a baseline and see how hydrogen production moves the needle, instead of assuming the three hydrogen production cases. There is speculation that hydrogen production can improve the economics of offshore wind (at some hydrogen take-off price), but this project is a great opportunity to put a finer point on that (if it is not too much of an expansion of scope).

Project #TA-062: Validation of Interconnection and Interoperability of Grid-Forming Inverters Sourced by Hydrogen Technologies in View of 100% Renewable Microgrids

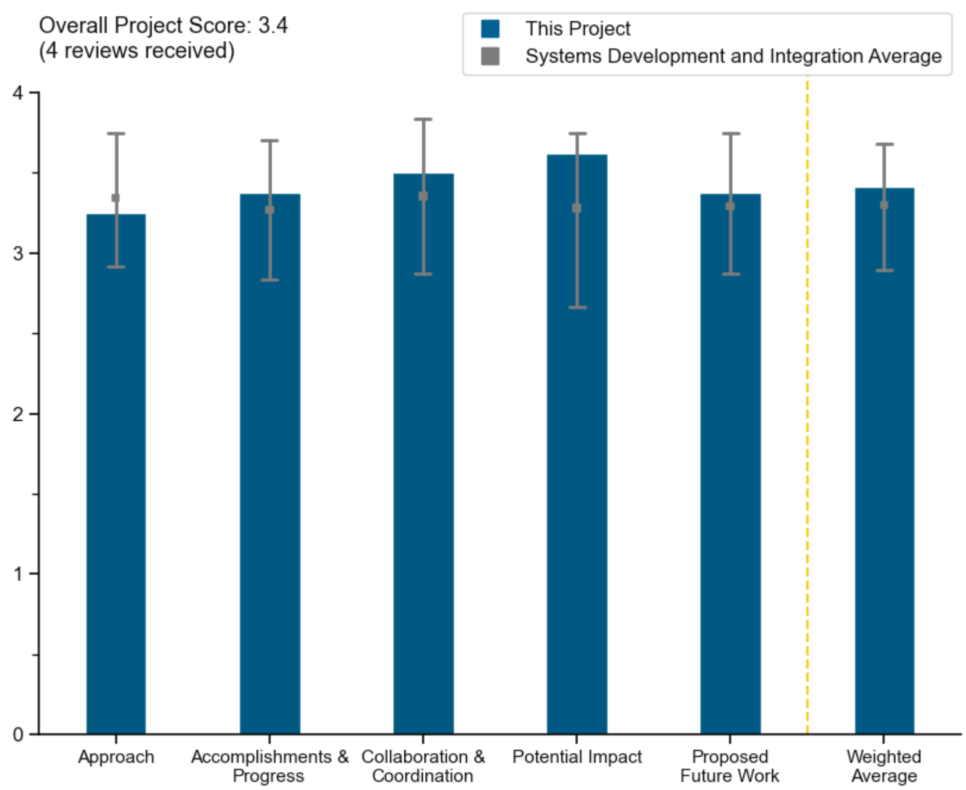
Kumaraguru Prabakar, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.16
Start and End Dates	1/1/2022–12/31/2024
Partners/Collaborators	Southern California Gas Company, University of California, Irvine
Barriers Addressed	• Intelligent electronics device capability description (ICD) file development and hosting in the public domain • First-of-its-kind power hardware-in-the-loop setup to run grid-forming inverter experiments • Complete power hardware-in-the-loop and controller hardware-in-the-loop integration with microgrid model • Complete test plan execution in hardware setup

Project Goal and Brief Summary

Grid-forming (GFM) inverters are increasingly important in distribution systems with microgrids. This project focuses on fuel-cell-coupled GFM inverters as potential assets. The project's goals include developing a testbed to evaluate updates to interconnection and interoperability requirements, leveraging existing assets for hardware-in-the-loop experiments, and accelerating industry adoption of GFM fuel cell inverters. The standardized sensing, operation, and control of these inverters will reduce installation costs and enable widespread adoption, making them an asset in distribution systems and microgrids. The project's outcomes will contribute to integrating hydrogen assets into the grid, reducing costs, and facilitating the market potential and scalability of GFM fuel cell inverters.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration 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 started in 2022 and will be completed in 2024. The project will develop a testbed to evaluate and document updates to interconnection and interoperability requirements for GFM fuel cell inverters. This project will also create a hardware-in-the-loop setup to run GFM inverter experiments. The plan is reasonable and doable.
- The project takes a logical approach. The team could leverage work done by fuel cell companies—such as Bloom Energy, FuelCell Energy, and Doosan NA—that have stationary fuel cell systems installed and have dealt with grid connection and interoperability issues.
- The approach is well defined and aims to provide recommendations for updates to existing standards. This will help to standardize operation and control, plus reduce smart grid integration cost.
- There was a discussion around direct current (DC) coupling storage (i.e., batteries) with the fuel cell on the same inverter, which seems like an excellent concept. However, the power hardware-in-the-loop (PHIL) experiments appear to include only a GFM inverter connected to a fuel cell stack. It is unclear whether there are any plans to incorporate energy storage on the DC-coupled side of the inverter for PHIL testing.

Question 2: Accomplishments and progress

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

- The team has completed Phase 1 of the project. The project executed a cooperative research and development agreement with Southern California Gas Company and a subcontract with the University of California, Irvine; completed the alpha version of interoperability codes; submitted an open-source software record and will make the technology available in the public domain after review; completed PHIL experiments with a GFM inverter; submitted a digest to the Institute of Electrical and Electronics Engineers conference to disseminate the methodology to run PHIL experiments with GFM inverters; and procured a microgrid controller to work with a Banshee microgrid model.
- Efforts appear to have been focused mostly on equipment procurement and installation. Hardware experiments were completed and shared with the community for test standardization.
- Draft interoperability codes were prepared and submitted. The project completed hardware-in-the-loop experiments and demonstrated a response of fuel cell to full load in <20 seconds.
- This project is about halfway through its intended duration, but costs incurred to date are less than 10%. It is unclear if this is in line with the expected budget.

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 includes the National Renewable Energy Laboratory, Southern California Gas Company, and the University of California, Irvine. This team can accomplish the goals laid out in the plan.
- Very good collaboration between the national lab, academics, and industry partners provides confidence that areas of test and exploration are well formed.
- It would be beneficial to have more collaboration with a grid operator, perhaps having a grid operator on the advisory board. Additional collaboration with fuel cell manufacturers/providers would be beneficial (Bloom Energy, Ballard Power Systems, Doosan NA, FuelCell Energy, Cummins, Inc., Plug Power Inc., etc.). Some of these have microgrid systems and systems that operate on the grid already.
- The partner list includes academic institutions, industrial organizations, and final end users but no inverter original equipment manufacturers. It is unclear whether there are any plans to discuss this effort with inverter manufacturers to ensure feasibility.

Question 4: Potential impact

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

- The efforts look to standardize test protocols and inform codes and standards. Output will inform manufacturers on how to optimize and integrate smart grids, with the intent of cost reductions. This standardization, along with development of codes for manufacturers to follow, reduces costs of system integration.
- Interoperability and interconnection costs can hinder adoption of new technologies. Current standards do not include fuel cells. Updating standards to include fuel cells will reduce installation costs and enable fuel cells to replace traditional generation on the grid.
- This project will propose updates to existing standards. If the proposed changes are accepted in these standards, the industry could be revolutionized, and these standards could break down the barriers for adoption.
- Inverter communication standardization is an important area, and this project appears to address this need well.

Question 5: Proposed future work

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

- Proposed future work will continue to address challenges and barriers. Standards will be made available for review and refinement, moving recommendations closer to final. Finalization of the controller integration will enable full testing of the experimental setup.
- The project will complete standards recommendations documentation and submit the document for review and dissemination in open-source. Interconnection is included. Proposing and updating the standards for integration should be the prime objective of this project.
- The proposed test plan appears to be sufficient.
- The open-source approach provides benefits.

Project strengths:

- This project incorporates several important relevant stakeholders required for GFM fuel cell inverter technology. The feedback from these industrial partners will be valuable in guiding the project. Being able to evaluate the response of these inverters in a microgrid simulation will provide good data on how the inverter would respond in real-world scenarios.
- Very strong collaboration ensures that setup, equipment, and test plans have been thoroughly vetted. This provides great confidence that the approach and results will have validity to the community.
- This is a very beneficial project, as standards are a major hurdle for integration.
- The project addresses important issues of grid connection and interoperability.

Project weaknesses:

- Incorporating feedback from inverter manufacturers would be valuable for better understanding how the proposed changes to the standards could be implemented.
- Collaboration with fuel cell companies is limited.

Recommendations for additions/deletions to project scope:

- DC coupling storage behind the GFM inverter would be valuable. The current PHIL allows for testing of alternating current (AC)-coupled storage, which is definitely valuable. The inclusion of DC-coupled storage may change some of the control paradigms around the fuel cell.
- The project should add collaborations with existing stationary fuel cell companies (Bloom Energy, FuelCell Energy, Doosan NA, Plug Power Inc., etc.).

Project #TA-065: Total Cost of Ownership Analysis of Hydrogen Fuel Cells in Off-Road Heavy-Duty Applications – Preliminary Results

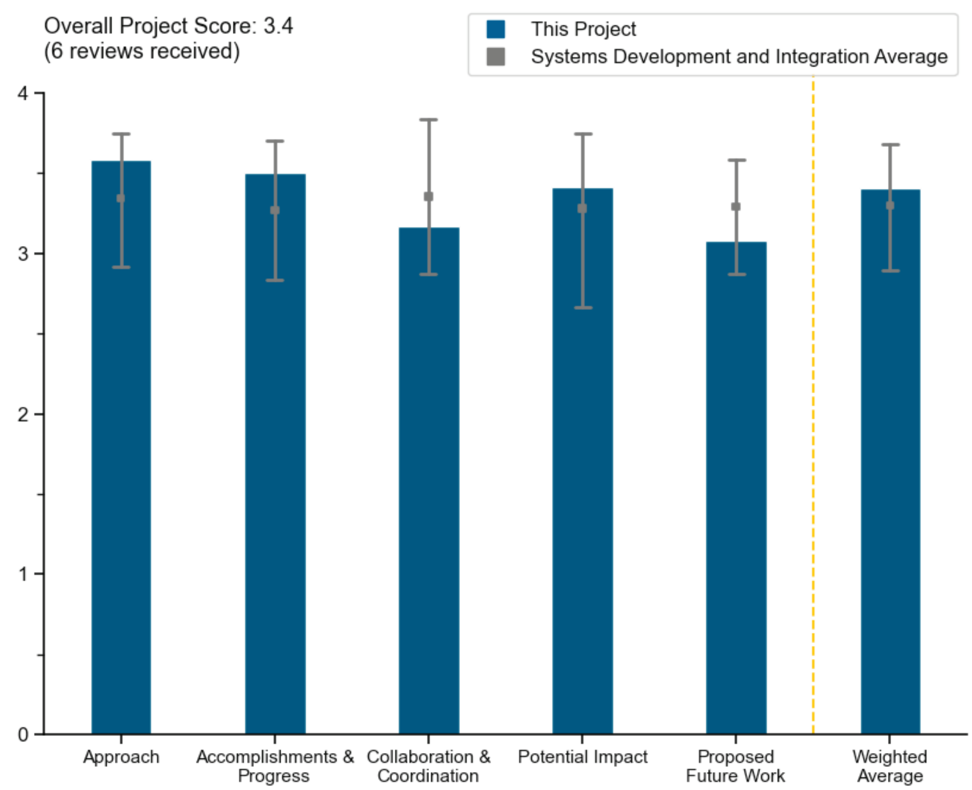
Rajesh Ahluwalia, Argonne National Laboratory

DOE Contract #	WBS 9.3.0.6
Start and End Dates	10/1/2020–9/30/2022
Partners/Collaborators	Collaborations (industrial companies contacted for feedback): AGCO Power, Caterpillar, CNH, Dawnbreaker, Empire Tractor, First Mode, Fortescue, John Deere, Komatsu, Volvo Trucks
Barriers Addressed	• System cost • Efficiency • Thermal management • Life cycle assessments

Project Goal and Brief Summary

Construction, mining, and agriculture equipment is the largest contributor to off-road greenhouse gas (GHG) emissions within the transportation sector. This project will determine the fuel cell and hydrogen storage performance needed to make fuel cells in off-road vehicles economically competitive with more commonly used technologies, such as diesel engines. Fuel cell systems being developed for heavy-duty trucks will be adapted for tractors, wheel loaders, and excavators; for example, systems will be resized for power requirements, and degradation will be reduced through voltage clipping. Researchers will determine the total cost of ownership (TCO), considering the uncertainties of critical powertrain design (e.g., degree of hybridization), parameters (e.g., vehicle miles traveled), and driving cycles. This project has the potential to pave the way for a green fuel alternative to power the nonroad sector.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Development and Integration projects.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach assumes a representative haul route and then evaluates the performance metrics of fuel-cell-powered hybrid electric haul trucks, which is reasonable. It is analogous to the use of urban and highway drive cycles to characterize the energy performance of passenger vehicles, because while use of a representative haul route will not exactly duplicate a specific scenario, it should have sufficient detail to permit the comparison of powertrain technologies. The presenter made a convincing argument that the one-dimensional model employed here is sufficient for capturing the essential features of drivetrain performance, in particular, the amount of fuel consumption, since that plays a significant role in determining the cost of ownership. The "simulate and compare" approach is appropriate here in part because the existing trucks already have hybrid electric powertrains, so the only changes are the replacement of the engine/rectifier/diesel storage with the fuel cell/power electronics/hydrogen storage, which is a well-bounded change. The use of the heat exchanger to place an upper bound on the size of the fuel cell system makes sense, given the relatively lower operating temperature of the fuel cell compared to the existing diesel engines.
- Argonne National Laboratory (ANL) showed an outstanding approach to the difficult challenge of developing a TCO model for off-road mining vehicles. There is a clear motivation for reducing GHG emissions from mining and showing how hydrogen fuel cells compare to conventional diesel powertrains at the scale required for large mining vehicles. ANL is incredibly detailed in the requirements and how they compare to fuel cell system status, ultimate goals, and current technology status. This shows where additional research and development is needed or what demonstrations should attempt to showcase. ANL showed a clear and concise approach in evaluating the hybrid power train, thermal performance, and liquid hydrogen storage required for equivalent performance.
- This is a comprehensive analysis based on thoughtful consideration of the issues for a fuel cell mining truck. Each aspect, vehicle, baseline diesel system, fuel cell, battery, heat rejection, and drive/duty cycle is defined with a focus on the key aspects.
- There is potential for the mining industry to adopt hydrogen for its equipment. This study is a great initial look into the conversion and can give insights for the industry.
- The project has a strong approach and knowledgeable principal investigator.
- The initial approach is acceptable overall. However, many assumptions are being made that need to be clearly stated. Fuel cell performance data models used are not representative of real-world fuel cells. Liquid hydrogen storage is being used without a validation that it will fit onto the vehicle used in the model. The methods used to hone in on a good system to model and baseline data capture are great and serve as a great start.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- ANL showed a clear accomplishment in down-selecting all aspects required for a comprehensive TCO assessment: technical equivalence, system configurations for hybrid fuel cells, and the fuel cell load-following system. The power demand is carefully chosen to meet all aspects of the drive cycle: grade, speed, and full power with regeneration accounting. This also highlighted the major challenge of rejecting heat in meeting the net power requirements. ANL provided an extensive comparison between the two systems and the system design rationale for exact kilowatts and kilowatt-hours required from the fuel cell or battery combination. The discussion for matching fuel cell durability and lifetime to battery capacity and degradation over a similar timeframe was a key result and accomplishment.
- Numerous accomplishments are cited, including definition of the market segment, consideration of duty cycle, heat rejection, and capital cost/TCO analysis.
- The project has already yielded useful conclusions regarding the suitability of hydrogen fuel cells for haul trucks from a cost perspective.
- The study gives a complete picture of TCO and will be used in the industry.

- The project shows favorable characteristics that fuel cells bring for mining applications.
- The data being produced to date is useful. However, more realistic modeling needs to be done based off fuel cell data in the real world.

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.

- ANL provided an outstanding list of collaboration partners, and it shows in the depth of detail in the TCO assumptions and the exact models of equipment under evaluation. Major players in mining equipment and mining operations were included in the comprehensive list of coordinating industrial companies.
- The group of collaborators is quite relevant to the subject matter and represents the industries that will be interested in the results. With these collaborators providing data, there is high confidence in the assumptions used in the analysis.
- While this is a fully ANL-internal analysis project, the ANL team was in discussions with numerous relevant industrial companies. This makes up for a lack of formal project partners.
- It would be helpful to understand more about collaborations with AGCO Power, Caterpillar, CNH Industrial, Dawnbreaker, Empire Tractor, First Mode, Fortescu, John Deere, Komatsu, and Volvo Trucks, including what inputs they provided and what impacts these key players had on the project.
- Several partners were contacted for feedback. However, no response was shown during the presentation. It was not clear how closely connected the project is to the various collaboration partners.
- The project seems to be relying on companies to supply feedback on the analysis, but those companies are not directly involved in the project.

Question 4: Potential impact

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

- This project has a very high relevance and impact. The results clearly show that fuel cell cost dominates the TCO cost and that a fuel-cell-only system will be lower-cost without the battery range extender model. The final output including the very high dependence on hydrogen cost shows how critical it is that DOE focus on cost reduction of hydrogen delivered to mining vehicles vs. business as usual with diesel fuel. A key slide was the tradeoff between fuel cell cost to price of hydrogen. There is a clear correlation between fuel cell cost targets and how important input fuel costs influence the overall comparison.
- The mining industry is a cross between the transportation sector and the hard-to-decarbonize sector. Hydrogen has the potential to bring renewable energy to this significant contributor. GHG reduction in this sector will also reduce the contribution of GHGs from other sectors, as all other materials are originally produced from mining. This project gives insight for leaders in the mining industry to confidently decide the path forward.
- This was an excellent project, with clear goals to provide information and data that can be used and discussed as a way to keep the conversations about hydrogen fuel cell use cases moving forward. The impact is high, and this project has use for more refined data modeling.
- The project provides strong relevance to Hydrogen Program goals because haul trucks are used in fleets that can be supported by centralized refueling infrastructure.
- The project provides strong impacts on future decisions for fuel cell powertrains in mining applications.
- The project makes the argument that nonroad is 20% of GHG emissions within the transportation sector, and construction, mining, and agriculture equipment is >50% of nonroad GHG emissions. However, mining vehicles of this type (100+ ton dump trucks) are likely not large GHG emitters. The team may be correct, but the argument is not convincing. That said, the TCO reduction of the fuel cell vehicle is significant and would have an impact on GHGs in this sector.

Question 5: Proposed future work

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

- The proposed work is to continue ANL's input to the Mission Innovation efforts and explore the cost of fueling infrastructure for off-road, heavy-duty applications. This will be a key aspect of the fuel cost inputs and will be very welcome to the stakeholder community.
- The proposed continuation to study the refueling infrastructure required to support haul trucks is the next logical step, given that the current work suggests hydrogen-fuel-cell-powered haul trucks are economically feasible.
- The project proposed to investigate refueling infrastructure for off-road, heavy-duty applications next. This is a logical extension of the current project. This is a reasonable topic.
- The project is completed, so there are no further tasks, but a willingness for further work in the area was expressed.
- The project has concluded; however, the presenter states that the team is open to continued support.
- Funding does not seem available for future work.

Project strengths:

- The project addressed a well-defined problem with relevant input data and a clear methodology. Results were straightforward and easy to interpret in a useful way. The project showed strong relevance to the goals of the Hydrogen Program because haul trucks are used in fleets that can be supported by centralized refueling infrastructure.
- The overall approach, methodical and logical execution of the analysis project, and inclusion of the TCO comparison are major project strengths. The thoroughness of the battery discharge/efficiency analysis and battery sizing is also a strength, as is the generation of a power use cycle from a postulated vehicle drive cycle.
- The major strength is the depth of detail and analytic capabilities demonstrated by ANL. Other major strengths are the close coordination examples shown by the comprehensive list of stakeholders.
- The project identifies critical assumptions in the analysis and lays out the needed results into charts that are relatively easy to understand.
- The project exhibited great initial set-up and down-select on the baseline technology. The project also had great overall analysis and comparison data generation.
- TCO modeling for fuel-cell-powered mine haul trucks was completed, and data was presented.

Project weaknesses:

- The radiator/thermal system is based on the same (presumably frontal) area of the existing diesel truck. This is a reasonable starting assumption, but it may be that additional area/radiator size is possible. Truck original equipment manufacturers (Class 8) state that with prudent design, they can achieve a larger radiator area. A larger area may be obtainable on these large off-road trucks, too. On Slide 6, the $/kW values for various powertrain components do not have a basis shown. The values seem high, so lacking a specification of their cost basis is a particular weakness. In addition, it appears that the power cycle was derived from the vehicle duty cycle. Presumably, this is because actual power/drive cycle data was not available. Not using actual data is a weakness. In a back slide, it is stated that costs are based on a manufacturing volume assumption of 1,000 vehicles/year. Burying this assumption and not defending its validity is a weakness. Finally, the TCO comparison is very good overall, but there should be a diesel future to compare against the fuel cell ultimate. The diesel trucks will keep improving, just as the fuel cell vehicle is expected to improve.
- A sensitivity analysis should be completed (if one has not been done already) to understand how changes in the standard haul route influence the battery sizing and other characteristics of the fuel cell powertrain. It would be good to understand if, for example, the battery size varies linearly with the climb length and steepness, or if there is a "knee in the curve"—and at some critical value where a technological limitation comes into play.

- The results were presented in academic journals and to working groups, but an article in an appropriate publication for the mining industry would be of benefit.
- The team did not explain how this data is being used in industry or how further investigation could affect project results.
- The project is not representative of real-world fuel cell performance data and hydrogen storage volume requirements.

Recommendations for additions/deletions to project scope:

- Real duty and power draw data should be added to the analysis, and a future diesel truck should be added to the TCO comparison. The project should document some of the cost assumptions for the powertrain components.
- The project should add realistic fuel cell performance models and size the hydrogen storage that would realistically fit on the chosen platform. This data would be important to see how far the current technology is from meeting the required performance metrics of the baseline technology.
- Further communication to the mining industry could prove to be the difference between the results getting used in the industry and just staying in academic publications.
- The project is over, but it would be very interesting, pending industry interest, to explore operation at an altitude where cathode humidification is not available from ambient air.