Systems Development and Integration – 2024

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 further guide RD&D conducted through the U.S. Department of Energy 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 relevant to the H2@Scale vision, particularly on high-impact end uses in 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 and resilience, demonstrate dynamic response to match grid demands and renewable power profiles, support market penetration of renewable energy systems such as wind and solar, and provide additional revenue streams for nuclear power plants.
- Chemical and industrial processes, with a focus on decarbonizing hard-to-abate 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 and support environmental justice by helping to build a clean economy.
- Transportation, which includes medium- and heavy-duty trucks and ultra-heavy-duty applications such as maritime, rail, off-road equipment, and other applications requiring significant power, range, and up-time. The focus for heavy-duty transportation applications is to demonstrate and validate the fuel cell and onboard hydrogen storage system durability and performance under real-world conditions. Projects also demonstrate and validate high-flow hydrogen fueling to support these transportation modes. Analysis is 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 validate research and development (R&D) innovations at a systems level under real-world conditions, determine gaps to help guide R&D programs, identify and demonstrate new and promising integrated energy systems for various end uses of clean hydrogen, and inform larger-scale demonstration and deployment programs.

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.
- Develop 10 MW low- and high-temperature electrolysis validation facilities by 2027.
- Demonstrate at least six integrated electrolyzer systems by 2025 with a combined total capacity greater than 3 MW, using at least two different electrical generation sources and targeting at least three different hydrogen end-use applications.
- Validate 90% efficiency (based on high heating value of hydrogen) for high-temperature electrolysis systems operating at nuclear plants utilizing onsite waste thermal energy.
- Test a 250 kW high-temperature electrolysis system using a fully emulated nuclear integrated test stand by 2025.
- Validate an integrated 1 MW (minimum) hydrogen fuel cell system at a real-world data center by 2024.

Chemical and Industrial Processes

- By 2025, complete a location-specific reference design in which hydrogen can be produced at less than $2/kg for an off-grid behind-the-meter renewable power-to-hydrogen integrated energy system that includes an industrial end-use application such as steel or ammonia.
- Demonstrate approaches to integrate clean hydrogen to decarbonize iron/steelmaking at a scale of at least 1 metric ton/week, with a path to capacities of at least 5,000 metric tons/day to meet the requirements of existing steel mills by 2024.
- By 2025, show the technical and economic feasibility of the thermal and process integration between a solid oxide electrolysis cell module and a direct reduced iron furnace with an electric-to-hydrogen production efficiency of <35 kWh/kg H_2.
- Validate emerging concepts for integration with industrial processes for synthetic fuels and chemicals by 2025.
- Complete pre-FEED (front-end engineering design) studies for the integration of clean hydrogen in hard-to-decarbonize industrial processes by 2027 to allow industry to develop a more detailed understanding of cost, performance, and emissions.

Transportation

- Complete prototype commissioning of multiple Class 4–8 fuel cell electric trucks through the SuperTruck 3 program to demonstrate how a substantial reduction of 75% or greater in greenhouse gas emissions and local pollutants can be achieved relative to diesel-equivalent trucks by 2028.
- Develop and demonstrate fuel cell systems capable of achieving 25,000-hour durability and 68% peak efficiency for heavy-duty truck applications.
- Deploy scalable hydrogen fueling stations of the future to support early fleet markets, such as heavy-duty trucks and buses capable of 8–10 kg H_2/min (average) fueling by 2029.
- Complete an interstate hydrogen fueling corridor study in collaboration with the Vehicle Technologies Office by 2025.
- 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, off-road mining).

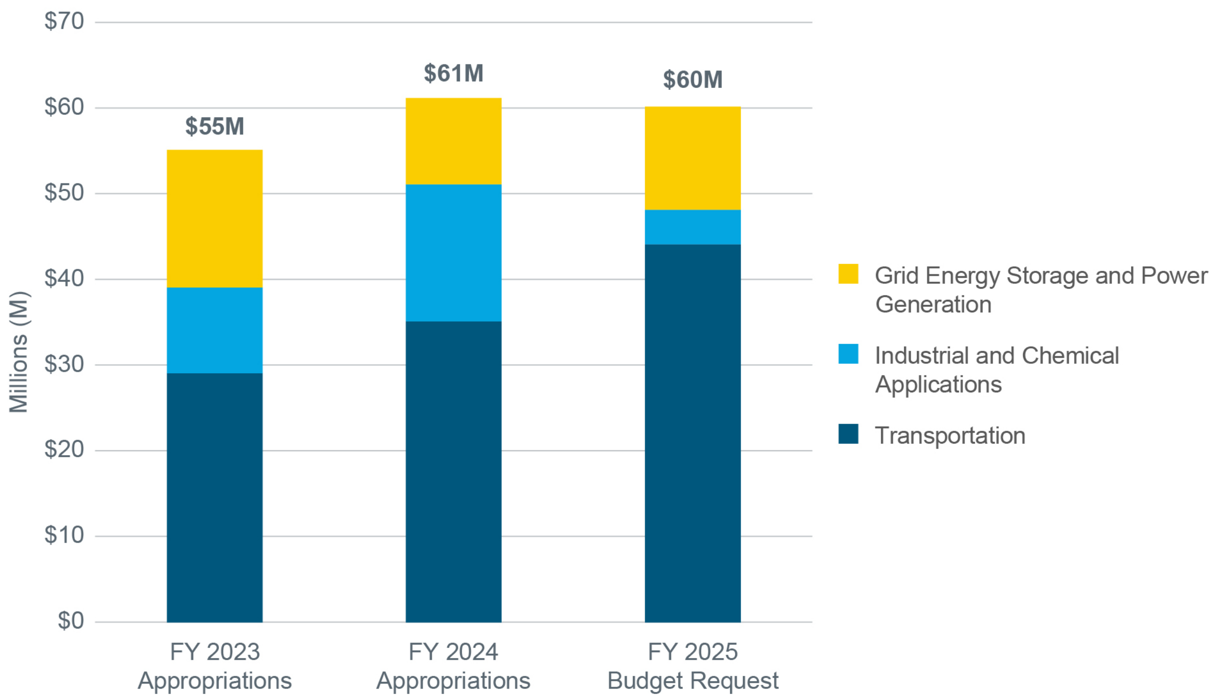
- By 2028, validate technical and economic performance of hydrogen and fuel cell integration in offroad applications.
- Demonstrate zero-emissions cargo movement at ports using clean hydrogen by 2030.

Budget

The Fiscal Year (FY) 2024 appropriation for the SDI subprogram was $61 million. Funding for industrial and chemical applications focused on decarbonizing iron and steel and on pre-FEED studies to integrate clean hydrogen into industrial processes. Transportation funding focused on SuperTruck 3 demonstrations, heavy-duty modular hydrogen fueling stations of the future, port equipment, and fuel cell system testing and validation. Funding for grid energy storage and power generation focused on high-temperature electrolyzer validation and RD&D for renewables- and nuclear-to-hydrogen.

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 (H2Hubs). The SDI subprogram aims to fund first-of-a-kind hydrogen demonstrations that will help de-risk technologies that will eventually be incorporated into the H2Hubs.

The FY 2025 budget request is $65 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 2024 Annual Merit Review, 36 projects funded by the SDI subprogram were presented, and 23 were reviewed (a breakdown of number of projects reviewed by budget category is shown in the table on the right). The reviewed projects received scores ranging from 2.6 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 23 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	12
Industrial and Chemical Applications	2
Transportation	9

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

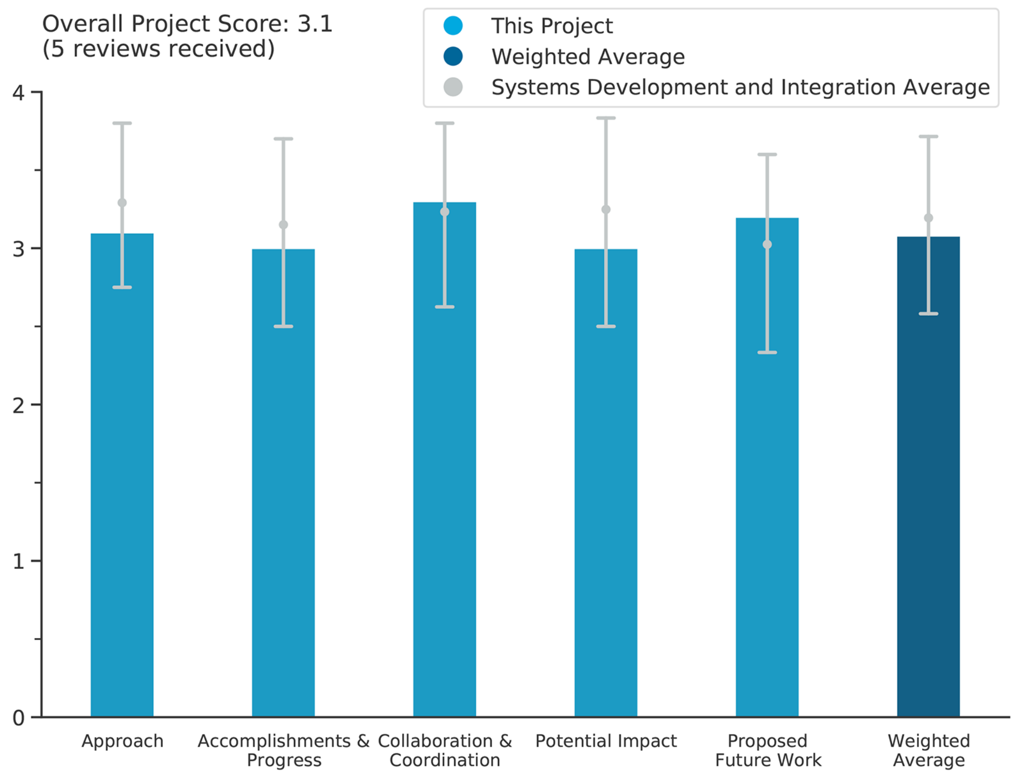
Jennifer King, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.23
Start and End Dates	8/1/2022–9/30/25
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 • Target systems that reduce costs 10%–20+% by 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



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 approach using multiple case scenarios is good and gives a well-balanced evaluation. Fossil-generated hydrogen through steam methane reforming, grid-connected hydrogen generation from electrolysis, and renewable energy to create green hydrogen covers relevant scenarios for future use. The incorporation of nationwide integration data and real renewable input from regional renewable offshore wind adds robustness to the work.
- The approach is excellent in that national labs should be exploring the edges of technology space, including industry impacts and designs as we transition to a renewables-heavy grid. However, industry impacts are generally believed to be significant, owing to the redesign that would be necessary around already optimized processes. Replacing baseload energy with intermittent energy may require significant storage of intermediates. This should focus on the technology pathway that would be used and not assume that a DOE target Shot will be met, let alone two of them.
- The project objectives are good. A more detailed breakdown of operation and maintenance (O&M) costs for onshore vs. offshore systems would be helpful. It would help to clarify the hydrogen produced vs. hydrogen delivered and their relevant cost targets. The project is focused on $1/kg H_2 produced, but it is not clear what the cost target is for hydrogen delivered.
- The goals and objectives were well-communicated and -understood by the team, including diversity, equity, and inclusion work.
- The overall approach makes sense.

Question 2: Accomplishments and progress

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

- Overall progress has been good, with milestones being met. Analysis shows scenarios and pathways to achieve hydrogen costs that meet Hydrogen Shot targets.
- Significant progress is noted, as the project is now in a position to work on green steel.
- The project is accomplishing the goals well. However, the team may need to consider some adjustment to the goalposts and tasks. Focusing on a specific hydrogen cost is fine, but it should be tied back to the end use and the cost needed to make e-ammonia or e-steel viable.
- The work shows that the cost of delivered hydrogen without the Inflation Reduction Act is greater than $5/kg. More explanation is needed on how this work (integration, shared components) exploits synergies and brings costs down. The team should include some best estimates from industry looking 10 years out and compare this to this body of work, e.g., major gas supplier X quotes that a realistic levelized cost of hydrogen (LCOH) delivered is $7/kg and includes these assumptions. This work shows that by doing x, y, and z, you can get to $5/kg.
- The total project costs and project end date should be included in the overview slide.

Question 3: Collaboration and coordination

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

- There is good use of national labs to provide input to the analysis. There is very good use of industry advisors to inform work and verify the approach to provide confidence in the assessment.
- The project has good cross-sector collaboration and a broad base of national lab participation.
- This rating could be excellent, but it would be helpful to understand this this collaboration a bit better, if there is an opportunity to highlight this more in the future.
- The work is done mostly by national labs, and there is an industrial advisory board. On the end users, there are variety of organizations, a steel maker, a university, a research institute, and an integrated oil major. For this project, having a steel maker and an oil major definitely helps. Perhaps an ammonia producer could be added.
- It is unclear what the role of the industrial advisory board is and how it will impact/guide the project.

Question 4: Potential impact

This project was rated **3.0** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The efforts undertaken provide great insight as to the scenarios that will provide a pathway to meeting cost targets for hydrogen generation. The cases show feasibility of off-grid scenarios to be cost-competitive with on-grid applications. This creates a roadmap for deploying technology in the most cost-effective way.
- This project is very relevant; however, its impact will be driven by both the technology development and whether the enabling technology achieves significant cost reduction (i.e., progress toward target Shot). Also, if Shots are achieved, the technology may be used in other ways. For example, if the Wind Shot is achieved, utilities may deploy wind rather than that wind being available behind the meter (BTM).
- While the project aligns with the Hydrogen Program's goals and objectives, the work shown here makes it clear that no locations can achieve $1/kg without policy credits. Perhaps there is a way to achieve lower production or delivery costs. Perhaps this is reality. If so, the project should highlight key areas for further work to achieve lower production and delivery costs.
- The project is aligned with DOE goals and objectives. There could be more to consider beyond the goals and objectives with this work.
- It is not clear how the nationwide analysis is reflected in the onshore/offshore wind evaluations. The cost differences between onshore and offshore are very small. It would be worthwhile to identify the breakdown in costs to identify potential cost savings (e.g., if O&M is higher for offshore vs. onshore).

Question 5: Proposed future work

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

- The proposed future work of a demonstration is reasonable, provided that the aforementioned approaches and relevance are addressed.
- The project plans are building upon past work, and there are clear plans going forward. There could be additional things to consider.
- The next phase of conceptual work will focus on the scenarios that show promise for meeting cost goals. Efforts will inform a potential demonstration at Advanced Research on Integrated Energy Systems (ARIES) to validate analysis with real data.
- It is not clear how the co-location and integrated design details work or where the benefits exist. Additional details on the 10 MW design and integration at ARIES would provide clues on how this advances the technology.
- It is not clear if the expansion effort is able to happen or what the cost requirements would be.

Project strengths:

- This is a five-lab partnership project that targets two important industries (steelmaking and ammonia) at the gigawatt scale. Each lab contributes certain expertise and knowledge to tackling the Hydrogen Shot and Floating Offshore Wind Shot. There is an industrial advisory board and a variety of different people working together. The project seeks to integrate and find synergies across the different technologies employed.
- This is great work, looking at opportunities for wind-to-hydrogen production with regional-specific cases. It is interesting seeing that the $1/kg goal is very difficult to achieve and that the Gulf Coast is almost a clear winner, based on storage opportunities.
- The collaborations between academics, labs, and industry are very robust. This provides significant confidence in the work done here.
- There is good comparison between different electrolyzer configurations and the impact from design considerations.
- The project addresses technology development that could be important in a deep decarbonization transition.

Project weaknesses:

- No weaknesses were identified.
- At least in this year’s presentation, not much was discussed on e-ammonia or e-steel economics. It left the reviewer questioning the LCOH needed for these applications. This was answered at a high level during the question-and-answer session, but future presentations should start with this to justify the LCOH target.
- From the material and oral presentation, it is hard to understand what synergies were found and whether this was just an integration of different pieces at the best estimated costs. Without any incentives, it looks like we are far from achieving a reasonable delivered hydrogen cost number.
- The proposed scenario of very-low-cost renewables available BTM leading to redesign of industrial processes is highly speculative.
- The plans for a 10 MW demonstration are not well-defined. It is not clear if this aspect will be possible.

Recommendations for additions/deletions to project scope:

- The demonstration at the National Renewable Energy Laboratory captures onshore-type technology. Perhaps there is another site where one can demo offshore-type technology at a reasonable cost.
- The cases considered did not necessarily seem to be chosen based on proximity to steel or ammonia industries today. This should be considered for future scenarios.
- A more detailed breakdown for the onshore and offshore costs to identify O&M differences is suggested.

Project #SDI-002: Hydrogen Microgrid in Underserved Communities

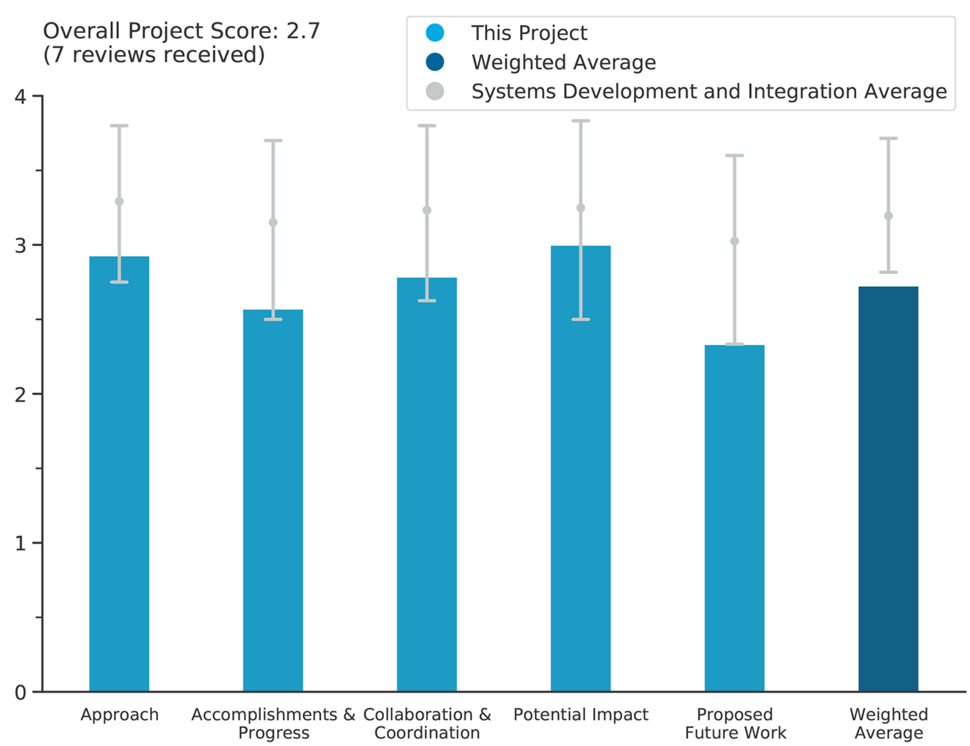
Kumaraguru Prabakar, National Renewable Energy Laboratory

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	• Conduct 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



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 good: develop a model and run analysis for determining optimal sizing of a fuel cell, electrolyzer, and storage to provide a fully renewable microgrid. Cases show the combination of renewable assets needed to provide extended resilience.
- The grid modeling tools will serve a useful purpose for co-optimizing the hardware selections for microgrids. The lab study is also demonstrating the controller effectively.
- It was nice to see progress with HIL at the lab. However, no movement with site development means that this is not likely to be delivered. No clear direction was stated as to how this will be turned around or what alternative implementation plans might be—presumably this was not called out for this project—but it would have been nice to have a slide showing how this could benefit the community of Borrego Springs.
- The overall concept and approach of this work is reasonable; however, perhaps the project should focus on the model and process optimization, rather than hardware deployment. The proposed scale is small, and it is not clear that such a scale would realistically mimic real-world systems.
- It is unclear whether there was an upfront understanding for this project about how limiting the existing 100% renewable microgrid system was when combined with available budget to achieve the end goal of increased resilience capability (and generating power for electrolysis to produce and compress hydrogen for later power generation). It is also unclear what the approach was for the lab demonstration and field deployment components of the project (only the approach for analysis was presented).
- Optimal sizing of assets for a microgrid operation is important, but the project could benefit from trying to incorporate stacked use cases beyond outage support (i.e., grid-connected operations).
- This project has a high budget. A demonstration was proposed, but no demonstration has started. The project budget utilization is low, and project completion is not satisfactory.

Question 2: Accomplishments and progress

This project was rated **2.6** for its accomplishments and progress toward overall project and DOE goals.

- Good progress was made toward goals.
- Overall progress is good. Scenarios were developed to show fully renewable microgrid configuration. Demonstration is at risk since hydrogen asset deployment for the demonstration has been abandoned. Verification of the model will go incomplete.
- The analysis and software tasks are progressing well. Unfortunately, the main hardware installations for the project are in limbo because the utility backed out. It is not yet clear how the project will be completed.
- The presentation did not clearly indicate what the accomplishments were. Progress in that assessment resulted in a number of scenarios, which provided sufficient information for San Diego Gas & Electric Company (SDG&E) to make a decision to pull out. It was unclear whether the focus was on zero-emissions power backup or something else.
- Previous comments were made about clearly described tasks and subtasks. In this update, it became clear that there were issues with costs. Actual field deployment will take more time and money. No clear path was presented for how this will move forward or evolve, since the field deployment will not take place.
- The project does not have a clear plan or has not made clear where the fuel cell or the electrolyzer was obtained. The three-year project has a budget of $4,674,000 but has spent only $823,000 so far. The project will be ending in August 2024. There is no real system demonstration.
- The loss of SDG&E will have significant impact on the project's ability to complete its stated objectives.

Question 3: Collaboration and coordination

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

- Support from the utility industry demonstrates responsiveness of lab collaboration.

- Collaboration with the controller supplier appears to be closely aligned. It is not clear what happened with the utility partner.
- The project has a good team, including NREL, SDG&E (field deployment lead), and PXiSE Energy Solutions (microgrid controller vendor). The subcontractor's contributions are not clear.
- Most of the content presented was developed by the National Renewable Energy Laboratory (NREL). It was not clear how much coordination and collaboration there was with SDG&E. "SDG&E has decided not to continue to pursue the installation of hydrogen assets in Borrego Springs." There should be some ownership/collaboration with this decision from the lead, but this comes across as SDG&E's sole decision.
- Collaborations appear to be adequate, but the key partner, SDG&E, has abandoned key components of the demonstration, putting project completion at risk. A new partner to complete the deployment of hydrogen assets should be identified, or an alternative approach should be considered. Inclusion of additional industry partners to verify the approach would add confidence in the model.
- SDG&E was the main partner, with PXiSE Energy Solutions as a subcontractor to the main partner. Collaboration is challenging if the main partner pulls out on the demonstration site.
- The involvement of SDG&E is not clear. Without the demonstration effort, the project may not be able to validate the approach.

Question 4: Potential impact

This project was rated **3.0** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Optimizing the mix of photovoltaic, battery, and hydrogen is important for designing hydrogen systems for microgrid applications. It would be good to determine how grid-following assets operate within a microgrid with a fuel cell as the primary grid-forming asset.
- If carried out as intended, the project will be an important demonstration of microgrid possibility. It is strongly recommended that DOE find an alternate site for the final deliverable.
- This is a project that could have significant impact for the Hydrogen Program, the local community, and others (vendors, utilities, and decision makers) in this area.
- The work done on creating models and running scenarios shows a pathway to microgrid resilience. The apparent inability to complete the full scope of work through demonstration will reduce confidence in scenarios and the model if they cannot be validated through real data.
- Lab demonstration results could have provided valuable information. It is unclear what the main limiting factor was toward sizing the equipment that resulted in the one-hour backup using hydrogen.
- The project aligns with its goals, but it is not clear that the demonstrating model will result in advancement, especially with uncertain project partner funding.
- Because of the slow progress of this project, its impact is not great. However, if successful, it would be very meaningful for other developers looking to build larger microgrids.

Question 5: Proposed future work

This project was rated **2.3** for effective and logical planning.

- The plans outlined based on analysis and lab experiments are within the scope of the lab's abilities and control.
- Finishing the analysis portion of the project and wrap-up is recommended; there are many lessons learned to be shared.
- The future work includes the following: (1) complete the development of hydrogen capabilities in REopt, (2) complete the review and validation of the hydrogen energy storage system model developed in REopt so the model can be made publicly available, and (3) prepare the final report for the overall Borrego Springs analysis. The project has much unspent funding. It is unclear why the project will not complete the demonstration with the expansion.

- The proposed future work between the lab and the controller partner is reasonable and would provide reasonable closure to the project. However, it would be greatly preferable to see some kind of demonstration from the project.
- The loss of SDG&E will have significant impact on the project's ability to complete its stated objectives. Finishing the project with simulations helps provide some additional value.
- Future work does not adequately discuss the mitigation plans to resolve the issues around deployment of hydrogen assets to validate the model and scenarios.

Project strengths:

- The major goals and objectives of the project are to implement, characterize, and analyze. Project strengths are the advanced hydrogen distributed energy resources and controls toward a 100% renewable Borrego Springs microgrid. The project does well on the characterize and analyze objectives.
- The modeling work and scenarios developed appear to show a path to microgrid resilience. The proposed journal article, once published, will inform others on how to approach this type of integrated renewable microgrid.
- The project strengths to date are in the analysis and modeling, which has been used to optimize system sizes for a given installation.
- Some techno-economic analysis work is insightful. A good project team was supposed to deliver great progress.
- Sizing of hydrogen assets for microgrid applications is an important area.
- A project strength is the detailed model for the parts that were considered.
- A strength of the project is the proposed initial project demonstration portion.

Project weaknesses:

- The main weakness is the uncertainty in the demonstration portion. The controller is being used with the Energy Systems Integration Facility in a separate project so that the development work can be leveraged.
- The loss of the SDG&E demonstration site prevents the ability for real-world operational testing of the hydrogen microgrid.
- While the project had budget and proposed leveraging of SDG&E funding scope, there are no plans for onsite implementation because of the higher costs of implementation.
- The final phase of deployment is needed to validate the model and scenarios. This would help to refine the model and get convergence against real-world data, as well as tune the scenarios.
- The project partner is limiting the size of the microgrid and power production tied to the Borrego Springs site.
- The project did not consider expanding hydrogen storage to add duration.
- The project has slow progress, with significantly lower budget spending.

Recommendations for additions/deletions to project scope:

- Power HIL testing may provide some value, particularly if the Borrego Springs load and generating assets could be simulated.
- Some level of demonstration based on the initial intent should be performed with a different utility partner if Borrego Springs is no longer an option.
- Instead of abandoning deployment, it is recommended that the project look for willing partners to complete the scope or engage industry to consider siting equipment through either donation or cost share.
- It is recommended that the project be extended to complete the field demonstration, if possible.
- Some additional comments and information from SDG&E would be helpful for understanding the challenges of implementation in the real world.
- There are no scope recommendations, considering this project will be wrapped up with SDG&E's decision not to move forward with the demonstration component.

Project #SDI-006: High-Temperature Electrolyzer Megawatt-Scale Test Facility

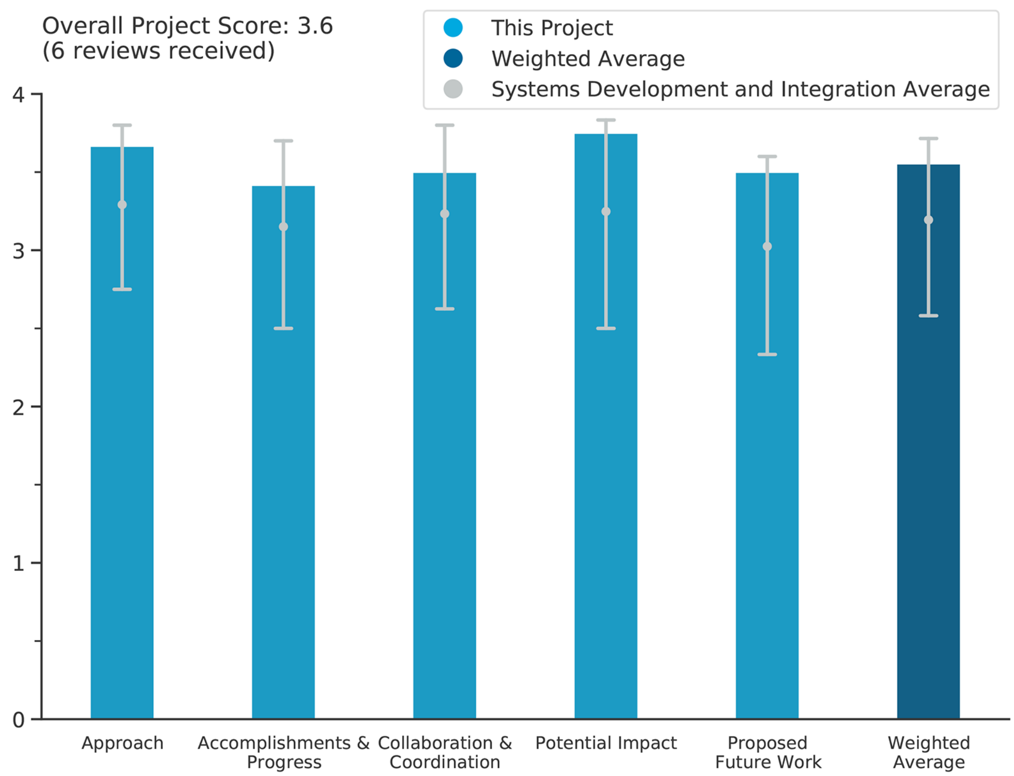
Richard Boardman, Idaho National Laboratory

DOE Contract #	7.2.9.25
Start and End Dates	7/20/2022
Partners/Collaborators	Amentum, DOE Office of Nuclear Energy
Barriers Addressed	• Commercial-scale thermal integration • Dynamic system-wide operations • New modes of operation—not yet proven

Project Goal and Brief Summary

The project aims to establish a test facility to validate the performance and reliability of high-temperature electrolyzer (HTE) systems at a megawatt scale. Moreover, the project seeks to integrate HTE systems with nuclear, geothermal, and industrial heat sources to demonstrate efficient hydrogen production, as well as support the deployment of HTE technology by providing critical data for commercial-scale projects and reducing technical, economic, and regulatory risks. Through this work, the project hopes to accelerate the commercialization of HTE systems, enable large-scale hydrogen, and demonstrate new industrial uses of 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 **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- It is very encouraging to see Idaho National Laboratory (INL) providing a stack/system testing platform for various vendors and companies eager to further develop/characterize/investigate their technologies. The presentation addresses the major objectives well, and the team is doing excellent work. The reviewer looks forward to seeing data from all tests and comparisons across the data from various vendors (to the extent possible). The reviewer challenges INL to consider incorporating internal research and development (R&D) technology to be tested in stacks and systems and working with vendors to incorporate such technology in commercial stacks as soon as possible to help guide improvements on the most important stack/system parameters. Understanding that there was limited time to share the project updates and that possibly some of the following questions are already being addressed but were not presented because of the allocated presentation time, it would be valuable for the team to address the following few topics via responses or in one or two slides during the next project update:
    - The team is asked to elaborate on the permitting status/progress of water rights and whether they are fully secured, wastewater discharge permitting and where discharged water will go, and air permitting for possible venting/flaring.
    - The team is asked to elaborate on how INL will ensure the absence of any bias/unfair allocation of time for customer/vendor/technology sign-ups for evaluation and testing. It is not clear how this process will work in practice. For example, it is not clear (1) whether it is first-come, first-served—and if so, whether there will be any entry criteria to be eligible for testing; (2) what benefit it will add to the common knowledge of the community if the vendor/customer technology is not funded via public grants (and thus is proprietary); and (3) whether there will be criteria requiring that testing/durability data must be disclosed to the community to be eligible for such tests—and, if such criteria have not been considered, why not.
    - Regarding the levelized cost of hydrogen (LCOH) for the HTE slide, the financial LCOH walk is interesting. Understanding that the project is in an early stage, the team should consider calling major vendors; engineering, procurement, and construction firms; and developers to understand the true costs and why the DOE goals to achieve \$2/kg by 2026 and \$1/kg by 2030 are far-fetched. It is imperative to set realistic expectations for the community to accelerate project deployment. For instance, it would be helpful to know (1) whether the assumed \$30/MWh electricity cost is a basis number, (2) what the cost of delivered energy is, including transmission and distribution, and (3) if \$30/MWh is the total energy cost, where such projects would need to be located, as they are certainly not in the United States.
    - Dynamic operation was called out on slide 41 as a path to reducing the cost of electricity. It seems that would mean more cycling and lower utilization (lower-carbon fiber) and thus the need to oversize the equipment.
- Overall, this project is great work, and future progress at INL is eagerly awaited. The team is asked to consider these questions and recommendations as a best attempt to help accelerate successful development of a solid oxide electrolysis cell (SOEC) testing platform at INL.
- This project is an extremely important Hydrogen and Fuel Cell Technologies Office (HFTO) effort to establish a large-scale SOEC demonstration facility in the United States. There are multiple demonstration projects in Europe, but so far, the United States has lacked this capability. Multiple demonstrations on a large scale would not only add credibility to HTE technology but also would provide a ground for the technology improvements via different lessons learned, balance of plant (BOP) and balance of systems, system integration optimization, and more realistic cost and techno-economic analyses.
- The overall project approach is sound, and planned work is relevant for increasing the scale of research test capability to de-risk larger-scale technology deployments. The project seems to account for major connection points and risks. More specifics for a pathway to nuclear heat integration would have been good to see; however, it was discussed verbally at a high level, and it is understandably tough to predict timing because of the safety assessments required. The approach of building the hydrogen capability first, using a steam generation system, and then moving toward future nuclear heat integration makes sense for de-

risking the timeline. The presentation provided sufficient details on the safety review process; however, slightly more detail on who would be involved in terms of expertise, etc., would be helpful.

- The use of nuclear heat in water electrolysis is an untapped resource that can reduce electricity consumption; this is a critical barrier in water/steam electrolyzers. Engaging the SOEC supply chain is a good strategy. Benchmarking with a low-temperature proton exchange membrane electrolyzer will provide true benefits of steam electrolyzers. Nuclear Regulatory Commission (NRC) licensing requirements are a critical need; engaging the NRC early in the game provides valuable guidance for preparing for the license application process.
- This is a world-class project with an excellent approach. Under SDI-006, INL is building a 20 MW HTE (0–20 psig) test facility in 2026. The cost is $20 million. INL has its own 25 MW microgrid. It includes wind and solar and will eventually include nuclear. INL is building a digital twin for testing and training.
- The project objectives are well-defined and critical barriers are identified. No diversity, equity, inclusion, and accessibility plan or community benefits plan is required.

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 on track for completion with the required capabilities. Design progress is good. Project risks are being retired, and mitigation plans are being executed as appropriate. Addressing risk factors is moving well. There is high impact for decarbonization, future R&D, and economic commercial applications. The work provides key data for probabilistic risk assessment and Hydrogen Shot progress. The project is a driver for industry to adopt advanced reactors. The project has staged hydrogen offtakers to match production ramp-up.
- The project's progress thus far is very good. The major design work has been completed, major long-lead equipment has been purchased, and some major construction for preparation of the site (concrete and steam generator building) has been completed. The safety analysis appears to be planned at the appropriate stage—during design execution.
- INL is considering multiple potential technical scenarios for water purification, oxygen collection, and onsite chemical production. BOP architecture and layout are based on added size and use flexibility (multiple size stack configurations, from 1 to 6 MW, could be tested) and containerization of sub-systems. The project is conducting a thorough hazard analysis and safety reviews.
- Engineering design of the facility has progressed well on multiple fronts toward the overall goal.
- The project is making excellent, orderly progress.

Question 3: Collaboration and coordination

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

- The project's collaboration effort is outstanding. Multiple vendors are bringing stacks onsite. The project is building multiple facilities and infrastructure. The laboratory vision is impressive, tying numerous projects together into a single vision, from small validations to full distributed grid support and nuclear reactor integration.
- Collaboration is crucial in nuclear heat application for electrolysis. The project has a good strategy and engagement of stakeholders. Leveraging National Renewable Energy Laboratory's Advanced Research on Integrated Energy Systems (ARIES) efforts is an excellent opportunity. Engaging utilities, reactor owners, and supply chain is well done.
- For an infrastructure build of this type, the project has outlined appropriate planning for increasing collaboration over the coming years when supporting future research activities.
- INL is working with many SOEC providers.
- It is unclear how the SOEC system will be fabricated and delivered on schedule by the manufacturer.

Question 4: Potential impact

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

- Testing capability of this size and flexibility with the possibility of future direct nuclear heat usage will be unique in the world and should significantly support future research scope to aid in the advancement of technology readiness for high-temperature electrolysis to aid in de-risking future commercial deployments at even larger scales.
- The use of nuclear heat is a win–win solution. It can be a game-changer to meet ambitious DOE goals. This underutilized resource is scalable. Utilities—owners of reactors—can now bring hydrogen into their portfolios; there is an important need to engage them.
- Scaling up water-splitting technologies is an important strategic plan to advance hydrogen production toward commercial viability. Establishing a testing facility at pilot scale and commercial scale is crucial.
- This project is very important for the entire SOEC industry.
- The project directly supports HFTO's mission for H2@Scale and Hydrogen Shot.

Question 5: Proposed future work

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

- The project team is aware of challenges ahead and has identified a sensible pathway to success. The plan for contracting construction services through commissioning of the system within a single calendar year seems ambitious and may prove to be a challenge at this scale.
- The public–private partnership model for new application of nuclear plants is a very valuable pathway. The project is ambitious and has good focus to complete remaining design tasks and order long-lead items.
- The team has a good understanding of the critical issues and has laid out a good plan to address the challenges.
- The project timeline is clearly outlined, and the main focus is on completing construction.
- Project planning is appropriate. The project team needs to stay on schedule.

Project strengths:

- The project is well-planned, highly strategic, and visionary. The project is essential to SOEC advancement.
- The project has high visibility and would serve as a model for direct SOEC technology adoption by the community and de-risk future industrial applications. The project considers a large variety of applications, from hydrogen use in bases, chemical plants for synthetic fuel production, use of different sources of energy generators, and energy generation in solid oxide fuel cells.
- The project has an awesome amount of space to safely conduct large-scale hydrogen research and ultimately expand capabilities and demonstrate direct coupling with nuclear energy.
- The use of nuclear heat in hydrogen, syngas, and other applications is a win–win strength. Having utility partners with nuclear reactors is a plus. Engaging the SOEC supply chain is also a plus.
- Comprehensive engineering design of a pilot-scale testing facility with integrated electricity, steam, and grid is a major strength of the project.

Project weaknesses:

- The high cost of this project could be from the potentially redundant efforts in oversizing (BOP and integration) and other multiple unknowns (water purification, safety features, and required power electronics specifications). The investment could be easily justified, however, because it is an enabling project. Many questions would be answered by operating megawatt-size SOEC systems.
- NRC regulatory approvals and related challenges are not trivial. It is unclear how the project team is engaging the NRC. In the past, this challenge has caused serious issues with no path forward.

- Though there is major potential for planned expansion, current capabilities for integration with other technologies appear somewhat limited at present.
- The project has minimal information on the success criteria defined for the testing facility.

Recommendations for additions/deletions to project scope:

- The funding of this effort directly enables the United States to demonstrate advancements in SOEC technology, enables faster progress in the field, and will promote commercialization of SOECs.
- Ultimately, the funding needed to demonstrate direct-coupled heat and electrical with nuclear should be added, if it is not already in the funding plan.
- The project should clearly outline the progressive scale-up from kilowatt to megawatt levels by years, with goals achieved and to be achieved.
- NRC engagement in appropriate fashion is encouraged.

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

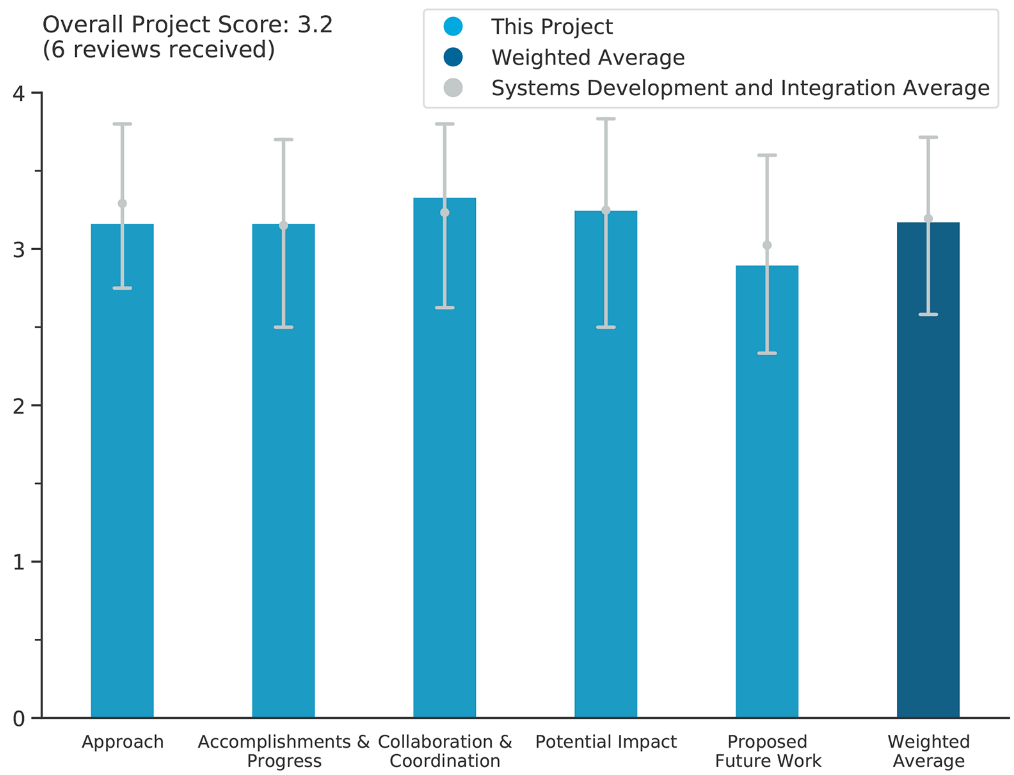
Peter Rupnowski, National Renewable Energy Laboratory

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

- National Renewable Energy Laboratory's (NREL's) experimental and developmental approach to fuel cell and electrolyzer quality control systems is exactly what is needed. It is a pre-commercial development, not being conducted elsewhere, that utilizes the unique capabilities of a national lab and benefits a broad array of fuel cell/electric companies. In this instance, there is no substitute for a hardware concept development and testing project.
- This project very clearly identified and pursued the objectives for improving quality control techniques for roll-to-roll (R2R) manufacturing processes. In the final year of a long-lived project, the work focused on the optimization of five nondestructive evaluation techniques to detect, identify, and quantify defects in membranes at comparatively high speeds (up to 5 frames per second [fps] reported). By limiting the scope to five techniques, the project team enabled higher-quality work that was coordinated with other activities, including Small Business Innovation Research (SBIR) projects. This project was not required to submit a safety plan but implemented basic safety protocols and training activities. The project did not explicitly include a diversity, equity, inclusion, and accessibility (DEIA) plan or a community benefits plan (CBP) but worked with small businesses and academic institutions.
- The approach includes meaningful research and development (R&D) work on R2R adaptable quality control measurements using various technologies. This approach starts from an understanding of proton exchange membrane (PEM) industry challenges. The tools are developed to address relevant quality control criteria for the membrane electrode assemblies (MEAs) used in PEM technology. The project team should consider the impacts of the heat from the Xe flashlamp on the substrate material. The reviewer has previously observed significant deformation of black plastic when it is subjected to a pulse from a 4800 W Xe flashtube at close range. It may be fine in this case, but it is worth considering the power of the lamp and the emissivity and feed rate of the catalyst-coated membrane.
- The project approach is well-thought-out. Given the relatively low budget, leveraging capabilities of partner organizations is an effective approach.
- The project team has demonstrated good progress.
- The project approach was described as understanding industry challenges, developing and demonstrating new methods and tools, and accelerating MEA and stack scale-up. However, there was little information about the process for identifying and planning the work, and the resulting approach appears scattershot. For instance, there does not appear to be a formalized process for identifying and prioritizing challenges. This makes it difficult to assess whether the topics being investigated are truly important or high priorities.

Question 2: Accomplishments and progress

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

- The project's transmittance-based detection of defects on semi-opaque inline films is a substantial achievement. The project's single-point thickness probe is also a significant achievement. The project's segmented cell will aid in understanding the performance impact of defects in low-temperature electrolysis cells. The project's x-ray-based areal density and porosity mapping is an important tool for detecting defects in porous transport layers and multilayer MEAs. The project's multi-spectral scanning of transparent inline films for thickness variation is an important step forward for rapid, inline, large-area membrane diagnostics.
- The project team has made progress toward improving the detection, identification, and quantification of defects in the multilayered membrane assembly during the R2R manufacturing process. Empirical results suggest that the five techniques properly characterized the respective samples after a detailed protocol was developed for each measurement technique. The presenter did note that there is likely a gap between this work and currently implemented state-of-the-art (SOA) quality techniques in industrial-scale R2R manufacturing facilities, but he added that intellectual property concerns prevented inspections of these SOA manufacturing facilities. The project team ensured that all team members, from interns to project managers, were properly briefed in applicable safety protocols. DEIA plans and CBPs did not apply to this project.

- NREL has established a toolbox that can be used to support MEA manufacturers as they scale up their processes.
- Several nondestructive testing methods have been tested and evaluated.
- The segmented cell is something that has been developed for fuel cells but is lacking for electrolyzers. This is an area that needs a good deal of development, as it is essential to ensuring the success of large manufacturing projects.
- There is a lack of clarity about what is truly a new accomplishment over the last year. Several accomplishments presented this year were presented in previous years. For instance, the segmented cell, which was described as a “brand new” capability, was presented last year, and whether there were any advancements from last year is not clear. There is also an issue with lack of validation that the tools being developed are actually proving useful.

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 work with 10 fuel cell/electrolyzer, membrane, and camera companies is a very high level of collaboration and coordination. The team’s participation in SBIR commercialization projects attests to the high level of collaboration and identified market need for the detection systems being developed.
- The project team has significant involvement with several industry partners. These partners will be the ultimate users of the quality control technology developed for R2R processes in this project. This project is a good match between a national lab and U.S. industrial partners.
- NREL has collaborated with multiple academic and industrial companies in this effort, including equipment vendors and potential end users of the technology being developed.
- The reviewer is pleased that the results of the work are having direct impacts and applications. It is essential that the work developed in this project is accessible for U.S.-based manufacturers.
- This project team coordinated work with one university, three SBIRs, and seven external companies. Many of the corporate collaborations identified diagnostic requirements for commercial processes. The team did not identify any successful technology transfers, despite pursuing opportunities.
- The project is interacting with numerous industrial partners through separately funded activities, but there is some question about how partners are identified and issues related to fairness of opportunity.

Question 4: Potential impact

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

- Improved quality control processes are critical to lowering costs and reducing waste in the manufacturing of fuel cells and electrolyzers, which are vital to the United States’ net-zero goals, Bipartisan Infrastructure Law targets, and EarthShot goals.
- This project strongly aligns with the Hydrogen Program’s goal to reduce the cost of components supporting the hydrogen economy. In this case, the project achieved this by quickly and accurately detecting and diagnosing defects in membranes or membrane components. The detailed protocols for the five diagnostic techniques will be particularly useful.
- The project aligns extremely well with the Hydrogen Program’s goals and objectives. The project objectives are necessary to achieve the overall goals of commercial scale-up and low cost.
- The project’s rapid quality control tools will be essential for MEA manufacturing at high volumes.
- The project’s quality inspection methods are essential to ensuring the success of large investments and projects.
- While certain aspects of the work could potentially contribute to improving manufacturing quality control, the absence of a structure and method for identifying and prioritizing industrial needs reduces the impact of the project. The project will soon be transitioning to R2R, and in this new form, it is imperative that the

project team develop a process for identifying and prioritizing research topics and subsequently validate project progress in addressing them.

Question 5: Proposed future work

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

- The future quality control work supporting the R2R Consortium, Million Mile Fuel Cell Truck (M2FCT), and Hydrogen from Next-generation Electrolyzers of Water (H2NEW) is reasonable and relevant and multiplies the impact of this work.
- This project does not appear to be going forward (i.e., there is no budget for Fiscal Year [FY] 2024). That said, NREL has identified several opportunities for continuing this work, both by collaborating with the R2R Consortium and by proposing future funding with identified partners.
- A logical set of next steps has been identified.
- This effort is scheduled to be folded into the R2R Consortium, with coordinated activities with M2FCT and H2NEW. There was no explicit plan to capture the lessons learned over the 17 years that this project existed and roll them into the new R2R Consortium. This exposes the Hydrogen and Fuel Cell Technologies Office to losing institutional knowledge through disorganization or lack of accurate records.
- The team plans to "work with and gather current information on challenges from as many industry partners as possible in the fuel cell and electrolysis space," but there does not seem to be consideration given to how to engage more partners in a fair and systematic way that provides solutions for the highest-priority problems manufacturers are facing.
- If quality control development is the focus of the project, the team should focus on identifying companies that develop quality control equipment and systems. Working directly with these companies will help the entire community.

Project strengths:

- Experimental hardware development of diagnostic systems is a major project strength. The NREL team has substantial expertise in R2R processing and inline diagnostic systems. The high number of SBIR projects and other commercial engagements with industry to develop these diagnostic systems is another major project strength.
- This activity was smaller than an SBIR Phase I grant in FY 2023 and accomplished a reasonable scope of work for the very limited budget. It is entirely possible to not fully assess all five different diagnostic processes while collaborating with multiple external partners prior to exhausting the provided funds.
- The development of high-quality products is essential to ensuring the success of any hydrogen project. Quality control is a necessary tool to reduce risk and improve the success of projects.
- The team has relationships with many industrial partners and has a long history developing quality control methods.
- This project has good tie-ins with U.S. industry to address industry needs.
- The project includes collaborations to obtain relevant results with limited budget.

Project weaknesses:

- While NREL's expertise is strong, there do not appear to be other national labs or university groups participating in the project. The inclusion of other fundamental science researchers may allow development of novel systems. As summarized in the Annual Merit Review slides, the project is a series of concept developments without an overarching classification of problems to be solved or potential approaches. The accomplishments to date seem to lack a rigorous test sequence for each diagnostic system on a series of films with known types of defects. There is no discussion of cost or speed (or m^2/min), which is critical to scale-up.
- The project needs a more targeted and systematic strategy. Certain project tasks seem to exceed the appropriate scope of an MEA manufacturing R&D project. While the exploration of segmented cells could

be valuable for different projects, it is a perplexing choice for a project that is nominally about manufacturing quality control.

- The project was limited by the number of samples to analyze. A larger number of samples would permit a more refined and robust diagnostic protocol.
- The project team must ensure the developed methods are industrially relevant.
- The future of the project is unclear.

Recommendations for additions/deletions to project scope:

- The project would benefit from articulation of a diagnostic framework that identifies the problems, the general approaches, and the specific scientific methods potentially addressing each problem. The project should develop a series of tests on known defects as a way of determining the detection thresholds. The project should quantify cost/m^2 of analyzed film. The project should quantify the speed of detection (in m^2/minute). The project does not seem to currently assess the compositional distribution of catalyst, instead using layer thickness as a proxy. This may be adequate but is not addressed.
- The project team should partner and work in collaboration with industrial partners and industrial suppliers to improve inspection techniques that are already developed. Companies that supply quality inspection products should be incorporated as advisors.
- The project should remove the work on segmented cells or move it to another project.
- The project has concluded.

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

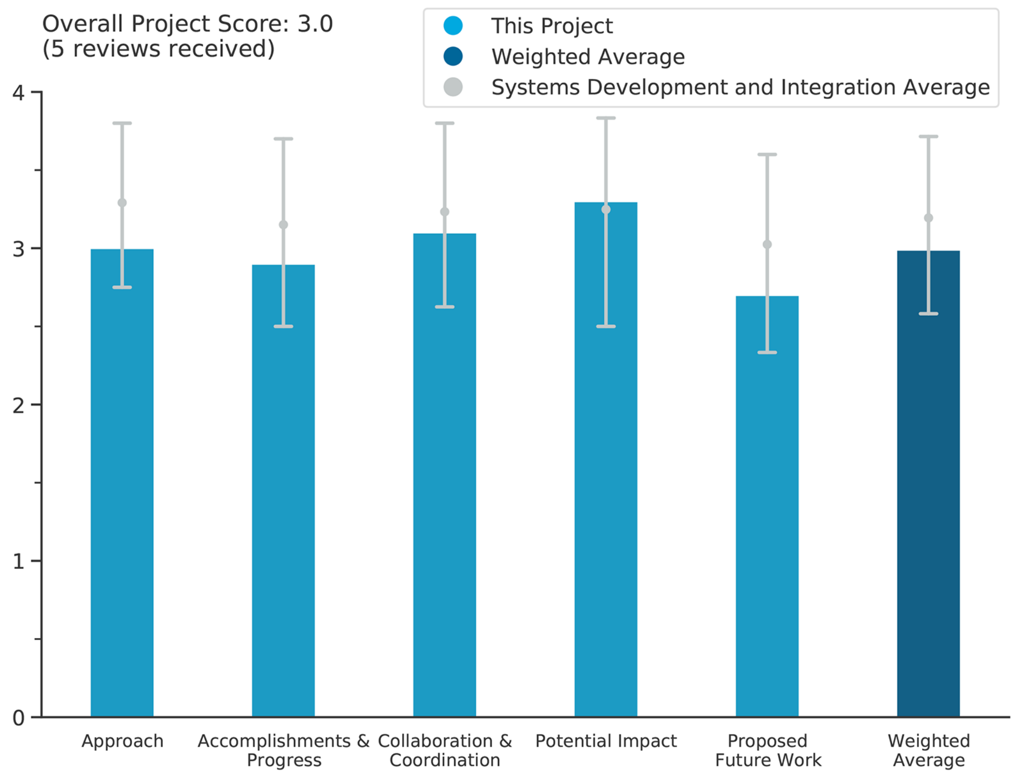
Steve Clermont, Center for Transportation and the Environment

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 substantially increase 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 **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project approach was well-defined, resulting in the overall achievement of building demonstration units that were deployed in service with the United Parcel Service (UPS). Some issues regarding maintenance and reliability should have been addressed in the risk plan and powertrain designs to help reduce downtime, but the impacts of COVID-19 and fueling infrastructure issues were extraordinary circumstances.
- This project includes wins for environmental justice and workforce development based on the location of the project in Ontario, California. The project was well-organized and -executed but ran into problems with its hydrogen source and use of older vehicles.
- The project is finally at a point of completion.
- The project team built the vans and developed training and education, which was certainly needed. The team involved the customer and National Renewable Energy Laboratory's (NREL's) analysis in developing a safety plan, which included engaging with first responders and having a third-party inspection. Use of the van was one of the environmental justice wins, but it looks like that was about 300 hours. The new benefits from this project are not obvious. The UPS staff were trained, but it is not clear that this training will have any ongoing benefit. Many of the project's issues were rooted in the choice of old technology, scrap vehicles, and lack of supply flexibility, which the team has recognized as a less-than-sound approach. In sum, the project had good alignment to barriers but lacked a quality plan and execution.
- The project was flexible and adapted to project changes, which extended the timeline significantly. The team had a good strategy to show the objectives, given hindsight and challenges (i.e., multiple funding streams/reporting and repurposing equipment near end of life). The Shell station disruption (Shell has since pulled out all stations in California and reneged on its awarded station obligations) showed the need to have backup options for partners. Unfortunately, in hindsight, the cost savings with old vehicles, the multiple funding partners, and an unreliable fueling partner took a toll on this project. The project may have looked good on paper, but realistically, looking at the numerous challenges, execution was not possible. Having shared stations with cars was not a good strategy, and other funding agencies looking to save funding with stations built for trucks and cars should consider the lessons learned.

Question 2: Accomplishments and progress

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

- The project team had a good backup plan for alternate UPS fueling locations in southern California, with the added cost of new safety reviews and training. It is very expensive with the funds that have been already spent. The team needed to work with Shell to get hydrogen in Ontario, which caused the project to miss the total commitment for operation and produced only a few months' worth of data. The project moved the market forward, and there are valuable learnings for making progress toward DOE goals.
- The project results show successful construction of the demonstration units and deployment with UPS. However, the maintenance and reliability issues, combined with impacts of COVID-19 and fueling infrastructure closures, caused major delays and eventual grounding of the demonstration units. While some of these issues could have been addressed early in the project, other circumstances were out of the control of the project team and are understandable.
- The team has achieved concrete progress toward the roll-out of hydrogen-powered (zero-emission) delivery vehicles through lessons learned, a comprehensive safety process, and interactions with commercial entities.
- There were many lessons learned on this project.
- The project team feels that the safety plan and approach can be a blueprint for other projects. The team operated a vehicle for three months then lost fuel supply. The milage was only about 10 miles/day when operated. It seems that delays were an issue in the last presentation year, so this is now two years of difficulty. The delays led to very little learnings on vehicle use and vehicle station interaction, and the

prime feedback was about the old vehicles chosen, not the hydrogen technology, so both delays and the lack of abundant data were avoidable issues.

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 has done well to get this project to the finish line.
- The project's collaborators did make meaningful contributions.
- Unfortunately, some of the main partners on the project did not follow through. It is unclear what collaboration or coordination may have prevented having a working fueling station and the limited demonstration days with disruptions from Shell. The effects included vehicle maintenance, and the multiple funding sources caused significant complexity, with each funder requiring different reporting and milestones. The project team did have an outstanding roster of partners and end users outside of Shell's lack of supply and follow-through on fuel obligations. The project included good connections for environmental justice and emissions reduction and working with local workforce development organizations.
- The overall collaboration with other organizations on this project was good and allowed for successful deployment of the demonstration vehicles. The team could have coordinated more closely with UPS and fueling infrastructure providers.
- The project's collaborating delivery companies were at first enthusiastic, but then their priorities changed. Their change in priorities is likely unrelated to the progress of this project; however, it impacted the project's ability to transition technology to commercial organizations.

Question 4: Potential impact

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

- Reducing petroleum use for working vehicles is aligned with medium- and heavy-duty (MD/HD) transport. The project has decent alignment to the strategy and goals of the Hydrogen Program because high-flow fueling is a DOE goal, and affordability is a goal everyone agrees on.
- The project works to meet the current administration's goals to electrify MD/HD vehicles to reduce harmful emissions and mitigate climate change.
- While the project itself will not lead to the adoption of hydrogen-powered delivery trucks, the lessons learned can help improve the likelihood of success of subsequent projects. The comprehensive safety report can be a blueprint for subsequent projects and fleets looking to use hydrogen.
- The project's progress has been difficult, resulting in very high costs that have approximately tripled since the beginning of the project. This is a valuable learning for the Hydrogen and Fuel Cell Technologies Office and DOE about the high cost of hardware demonstrations. Retrofitting platforms before electric drive chassis were available and using 20- or 30-year-old vehicle equipment led to maintenance and operation issues for daily service. One lesson learned is regarding too much cost-cutting (e.g., multiple funders, old vehicles), which highlighted the need for new equipment, as well as the need to have operators (fleets and drivers) who trust the technology and will be the front-facing champions or detractors of new technology deployments.
- The project has many lessons learned.

Question 5: Proposed future work

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

- The project speaker was clear that the project is wrapping up, so future plans are not necessary. However, he made concrete recommendations for future projects based on the lessons learned in this one. Examples are listed in the bullets below.
    - Future projects should not retrofit existing vehicles powered by internal combustion engines, particularly when the vehicles are old. The existing design becomes an impediment to

implementing a new drivetrain well, and the old vehicles inhibit driver acceptance even when a novel drivetrain is a major improvement. Additionally, the registration of old vehicles can be problematic.
    - Future projects should not underestimate the importance of ensured refueling infrastructure, as refueling access was a consistent problem for the project. Project teams should plan to use multiple suppliers to reduce risk.
    - DOE should continue to invest in such demonstration projects.
    - There should be investment in design and development of vehicles that are hydrogen-powered from the beginning.
- The current objective is to close out the project and complete a final report, which is due July 2024. This is the logical conclusion for this long-running project. The lessons learned (listed here) are key for all funding partners to acknowledge, not just the project recipients: (1) design and development of new vehicles, not decades-old equipment, is important, and (2) the team should invest in more stations, with redundancy in case one station goes down (there is a need to go to more reliable compressors and supply chain); projects can use a lighthouse concept to share demonstration infrastructure. It is very challenging to hear that there are no funds to package learnings from this long-running project. Lessons learned could benefit community training, fuel cell integration, funding agency project/research, development, and demonstration design, etc.
- While the project met the major milestones on building and deploying the demonstration vehicles, the issues with maintenance, reliability, fueling infrastructure, and logistical challenges seem to have halted the project. There do not appear to be any significant plans moving forward, and lessons learned should be communicated for the future deployment of hydrogen-powered MD/HD vehicles.
- The team is closing out the project.
- The project will close out and report.

Project strengths:

- The project results were successful in the construction of the demonstration units and deployment with UPS. The overall collaboration with other organizations on this project was good and allowed for successful deployment of the demonstration vehicles. The project works to meet the current administration's goals of electrification of MD/HD vehicles to reduce harmful emissions and mitigate climate change.
- The project was novel when it began several years ago. Today, the lessons learned can help improve the likelihood of success of subsequent projects, and the comprehensive safety report can be a blueprint for subsequent projects and fleets looking to use hydrogen.
- The proposal started with a great list of partners, and it looked very exciting to have so many government agencies working together. At the time, having working fuel cell and storage equipment was significant. At scale, the technology impact would have been very relevant for the communities where the trucks were to be operated.
- This project has many lessons learned with industry project partners that undergo all kinds of changes both internally and with technology and supporting fueling infrastructure. Most project challenges are related to "people."
- The project team primarily learned how to set up safety in stations.

Project weaknesses:

- The project seems to have concluded because of issues with maintenance, reliability, fueling infrastructure, and logistical challenges. While fueling infrastructure and COVID-19 were extraordinary unforeseen challenges, maintenance and reliability issues could have been addressed in more comprehensive risk plans and powertrain designs to help reduce downtime. The use of salvage van chassis resulted in major issues with registration in California, as well as reliability issues. There was a lack of discussion regarding technical lessons learned for the vehicles' powertrain selection comparisons (comparisons to incumbent technologies, onboard storage performance, packaging, etc.), ability of vehicle range to meet UPS route requirements, fueling infrastructure (pressure class H35 vs. H70, flow rate, etc.), and/or vehicle design to meet cargo requirements. These aspects should be addressed. It is understood that the vehicle demonstrations ended early for justifiable reasons, but important observations could be provided to DOE and the MD/HD hydrogen community to drive current decision-making processes in vehicle design, fueling infrastructure, and techno-economic analysis.

- The project vehicles have become obsolete, and the fuel cells are now very old technology because of the project extension. The use of scrap vehicles for registration added further complications, but it finally got through the California Department of Motor Vehicles. The lead fueling partner Shell was not able to provide hardware and stations, which severely limited operating hours and degraded trust with the fleet operators and their truck drivers. Multiple funding agencies created reporting burdens with conflicting requirements. Early equipment demonstrations are expensive, and more funding was required.
- Project weaknesses include the team's reliance on older existing vehicles that were deemed no longer roadworthy at the outset of the project, reliance on a single hydrogen supplier, and the lack of significant driving experience as the basis of conclusions and driver feedback.
- The project suffered from an insufficiently complete funding package over the years, combined with insufficient flexibility to adjust goals (to lower vehicle numbers).
- The team's prior planning was insufficient. In the end, no significant information was gained beyond lessons learned.

Recommendations for additions/deletions to project scope:

- Because the vehicle demonstrations ended early, the project should focus on transmitting lessons learned to drive current decision-making processes in MD/HD hydrogen vehicle design, fueling infrastructure, and techno-economic analysis. Industry could learn a good deal from this valuable demonstration project.
- The project is at the end of its life, and it would be good if DOE could provide funds to capture lessons learned. DOE should also take note of the partners who went above and beyond and those partners who did not follow through on their commitments.
- The best recommendation is to complete and close out the project, as the project team intends.
- The project team should close out the project.

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

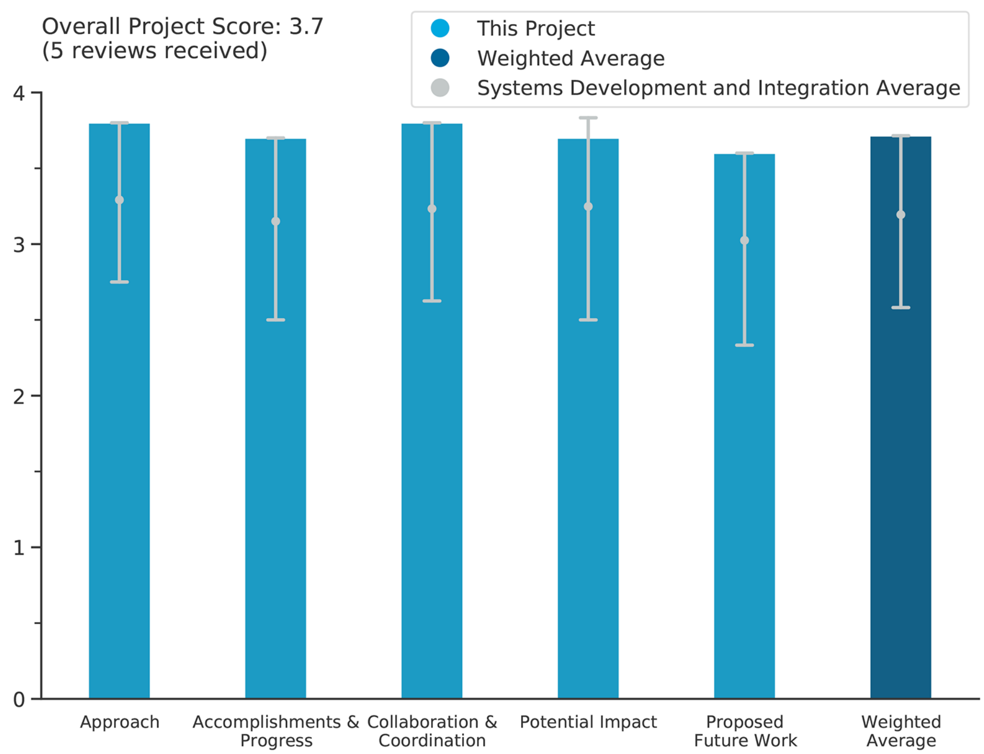
Micah Casteel, Idaho National Laboratory

DOE Contract #	WBS 7.2.9.1
Start and End Dates	9/30/2020
Partners/Collaborators	Strategic Analysis, Inc., Bloom Energy, FuelCell Energy, Inc. OxEon Energy, 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 **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Idaho National Laboratory's (INL's) approach to solid oxide electrolyzer cell (SOEC) stack testing for industry is well-thought-out and thorough. The project draws upon decades of experience with solid oxide cell stack design and testing at multi-kilowatt scale (5 to 50 to 500 kW). The span these test systems cover is impressive and provides unique value for the United States in evaluating SOEC technologies. The testing of commercial 5 kWe SOEC stacks for Nexceris and FuelCell Energy is impactful and provides third-party validation testing of the performance and durability of U.S.-made SOEC technology produced by companies that have been supported by DOE. This validation testing is very impactful when potential customers consider the company's technology, and the data can help expedite deployment of the stacks and systems. This benefits not only the companies supported by DOE but also the end users. This is one way that taxpayers directly benefit from these ongoing DOE programs. National labs like INL provide particular value through these validation efforts, and more of these efforts should be encouraged.
- This project appears to be an ongoing annual operating plan supporting testing, maintenance, and upgrades of the SOEC test platform, among other items. It seems that the approach to stewarding and operating the test platforms is sound, and data has already been collected for thousands of hours to support the intended goals. There are plans in place for what sounds like needed upgrades and maintenance to the system. The portion for the approach to bus fueling architecture was less well-laid-out, but it seems that a hold point is the availability of the required buses themselves from the commercial market, which was explained to be nonexistent and is to some degree outside of the project's control. Reconsideration of alternative approaches may be required for the bus demonstration route if a supplier for the buses cannot be found. In parallel, it was described that other system size upgrades are being made to support the future bus capability, and it makes sense to continue pursuing this to make progress toward the ultimate goal of interconnection, especially considering supply chain challenges and limitations on bandwidth for a small team.
- It is great to see where SOEC stands at INL and the progress made so far, along with future plans. This project has very impressive work and an excellent SOEC manufacturers list. Perhaps it would be worth considering additional industry collaborators and bringing them on early to the collaborative team. The team should consider the voice of the customer. The approach is well-planned and highly collaborative. The following questions and comments could be considered as an attempt to further strengthen already excellent work.
    - Slide 10 has very interesting dynamic operation cycles. It would help to know whether instantaneous cycles are better at thermal performance, since the thermal mass/heat is still maintained within the stack. It would be interesting to see future dynamic operation cycles with variable frequency.
    - It would be very advantageous to standardize the way data are being presented/summarized across different stack/system vendors. For instance, one should standardize and compare operation of different stacks/systems using a fixed set of conditions, perhaps during the first few hundred hours. This will give an apples-to-apples comparison. For instance, slide 15 presents very different data than other stack tests. It is not clear why this is the case.
    - Perhaps it would be advantageous to present one to two slides in the future showing how different vendor operating stacks compare. It is understood that all vendors have their stacks and systems optimized for a specific set of conditions. Perhaps one can pick a standard set of conditions for all stacks and plot the comparison on a single figure for performance tests and then durability tests in a separate figure. Perhaps this can be simplified at a high level to tell a story.
    - The team should continue the great work. The reviewer looks forward to future updates.
- INL has established a unique and extremely useful testing capability for solid oxide electrolysis stacks and systems. This project is providing extremely valuable services to industrial companies in the HTE space.
- The approach is very well-developed, with a combination of modeling and demonstration to validate.

Question 2: Accomplishments and progress

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

- INL's accomplishments in this effort thus far are exemplary. The researchers have drawn upon deep expertise to tailor the stack testing stations to large, flexible needs. The modularity of the hardware and software implementation makes this system flexible so that it can meet the needs of various commercial stacks. The project has made significant improvements to the consistency of steam delivery, which is a major, often underappreciated challenge. The principal investigator raised an excellent point that, traditionally, steam has been used as a thermal feed, not as a chemical feed. Conventional methods of controlling steam flow are based on managing heat, but the molar flow rates are often under-constrained and can cause major swings in steam concentration in the active electrodes of SOEC stacks. The data collected by INL also debunks some outdated thinking that SOECs perform poorly in dynamic operation. Contrary to conventional wisdom, the team found that faster dynamics actually lead to lower degradation rates by avoiding long periods of time between open-circuit voltage and thermal-neutral voltage.
- INL's SOEC stacks and systems testing capability has increased tremendously in the past year, and the number of industrial stack and system developers taking advantage of this capability also has increased. The lessons learned regarding best practices for SOEC stack testing are also providing value to industry.
- With 1,000s of hours of test data already produced, accomplishments and progress seem to be well on track for the scope of work revolving around ongoing testing. There also appears to be good progress on the system upgrades to scale at the next order of magnitude that ultimately supports the future vehicle fueling, i.e., the 500-kW-scale capability. The progress on the front of bus deployment seems to be minimal owing to the unavailability of commercial coach bus vehicles.
- All work is on track, and significant progress has been made toward all tasks.

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.

- INL's effort is inherently collaborative. The researchers are building the SOEC test facility to evaluate stacks and systems developed by other groups, especially industry. The initial 5 kWe testing of a FuelCell Energy stack has provided valuable data for that company and for INL. Nexceris SOEC stack testing is expected shortly, and further industry partners are developing test plans as well. The team has successfully conducted 50 kW system testing for OxEon. Bloom Energy systems have been tested with the highest direct current (DC) efficiency to date for any electrolysis system. This is an excellent use of national lab expertise to further the research, development, and deployment of U.S.-made innovative energy technologies.
- It appears that this research test capability is being used very effectively to support numerous different technology partners that are actually developing the SOEC technologies for commercialization. The hours clocked indicate high uptime, which is always a challenge for research systems, so it is therefore obvious that strong effort is being put forth to meet the needs of the research partners. Nine partners were listed, along with an invitation for more interested parties, so it is clear that the assets are prioritizing collaboration.
- The project has an outstanding use of industry and manufacturers to support research and verify the approach.
- INL is working with all the major SOEC technology developers in the United States and the world.

Question 4: Potential impact

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

- This work is very relevant to validating the durability and efficiency of commercial SOEC stacks and systems. SOECs can produce clean hydrogen with less electricity than other methods, and electricity price is the main contributor to operating expenses and levelized cost of hydrogen, according to Hydrogen and Fuel Cell Technologies Office reports. The durability has often been a concern for SOEC systems, so the third-party validation of durability at INL will increase customer confidence in these systems. With demand for clean hydrogen expected to increase, in part thanks to the Bipartisan Infrastructure Law and Inflation Reduction Act initiatives, this validation is especially timely, relevant, and impactful.

- The research has the ability to show how integrated systems can meet goals of $1/kg. This will be done through addressing multiple areas: improving the technology readiness level for stack and systems by validating performance, developing interfaces for thermal and electrical power, developing integrated systems that demonstrate high efficiency, reducing the cost of balance-of-plant components, providing a credible and public reference of projected costs, and developing a safe, reliable design and operating procedures for post-processing gases from >100 kW SOEC systems. Looking at everything from component to installed performance cost will provide a model for how these systems should be installed and operated to meet goals and achieve broader deployment of the technology.
- Early, small-scale testing at the 5–25 kW level is a key enabler for technology developers that will have impact by reducing market entry cost for new and existing (scaling) players. This is a good role for a national laboratory to be in to leverage existing expertise and uniformity of test approach. The bus demonstration portion has a less clear pathway of impact but appears to be in the early stages. Overall, it is an exciting possibility, considering the real-world use case that it would represent for the technology.
- This work is extremely relevant and provides DOE with an unbiased perspective on performance and durability of SOEC stacks and systems. INL also provides a valuable service to stack developers, contributing state-of-the-art testing capability to which industry would otherwise not have access.

Question 5: Proposed future work

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

- The continued system buildout of the larger test stands and the continuing testing of commercial stacks and systems are exactly what this project needs to focus on to maximize its value to the United States.
- The proposed future work is well-aligned with project goals and should provide the full analysis through demonstrating how these technologies should be integrated and operated.
- The plans to continue testing commercial stacks and to extend INL's testing capability to larger systems are perfect.
- The pathway for continued and increasing support of kilowatt-scale to hundreds-of-kilowatts-scale was clear and seems to be well-laid-out and in alignment with existing and planned capabilities. The pathway to success for the bus demonstration was a bit less detailed, but next steps seem appropriate in light of the challenges in procuring the buses themselves.

Project strengths:

- The collaboration with U.S. companies developing SOEC technology is phenomenal. The 5, 50, and 500 kW stack and system span cover significant ground in third-party validation of commercial stacks and systems with incredibly well-instrumented test stands that help determine the efficiency and durability of these technologies and de-risk them for customers of these systems that want to produce clean hydrogen in the United States with U.S.-made technology.
- Thousands of hours of meaningful data to support scaling SOEC technology are already clocked, demonstrating significant accomplishment already. More partnerships and order-of-magnitude capability increases are planned and in the working pipeline.
- The project approach and task plan are well-planned for improvements at the stack and system levels. The demonstrations to validate the work are well-done. The team of collaborators is impressive and adds confidence in the work and the results it generates.
- INL is supporting the SOEC industry with much-needed validation testing and is providing DOE with an unbiased perspective on the state of SOEC technology.

Project weaknesses:

- The pathway to overall/high-level success with the bus demonstration is not well-laid-out, at least in the presentation material, which is likely a function of limited presentation time and the challenge of obtaining vehicles. It would be good to see a more formed plan for this aspect.

Recommendations for additions/deletions to project scope:

- The team should include more defined stages to success for the fuel cell bus demonstration, including specifics around equipment technical details. The pathway needs to be identified clearly to continue investments and pursuit of that end goal.

Project #TA-029: Autonomous Hydrogen Fueling Station

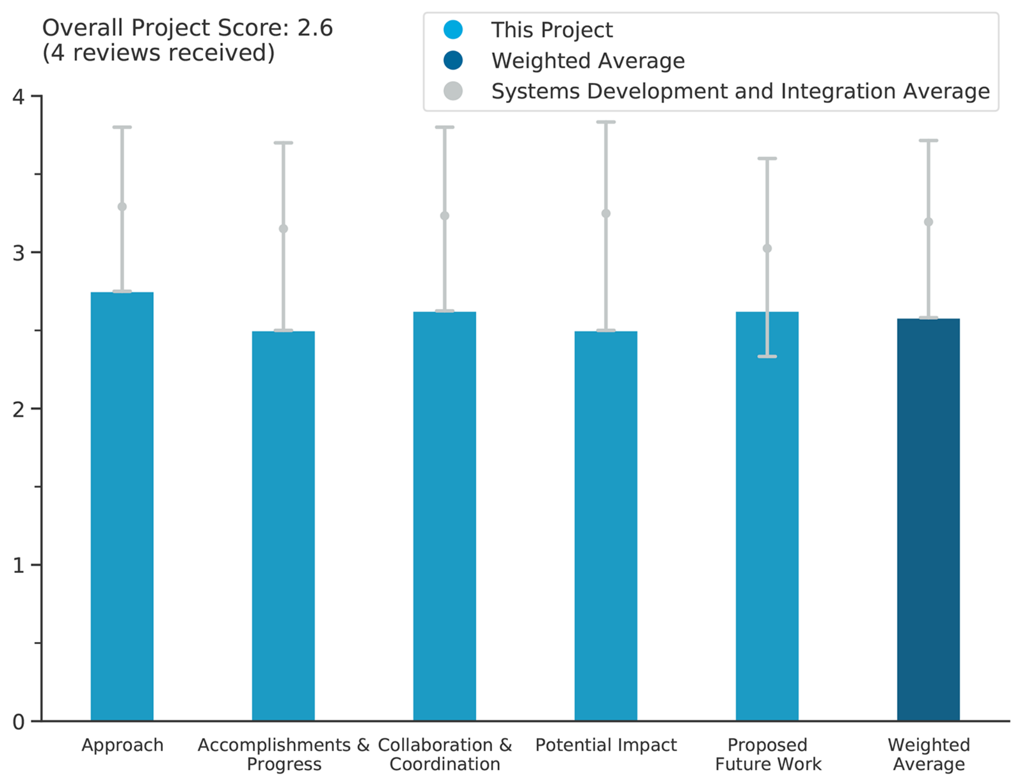
Keith Brown, Plug Power Inc.

DOE Contract #	DE-EE0008421
Start and End Dates	10/1/2018–9/30/2024
Partners/Collaborators	National Renewable Energy Laboratory, Vecna Robotics, Mekable
Barriers Addressed	• Hydrogen delivery: low-cost, rugged, reliable dispensers • Hydrogen helivery: hydrogen refueling for automated vehicles (on-road and industrial) • Market transformation: high capital cost for hydrogen fuel infrastructure

Project Goal and Brief Summary

The project aims to research, develop, and commercialize an automated hydrogen dispenser system for both material handling and on-road fuel cell electric vehicles (FCEVs) with high connection success rates. The researchers seek to enhance the efficiency and reliability of hydrogen refueling operations, reduce labor costs, and further the deployment of fully autonomous FCEVs. By closing critical gaps and advancing these technologies, the project supports the broader utilization of hydrogen fuel cell systems in both material-handling and automotive 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 **2.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project approach is well-defined, and technical, safety, and cost requirements and challenges are clearly identified and defined. Prior to the project's pause, the efforts to date appeared to be addressing the technical, safety, and cost challenges. Plug Power Inc. (Plug Power) has more than 35,000 fuel cell systems operating in material-handling applications. The autonomous refueling operation of Plug Power systems presents some unique challenges, such as water removal (which requires a separate nozzle) and the ability to read performance data from the unit. The project's safety plan was evaluated at the start of the project in 2019/2020 and was reviewed when the project was restarted in 2023. Appropriate International Organization for Standardization, International Electrotechnical Commission, and American National Standard Institute/Robotic Industries Association standards for robotic systems were identified and addressed. At that time, Plug Power's own environmental, health, and safety group noted three areas of concern: robot safety, hydrogen safety, and vehicles driving away before the nozzle is removed. These concerns have been addressed for the prototype demonstration, such as putting a fence around the robot to prevent workers from being nearby during filling and positively pressurizing the electronics with air to prevent hydrogen from contacting the motor(s) or controller(s). However, additional work is required to address these concerns for a production system. The project was awarded before diversity, equity, inclusion, and accessibility (DEIA) principles and community benefit plans (CBP) were required.
- This project is now judged against some criteria that were not established when this effort was started, but there are no DEIA efforts or CBPs to review. The safety criteria and evaluation of the project are documented and well-thought-out. The approach is also well-thought-out and reasonable, especially in understanding the cost drivers for any potential customers and end users.
- The overall approach of the project team appears sound and logical.

Question 2: Accomplishments and progress

This project was rated **2.5** for its accomplishments and progress toward overall project and DOE goals.

- The project team appears to have made significant progress prior to the shutdown. Plug Power determined that existing robotic systems were too expensive for material-handling applications and design, then assembled its own in-house design with the electrical design and wiring of a motion system completed shortly thereafter. The team designed and implemented the control architecture and associated software for control of the robotic arm. Vecna Robotics demonstrated the vision system and motion control through 199 successful connections to and disconnections from the fuel cell stack.
- It is great to see this project start back up after a period of inactivity. The progress made before the break was good and clearly moving in the right direction. Since the progress was stopped, that has an impact on the overall project success to this point.
- The reviewer recognizes and appreciates the challenges the project faced with COVID-19 and personnel. However, a two-year lapse in project work is significant and would appear avoidable or addressable well before that time.
- The project has limited accomplishments, considering the long project timeline.

Question 3: Collaboration and coordination

This project was rated **2.6** for its engagement with and coordination of project partners and interaction with other entities.

- Focusing solely on past performance, the team appears well-structured to develop the technology, with Vecna Robotics and Mekable focusing on the robotic arm and control algorithm developments and National Renewable Energy Laboratory focusing on the on-road vehicle refueling research and development and testing. The team needs to communicate a better understanding of how the collaboration will move forward after the restart.
- The project has good coordination and collaboration across the team.

- The project's partners appear appropriate. The lead partner appears to be the biggest drag on project progress.
- It appears the only collaborators are a national lab, which provided data to be reviewed and does not appear to be involved in any active work, and the company providing the robotic platform.

Question 4: Potential impact

This project was rated **2.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project's fuel-cell-powered forklifts for material handling has been the most successful deployment of fuel cell technology to date. The material handling industry seems to be moving toward autonomous operation, so the development of an autonomous hydrogen refueling station targeting forklifts is well-aligned with the long-term industry direction. The reviewer is aware of some discussions in the off-road vehicle sector, particularly the mining industry, about developing autonomous hydrogen refueling capabilities. The reviewer is less aware of discussions about developing autonomous hydrogen refueling capabilities for on-road vehicles, but there could be merit for light-duty vehicles, in terms of improving safety by eliminating the consumer from the refueling process, and for off-road vehicles, both in terms of improving safety and lowering cost. However, these markets are less mature than the forklift market, and the need for autonomous hydrogen refueling is less urgent.
- The project has clearly listed its objectives and could have an impact on safety if the technology is a success and widely used.
- It is unclear how the project is relevant for material handling or light-duty refueling. This project seems more relevant for heavy-duty vehicle refueling, but it is understood this is outside the scope.
- The project appears to be putting the cart before the horse. Until autonomy is established, it is unclear why this is needed or whether it makes sense in the world outside of controlled warehouses. Those questions aside, there could be limited, yet useful, value to this project in that confined parameter. It is questionable whether there is need or opportunity outside of warehouses (i.e., on-road consumer/fleet vehicles), but the project could be ahead of the curve.

Question 5: Proposed future work

This project was rated **2.6** for effective and logical planning.

- The proposed future work with data collection and testing seems spot-on as the project finishes up.
- Future work is targeted at providing a great resource for reference, as well as baseline information.
- The project paused for two years because the Plug Power personnel initially involved in the project left Plug Power. During this time, there were considerable advancements in the development of autonomous hydrogen refueling capabilities by other organizations. Plug Power plans to demonstrate 200 dry connections/disconnections and hydrogen fills in 2024, picking up where Vecna Robotics left off in 2021. Plug Power has decided to survey the autonomous refueling market to identify current leaders, to evaluate the cost of adapting current technology to material handling, and to evaluate the business case for autonomous refueling. This decision is appropriate, given advances in the technology that have occurred during the project pause. The outcome of the proposed future work should serve as a go/no-go decision on whether to continue the project and move to Budget Periods 2 and 3, as defined in the approach slide, or to terminate the project.
- Starting with a declaration of additional funding needed is inappropriate. The team should demonstrate the need, then discuss needed funding. It is not clear why this project was undertaken if the lead needs to evaluate the business case—or whether there is any need or justification for the project.

Project strengths:

- There will be a demand for autonomous refueling technology in the material-handling industry as the industry moves toward autonomous operation. The proposed workplan to evaluate the current state of autonomous refueling technology and the business plan is appropriate, given the two-year pause in the project.

- This innovative effort is targeting an area of potential need as robotics in logistics continues to grow.
- The project addresses what could be a potential future need in an autonomous world.

Project weaknesses:

- The project made significant technical progress prior to the principal investigator leaving Plug Power in 2021, when the project was paused. Other organizations made significant advancements in the development of autonomous hydrogen refueling technology while the project was on pause. While Plug Power plans to focus on evaluating the current state of the technology and its business case, comments made by the presenter during the presentation suggest that Plug Power may have less interest in developing and marketing its own refueling technology, particularly given the low cost of $10,000/unit the market is willing to accept. The business case is not clear, given current costs for an autonomous refueling system compared to those of manual labor, which are not significant.
- Even the project's lead is uncertain of the project's relevance or need. The current progress is insufficient, even considering COVID-19 and internal personnel issues.
- The project lacks collaborators; diversity, equity, and inclusion activities; and a CBP.

Recommendations for additions/deletions to project scope:

- A decision should be made to continue or terminate the project based on the outcome of evaluating the status of autonomous refueling technology and the business case. Based on that outcome and whether there is a need or opportunity to move forward, the team needs to make sure that Plug Power plans to market the technology or transfer it to company that will market the technology. If the decision is made to move forward with technology development, there needs to be a clear understanding of how this project will address the on- and off-road vehicle markets. Right now, the focus seems to be solely on the material-handling market. Whether the focus should be only on the material-handling applications is a matter of question.
- Whether the project should continue seems uncertain. Perhaps the lead partner should determine whether the researchers find a business case, or the project should find a partner who does believe in it (and can sell it to DOE and obtain public funding).

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

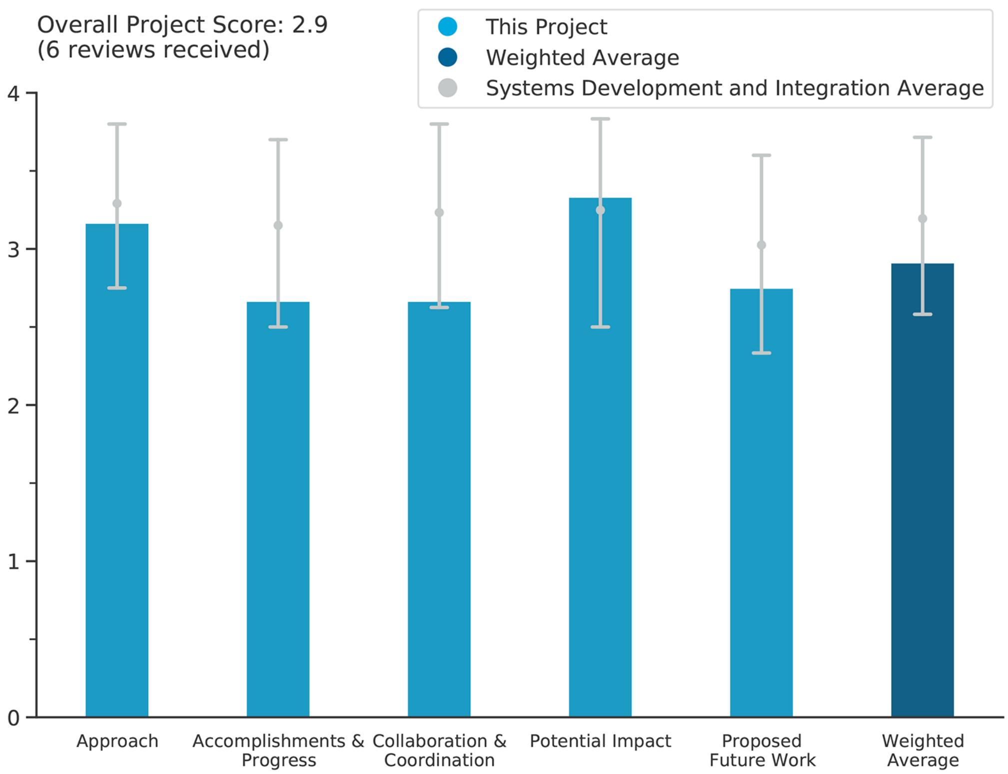
Paul Brooker, Orlando Utilities Commission

DOE Contract #	DE-EE0008851
Start and End Dates	10/1/2019 to 02/28/2026
Partners/Collaborators	OneH2, University of Central Florida, National Renewable Energy Laboratory
Barriers Addressed	• Cost, system integration, and performance

Project Goal and Brief Summary

The project goal is to demonstrate integrated hydrogen production and consumption for improved utility operations. Using grid-integrated hydrogen assets, the project will produce hydrogen via electrolysis designed to provide operational value to the utility from photovoltaics (PV) smoothing. The hydrogen will then be employed to fuel fuel cell electric vehicles (FCEVs) and fuel cell generators. Multiple usage profiles will be explored for the FCEVs, such as consumer and fleet operations for contingency events. Dispatch profiles for fuel cell generator systems will be explored over multiple use cases, such as grid peak shaving, load shifting, PV smoothing, and customer service models such as demand reduction and emergency back-up power.

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.

- This is an exciting project that is likely to have meaningful impact for grid-scale deployments. The project involves internal demonstration and experience gained by a utility provider, including extensive, real-world cost modeling for deployment of hydrogen technologies to solve today's real-world challenges for renewable power generation. The technical approach and target for hardware capability seem sound and relevant. There are interesting add-on demonstrations planned, including mobile backup power unit fueling and more.
- This is a great project and supports the DOE goals. The reviewer looks forward to continued progress. The team should keep at it and not let the novation stop them.
- The overall project approach provides important demonstration data on how electrolyzers actually perform in this kind of dynamic grid environment. Most of the work to date has been modeling but should provide relevant background for the project when equipment is actually integrated.
- The project is under way/just beginning, and further details could come out with regard to the approach in achieving targets of \$1/kg H_2 produced and \$2/kg H_2 delivered. Modeling work will inform dispatch strategies with real-world scenarios. The chosen approach with real-world demonstration is useful for creating lessons learned and showing steps to overcoming barriers.
- The project approach is good, especially with the grid integration. The analysis needs more definition and details. The analysis should include the cost of hydrogen and the impacts of key components of the hydrogen production.
- The overall concept is good, but the approach relying primarily on grid services is a misapplication of the primary benefit of hydrogen technology.

Question 2: Accomplishments and progress

This project was rated **2.7** for its accomplishments and progress toward overall project and DOE goals.

- The project is under way/just beginning, and further details could come out with regard to the approach in achieving targets of \$1/kg H_2 produced. Techno-economic analysis is in Year 1 and 50% complete. One request is that, for next year's review, the presenter show the pathway to achieving levelized cost of hydrogen (LCOH) <\$2/kg H_2 produced. Similarly, the expectation is that Tasks 3, 6, and 7 will show accomplishments and progress toward meeting overall project and DOE goals. The cost barrier is quite a critical goal for further adoption of hydrogen fuel. Currently, the minimum cost for hydrogen production (slide 14) shows a minimum point above \$2/kg with the use of PV + grid at a 25%–30% electrolyzer capacity factor.
- With the ongoing novation, the progress on modeling is excellent. It would be good to see additional modeling tasks, however. It is not clear what the benefit is of additional short-term electrical energy storage between the PV and electrolyzer to help smooth the power profile to the electrolyzer. This could help improve electrolyzer efficiency and life. The team should consider the implications of 45V in the modeling, especially when using grid energy vs. PV. This presents an interesting balance between utilization, carbon intensity, etc. on the LCOH.
- The project started in 2019 and has spent only 10% of the funds with no hardware in existence, so at a high level, overall progress is not good. However, it appears that there has been a pause and switch of lead institutions, which is the driving factor behind the stall and thus is not a critical barrier to the current "restart" of the project.
- The project has been delayed, and a large amount of work is pending. The project analysis is only partially complete. The project has spent more than \$900,000, so the analysis and pending expenditure schedules should have been completed. A significant amount of work has been devoted to project safety, which is a good accomplishment.

- Progress has been hindered by the contractual issues caused by Plug Power Inc. backing out of the project as the prime. Orlando Utilities Commission (OUC) is doing what it can to continue to execute on the project and has just gotten under contract with DOE.
- Low spend rate and multi-year project delays raise questions about the project team's effectiveness.

Question 3: Collaboration and coordination

This project was rated **2.7** for its engagement with and coordination of project partners and interaction with other entities.

- While the project is in its early stages, there appears (from both the slides and the oral presentation) to be a coordinated effort to deliver on the various tasks. The reviewer is looking forward to continued progress and collaboration, especially with OneH2 on the hydrogen compression, storage, and dispensing side for the demonstration.
- The project is being led by a utility company for its specific use case, which is an exciting approach to ensuring the relevance of the work. This lessens the need for collaboration on the front of ensuring relevance to the industry, as it is inherent to the project. However, there are a few partnerships outlined to pull in expertise from relevant subject matter areas, as well as a connection with a university, which strengthens diversity, equity, inclusion, and accessibility impacts.
- The project has been significantly delayed because of contracting issues, which are not the fault of the new prime, so partners are just starting to collaborate; but progress is being made, and the existing team seems to be working together. Next year will be a better indication, once other partners/suppliers are finalized.
- With Plug Power Inc. no longer on the team, there is a gap that needs to be filled with hydrogen expertise in designing this site and doing the appropriate safety reviews. Hopefully, this will be solved next year. The team should consider a third-party risk consulting company to help with the hazard analysis.
- This project would benefit from both Electric Power Research Institute collaboration and more project management.
- Collaboration is limited. A utility should be included in the collaboration and coordination. The project plans to connect to the grid. More information about the process of connecting to the grid was not specified.

Question 4: Potential impact

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

- The potential impact and relevance on direct operations of the utility were very well-laid-out from both the technical and cost sides of the coin. The project promises to provide an exciting real-world demonstration for a utility (one servicing clients today) that includes substantial renewable energy generation for the purpose of grid regulation (dispatchable load). The demonstration scale allows the project to prove out performance, address risks, optimize controls, and learn about the impacts of larger-scale deployments before making the full investment into grid-scale systems.
- This project seems well-aligned with the Earthshot goal of reducing hydrogen costs to \$1/kg H_2 in a decade. The project will also enable increasing the use of PV while mitigating its effects if the sun does not shine.
- The goals of the project are highly relevant to the Hubs and other projects by laying the foundation for optimization of hydrogen supply (distributed vs. centralized) and dispatch scenarios.
- This project aligns well with the DOE Hydrogen Program goals.
- This project has great alignment potential, but current challenges and the selection of grid services as the target application place the accomplishment of that in question.
- The project's plan to connect to the grid is an interesting approach and could be important. The project planned to produce hydrogen, but the disposition is not certain and still in development. If dispensing equipment is delayed, hydrogen will be vented to the atmosphere. Many of the components are long-lead delivery items. These delivery periods could extend/delay the project for years.

Question 5: Proposed future work

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

- The strength of the proposed work is in the overall plan's relevance and eventual impact on industry. A good site and overall plan for future work have been identified. It is clear that the details of the hardware side are not well-laid-out yet, except at the highest level, which makes sense considering the "restarted" nature of the project—so that is a minor weakness that hopefully will be rectified over the next project year.
- The plan has not been fully established for the hydrogen subject matter expert (SME) to help design and implement the project plans. Even the fuel cell system and vehicle vendors are not identified. Much work is needed here, but hopefully next year, solutions will be presented. The team should be cautious in going down the path of a diesel vehicle retrofit. The team should consult the fuel cell United Parcel Service (UPS) team about the downsides to this path.
- It is so early on in the project that "future work" is basically the whole project. The approach is responsive to barriers.
- Future work needs to address, with specificity, the project weaknesses and execution of the project plan.
- Proposed work depends largely on suppliers and others' execution of plans and designs. These include working out a contract with an electrolyzer provider, completing site design, and purchasing equipment, including long-lead-time items. There could be significant deviations, depending on negotiations, supply chain, etc. One item listed for analysis work around electrolyzer dispatch should be more within the control of the project participants.
- The plans for future work are good but ambitious. A comment was made that future hydrogen supply could be made to NASA. However, this was a passing comment. The plans to acquire equipment do not seem to exist. Equipment specification sheets and bids were not mentioned. Equipment purchase and delivery will take years, which will extend and delay the project.

Project strengths:

- Direct exploration of hydrogen technologies by an established utility is an exciting opportunity to demonstrate real-world use cases (i.e., to address problems that exist for the utility today). These include grid services for high penetration of renewables, back-up power applications for resilience during extreme weather events, and long-duration energy storage opportunities at grid scale.
- This project has a prime contractor in the form of a utility working to provide lower-cost hydrogen, as well as providing dispatching strategies for PV smoothing. The project has the right mix of analysis work and real-world deployment. Feedback to original equipment manufacturers will enable development of new use cases and result in product improvement.
- The goals and aims of the project are great, and having a utility engaged and supportive is very important.
- Key benefits are a good concept and utility involvement.
- The project is planning for connection to the grid.
- It is too early in the project to demonstrate true strengths, aside from the approach. The next 12 months will be more telling.

Project weaknesses:

- The reviewer looks forward to further progress. The team should keep an eye on potential deployment roadblocks and provide more information on the pathway to reducing hydrogen cost through analysis work. The timeline for this project has been challenged with two principal investigator changes and contract negotiations.
- The biggest project weakness is the length of time that has passed since the initial contract was awarded. This is largely outside of OUC's control, but this happens frequently when there are issues with a major subcontractor on a project.
- Hardware progress thus far is non-existent, but the "restart" of this project will hopefully "repair" and address this weakness, considering that the budget to do so still exists.

- The project weaknesses are schedule, spending, and application areas.
- The team needs to establish the hydrogen SME for the design and implementation phase.
- The analysis seems to be slow. The analysis should include cost analysis of hydrogen and an understanding of the cost parameters impacting the project. The project has not prepared equipment bid sheets or gone out to equipment manufacturers for quotations. The project is and will continue to be delayed.

Recommendations for additions/deletions to project scope:

- The project scope is good. Further details should be added, with pathways to reducing hydrogen costs and modeling work with dispatch strategy.
- The project should add more specific plans surrounding the safety assessment process and the demonstration of the team's relevant experience on hydrogen systems.
- The team should consider working with a contractor to refine/reduce scope to something more manageable.
- The project had over a six-year timeline. The project has incurred several delays and will need a no-cost extension. Based on the project status and expected equipment delivery, the project could take an additional three to five years to complete. Since only $900,000 (10%) out of the planned $10 million project budget has been spent and the project may need to be extended three to five years, it is recommended that the project be stopped and the funds be used for other high-priority projects.
- No changes are recommended at this time.

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

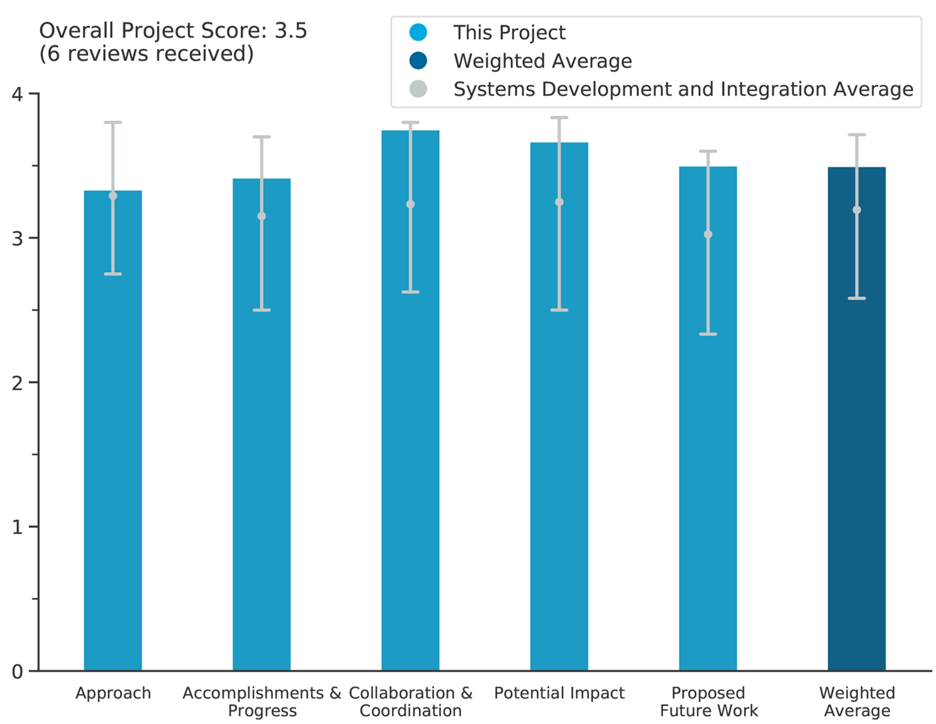
Rich Myhre, Frontier Energy Inc.

DOE Contract #	DE-EE0008850
Start and End Dates	10/01/2019–7/31/2025
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 hydrogen delivery infrastructure, given the current absence of demand for hydrogen from the transportation sector

Project Goal and Brief Summary

This project will determine how hydrogen production costs can be minimized by using multiple generation sources, including steam methane reforming (SMR) units that use renewable natural gas and electrolysis powered by wind and solar. Baseload stationary power generation will be collocated 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 approach of integrating multiple types of hydrogen production technologies with pipelines and storage for multiple end uses is a very good way to understand hydrogen node/hub performance. The project team is doing this in an academic setting, which will allow for integration of research and development and workforce training in an open environment that allows different companies to engage. This project has the potential to generate very important data and training, while not creating a government mortgage, and will likely be less expensive for stakeholders to use than if a similar system were developed at a national laboratory.
- The project approach to safety for initial planning/design/build appears to be well-laid-out, including a Hydrogen Safety Panel (HSP) evaluation, third-party hazard analysis support, and engagement with authorities having jurisdiction (AHJs). The architecture of the site is well-thought-out, with a modular approach to different technologies at a manageable scale. The project has one slight weakness, which is the reliance on mostly virtual connections for the renewable coupling aspect, but this project builds out the core hydrogen capability that can be expanded in the future.
- The overall project approach is sufficiently comprehensive, including hydrogen production, storage, and dispensing, as well as community outreach. This project is very useful as a demonstration because it can test the interfaces between several different pieces of equipment holistically.
- Real-world demonstrations on integrated hydrogen technologies are important in identifying the response to new use cases. The proposed project will help inform improvements to integration efforts.
- The project contributes to overcoming most barriers. The project team has identified all the necessary barriers and also presented the plan to overcome the barriers.
- The overall approach is reasonable, but the scale and applications are not clearly justified.

Question 2: Accomplishments and progress

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

- The project hardware is now in the ground, and thus good progress has been made toward the end goal of a functional system. Commissioning efforts appear to be under way and planned for the near term, showing good progress toward operation and the intended data collection. The project team is clearly motivated and dynamically adjusting and addressing challenges as they arise, demonstrating the nimble nature of the university system for accomplishing research at the planned scale.
- The project team has made good progress toward stated objectives.
- The project team has made good progress toward operations. Equipment delays are a function of recent supply chain constraints.
- The project team is moving along quickly. The safety is well-done. The team engaged the HSP and followed the Panel's recommendations. The project team needs to treat safety as paramount, given that this is at a college. The commissioning is on schedule. The team has done a good job keeping close to schedule in such a complicated project and location. This project has the potential to generate a tremendous amount of important data, but it is unclear how these data will be stored. It is unclear what the plans are to share the data.
- The project seems to have come a long way in the last 12 months, with hardware in the ground and initial fueling events started. One SMR unit is installed and functional. The project team mentioned electrolyzers, but it was not clear whether any were installed other than the stack in the SimpleFuel car fueler.
- The project team covered accomplishments and projects well, but it would be helpful in the summary to bring in project key targets, in terms of key performance indicators (KPIs) or any other quantifiable number. The project team met the end goal of \$4/kg H_2.

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 team demonstrates extensive external collaboration, with plans for continued stewardship and building up of relationships in the broader community and industry. This collaboration appears to be a particular strong suit of this project, and the project will serve as a learning and demonstration center for hydrogen technologies in Texas.
- Collaboration among the team members installing equipment on the site is apparent through their working together to solve equipment issues, such as the degradation of the tank fittings and supply chain issues that had to be worked around to obtain acceptable parts. Across the broad list of collaborators, there was significant cash investment in the project, as well as engagement in quarterly meetings and brainstorming workshops.
- The project team has collaborated and coordinated with all necessary stakeholders. The project role is well-explained.
- This project has a large, diverse team that is well-organized. The team is committed, as illustrated by the cost share. It is unclear how labor unions have been engaged.
- The project team presents a good set of engaged partners. It is not clear from the slides how many partners are actively participating in the project vs. providing high-level input.
- The project includes academic collaboration.

Question 4: Potential impact

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

- The forward-looking plan of larger developments of hydrogen technology in Texas, the training of workforce opportunities at the university, and the highly collaborative nature of the project promise to deliver significant impact at a reasonable scale and cost for the demonstrations and research intended.
- This project supports the H2@Scale vision and the Regional Clean Hydrogen Hubs Program (H2Hubs). The project shows how to integrate multiple technologies, and it also can be used for training.
- When awarded, this project represented one of the few integrated demonstrations of developed hydrogen technologies. While small compared to the hubs, it helps to show the feasibility for larger integrated projects. The outreach from the project team to local communities has also significantly increased since last year and will be good groundwork for the hubs.
- The project is strongly aligned with the Hydrogen Program’s goals and objectives and likely to significantly advance progress toward its performance targets.
- The project demonstrations include real-world operations, which are valuable to the technology space.
- The project has a high potential for relevance, provided that the lessons learned are transferred to other projects.

Question 5: Proposed future work

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

- The project’s future plans are very relevant and use the system for training of students, AHJs, permitting agencies, and data. The project data-sharing plan with hubs is key—the project team is planning an open-access data portal that will share the data. This is excellent and makes the project very impactful. The project team may have supplemental data by request.
- Future work for the project represents primarily operation and data collection for the demo, which represents the success of the implementation phase. Work beyond the project has also been defined, including significant continued work in outreach and extension of the models to other sites.
- The project team describes an ambitious plan to steward and build upon this initial capability installation extending into the future through education, workforce development, and connection to broader hydrogen

industry developments within the state. Additional specific details on the pathway to this future work would be welcome; however, it is understandable that this is difficult to achieve within the allotted time.
- The future plans of the project team build on past progress and contribute to overcoming most barriers.
- Defining some potential hydrogen demand profiles would be helpful. Understanding the hydrogen consumption could help determine future operational scenario testing.
- The project team needs to address the fundamental premise that co-located hydrogen production methods are cheaper, more reliable, etc., than a single method.

Project strengths:

- The project has a comprehensive scope, as it aims to develop a robust framework for hydrogen production, storage, distribution, and utilization, addressing multiple aspects of the hydrogen supply chain. The project team also chose a strategic location in Texas, which, with its rich energy infrastructure and resources, serves as an ideal location for demonstrating large-scale hydrogen projects. In summary, the project stands out for its comprehensive approach, strategic location, strong partnerships, technological innovation, environmental focus, economic potential, policy support, and public engagement efforts.
- This is a very good project with high impact. The project integrates many different hydrogen generation technologies and includes important areas such as pipelines and storage. The team is very large, with many industrial partners that will be able to use the information here.
- The project team's use of established, professional industry players to do the core of the design and build work is a good choice for ensuring a safe and functional initial build-out of the capability. The wide range of collaborations and plans for extensive outreach and growth based on this capability make it a good investment.
- The project team has made good progress in the installation of equipment and integrated demonstration of components. Outreach and presentations related to the project have ramped up. The team has also shown ingenuity and persistence in overcoming equipment challenges.
- The project team is good, and commissioning is nearly complete.
- This project has good physical demonstration with good collaboration.

Project weaknesses:

- The nature of a university system is to utilize undergraduate and graduate students to do a majority of the operations for research labs. This arrangement will prove to be a challenge to execute safely, especially for management of change at the station from the initial design. It is encouraged that there be dedicated faculty research staff members fully in charge of the system, and its safety, maintenance, and modification, to ensure that students have a safe teaching environment with closely monitored on-the-job (OTJ) training. Training courses for the students are critical for education and growth but are not substitutes for OTJ training from experienced staff members. A formal process for management of change and a revisit of the hazard analysis to assess the impacts of changes should be implemented for hydrogen systems, which is not a typical approach for universities for less hazardous laboratory-scale research.
- Collaborating and working with multiple stakeholders could get complex, and a control of measures sometimes takes long lead time. There are also technical challenges. Regarding infrastructure development, building and maintaining hydrogen infrastructure, including production, storage, and distribution, requires substantial investments and advanced technological solutions. The scalability and integration of these systems into existing infrastructure pose significant challenges. Regarding hydrogen production efficiency, current methods, such as electrolysis, still face efficiency and cost barriers. The energy conversion efficiency and the carbon footprint of these processes need further optimization.
- This project has uncertain tech transfer and includes an unproven key hypothesis in the usefulness of multiple hydrogen pathways at a single site.
- It was not totally clear what "re-qualification" was performed on the storage tanks. While the repairs were relatively minimal, there are typical standards around pressure vessels.
- The project team should identify additional opportunities for cost reductions or value streams, beyond economies of scale.

Recommendations for additions/deletions to project scope:

- It is recommended that the student safety training be reviewed by the HSP or Center for Hydrogen Safety.
- The project should model/simulate future hydrogen consumption for stationary and fuel cell electric vehicle applications.
- A plan should be established for management of change and safe operation and maintenance of equipment.
- Engineering target KPIs should be included for sub-suppliers and for the overall project.
- The project team should consider a more rigorous evaluation of hypotheses.

Project #TA-039: Solid Oxide Electrolysis System Demonstration

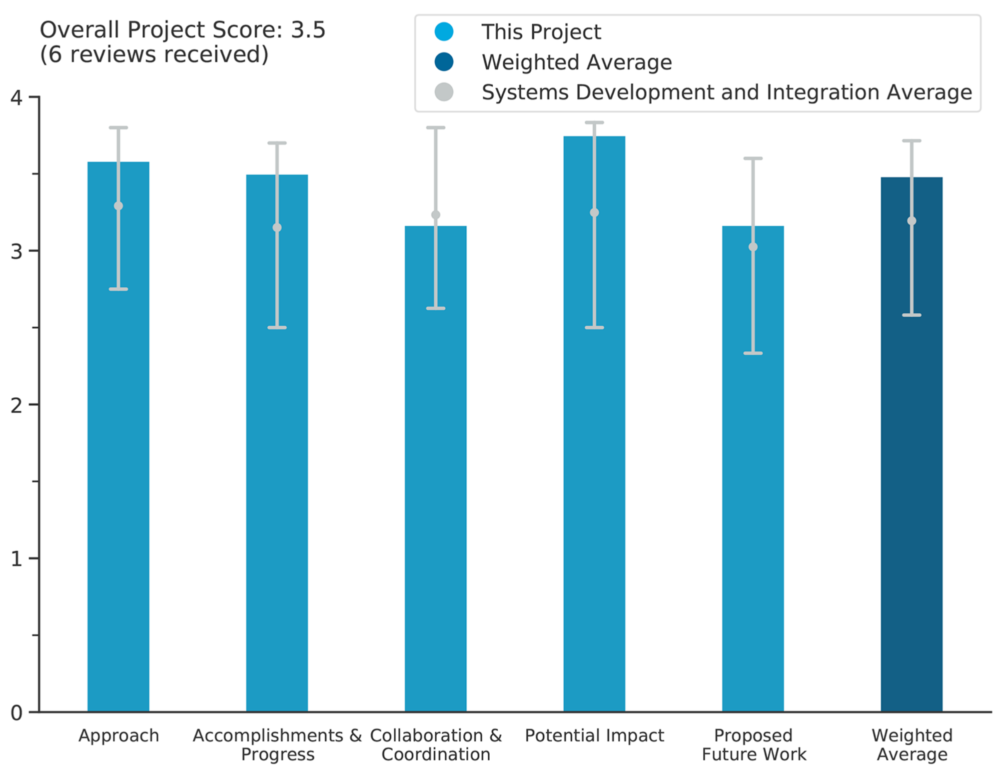
Hossein Ghezel-Ayagh, FuelCell Energy, Inc.

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 the 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 a 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 to increase 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 project's approach involves an order-of-magnitude scale-up of the SOEC technology, including full balance-of-plant (BOP) and system architecture. This is a valuable thrust toward the next steps to commercializing the technology by demonstrating the performance and integration of the systems needed for a relevant commercial unit size. The project's move from single-stack testing to 16-stack testing represents a reasonable jump in demonstration scale. The planned (and current) factory acceptance testing (FAT) process seems to be both robust and critical for success, considering the challenges encountered. The described pathway of development and milestones were reasonable.
- Overall, the approach is reasonable. The hardware-in-the-loop simulation of integration of the SOEC system with a nuclear power plant is a low-risk approach to validating the integration for clean hydrogen generation. The system size of 250 kW is meaningfully large for this effort. The system development approach is sound, and FuelCell Energy has extensive experience in developing these systems.
- The project focuses on designing, constructing, and operating a 250 kW SOEC prototype. The technical approach is very sound and well-thought-out. This will be unique and will represent the largest operational system in the United States, which would provide credibility to the SOEC technology.
- It is great to see good progress on the project. Techno-economic analysis (TEA) will be conducted at a later stage in Budget Period (BP) 2. It is unfortunate that electrical shorting occurred within stacks, and ideally, replacements will be implemented quickly. It would be nice to learn more about the root cause analysis and mitigation strategies. The reviewer hopes the Idaho National Laboratory (INL) tests go well and anticipates the results of BP 2.
- The project is well-thought-out, and the milestones make sense. The project team has addressed the comments from the 2023 Annual Merit Review.
- The team is pursuing technically sound approaches for system design and fabrication at FuelCell Energy and system testing at INL. It is unclear why the TEA work was planned for the end of the project. A more effective approach would include conducting initial TEA work, performed early in the project to help define test plan requirements for the demonstration, and then finalizing the TEA after the demonstration was completed.

Question 2: Accomplishments and progress

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

- The project team has met most of the project milestones. The team has fabricated the stacks and assembled the stacks into a system. The stacks passed the factory acceptance tests. Hazard and operability analyses have been completed, areas of concerns have been reviewed, and safety features have been installed. The project team has made progress in module installation in the mechanical BOP skid.
- The project team has made good progress. The project is slightly behind schedule, but given the scope, this is not surprising. The strategy to have one skid with the electrical and controls and a second with the BOP and SOEC is a good strategy. The 75% (lower heating value [LVH]) system efficiency, which includes generating the steam, is good system efficiency. The 84% efficiency (LVH) when steam is provided is excellent. The stack efficiency is very high at approximately 96%, and the 10°C temperature differential for the stack is very good. There are many voltage leads for diagnostics; it is unclear whether the intention is to have them in a final commercial product. The reviewer appreciated the speaker's openness about the project challenges.
- The project has completed all significant fabrication work of cells, stacks, and BOP (18 full stacks fabricated), demonstrating substantial success toward a fully functioning system that is ready for the next stage of the project (INL testing). The team appears to have encountered some challenges during the FAT process, but this is not unexpected for mid-stream technology readiness level development and advancement. The overall advancement of the project seems reasonable, considering the order-of-magnitude jump being made and the project timeline.

- The team has made significant progress overall, but some remaining issues are delaying the commissioning that completes the BP 1 go/no-go milestone. This delay is unsurprising in such a complex integrated system, but the commissioning is nonetheless vital to the project. The BP 2 work at INL cannot commence until the system is successfully commissioned.
- It seems that much progress has been achieved during the past year, and the project is on track for a successful demonstration.

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.

- INL has been a global leader in the understanding of SOEC system integration with nuclear heat and electricity since at least the early 2000s. The team at INL is the best possible choice for third-party validation of commercial SOEC systems with heat and power integration with a nuclear power plant. This work will unlock the potential for SOECs to deliver efficient, clean hydrogen that takes full advantage of the thermodynamic benefits of water splitting for SOEC operation at elevated temperatures. This collaboration will reach its full potential once INL receives the FuelCell Energy system, following the successful commissioning of the system.
- The technology appears to be primarily developed by a single entity, with evaluation and testing performed at a national laboratory test facility. Thus, the collaboration portion is not a particular strong suit of the project but is also no cause for concern. The inclusion of an experienced testing site at INL is a very meaningful collaboration and a good approach. It would be good to see a demonstration of more cross-collaboration between the two, if possible/applicable.
- FuelCell Energy is operating this project in direct collaboration with Versa Power Systems and INL. The roles and responsibilities of each contributor are clearly described.
- The project's only collaboration outside of FuelCell Energy and its subsidiary is with INL. This collaboration seems to be going well, and INL has good facilities for testing the SOECs.
- INL and FuelCell Energy make a strong team, but overall, there appears to be very little collaboration or interaction with other organizations. The inclusion of a collaboration or partnership with a nuclear power plant operator would be useful for defining requirements, although FuelCell Energy has such a collaboration on a DOE/Office of Nuclear Energy project. Versa Power Systems should not be considered a collaborator since it is 100% owned by FuelCell Energy.

Question 4: Potential impact

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

- FuelCell Energy's system is designed to operate either independently, supplying its own heat, or integrated with a source of waste heat that can supply steam and heat to the system and displace some of the electricity required to operate the SOEC system. The electricity cost is the primary contributor to operational expenses of water-splitting systems, according to recent DOE reports. Operating SOEC systems with fewer required kWh/kg of hydrogen produced lowers the operating costs of the system and lowers the levelized cost of hydrogen (LCOH). This lower LCOH is required to hit the Hydrogen Shot goal of $1/kg of clean hydrogen.
- The integration of a solid oxide electrolyzer with a nuclear power plant for hydrogen production makes good technical and commercial sense and provides a path toward low-cost hydrogen production. Ultimately, the question remains whether SOECs can be integrated with existing nuclear power plants (with waste heat utilization) or whether the application will require new builds (integrated SOECs with modular reactors). Regardless, the project has high relevance and potential impact.
- This project is a much-needed demonstration effort that would accelerate progress and add credibility to SOEC technology. It would answer many questions/unknowns at this system size (250 kW) and provide guidance on further potential system scale-up and integration.

- SOECs offer the highest potential efficiency of the electrolyzer technologies. Since electricity is the major cost for electrolyzers, they have the potential for low-cost hydrogen. Nuclear power offers dispatchable power and thermal energy, and integration with a nuclear system is a very good plan.
- The order-of-magnitude jump in demonstrated power is a relevant stepping stone on the pathway to commercial deployment, which could have impact in some use cases (e.g., baseload, high-efficiency hydrogen generation via nuclear power with heat integration).

Question 5: Proposed future work

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

- The description of the future work is brief, but it includes the important high-level categories. It is vital to complete the commissioning. The INL team's evaluation of performance and durability will be very valuable to the project and to DOE. The TEA work is important for determining how attractive this technology is for the production of low-cost clean hydrogen.
- At this point, the obvious next steps are exactly as planned by the project team: to complete the solid oxide fuel cell system and execute the testing and then complete the TEA.
- The future work described by the team includes integration and simulation of running with a nuclear power plant. This future work could be strengthened by doing parametric studies on system performance. The presentation did not mention whether some of the stacks would be sent to Pacific Northwest National Laboratory (PNNL) after testing is complete for post-test analysis.
- The future work for the project team is to perform TEA at high-volume system production.
- The team's general plan of finishing FAT and moving into testing at INL is sound. There is slight concern regarding the twice-failed FAT and a pathway toward resolution of the issue. The team appears to be developing this pathway to resolution, but understandably, there is not significant information yet as to what the resolution will be.

Project strengths:

- FuelCell Energy brings decades of expertise in these systems to the project. FuelCell Energy is one of the most appropriate integrators in the United States for such a complex and large (250 kWe) system. The integration with nuclear heat and electricity should enable very low kWh/kg hydrogen demands that should lower the LCOH for truly clean hydrogen from a steady baseload power plant.
- This project's technology is a first-of-a-kind 250 kW demo system in the United States, using lower-temperature (<730°C) SOEC technology. The team understands both the advantages and limitations of SOEC technology well, and the system design addresses both.
- This project represents a significant jump in an integrated solution for SOEC technology at an increasingly relevant scale. The potential for high-efficiency operation with heat recovery is promising for some applications.
- FuelCell Energy's stack technology and INL's system testing capabilities will provide an important demonstration of a promising production approach.
- The project team is strong and has demonstrated the technology. This project is in a high-impact area.

Project weaknesses:

- Given the large number of cells (6,000) with a yield of 80%, it is impressive that so many stacks are performing well. The project team may want to consider making larger cells. The large number of diagnostic wires may cause an increase in the power electronics.
- The complexity and scope of the project have exposed it to delays in the initial buildout of the skids and in the commissioning of the system. The delays appear quite significant at this point, but the no-cost extensions have given the project more time. Hopefully, the complexity risk can lead to a larger payoff once the stacks without electrical shorts are installed.

- Twice-failed FAT due to unexplained issues is concerning, though not overly so, as challenges are expected because of the development nature of the project. A clear pathway to resolution of this issue is of critical importance as a next step toward project success.
- The project's lack of input from any nuclear power plant operators on the requirements and demonstration test plan is a weakness.
- TEA should have been considered much earlier in the project.

Recommendations for additions/deletions to project scope:

- This is an important demonstration project, and the team effort to deliver the system on time is outstanding.
- The project team should plan to send some stacks to PNNL after testing is complete, if this is not in the plan already.
- The reviewer does not suggest any significant additions or deletions.

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

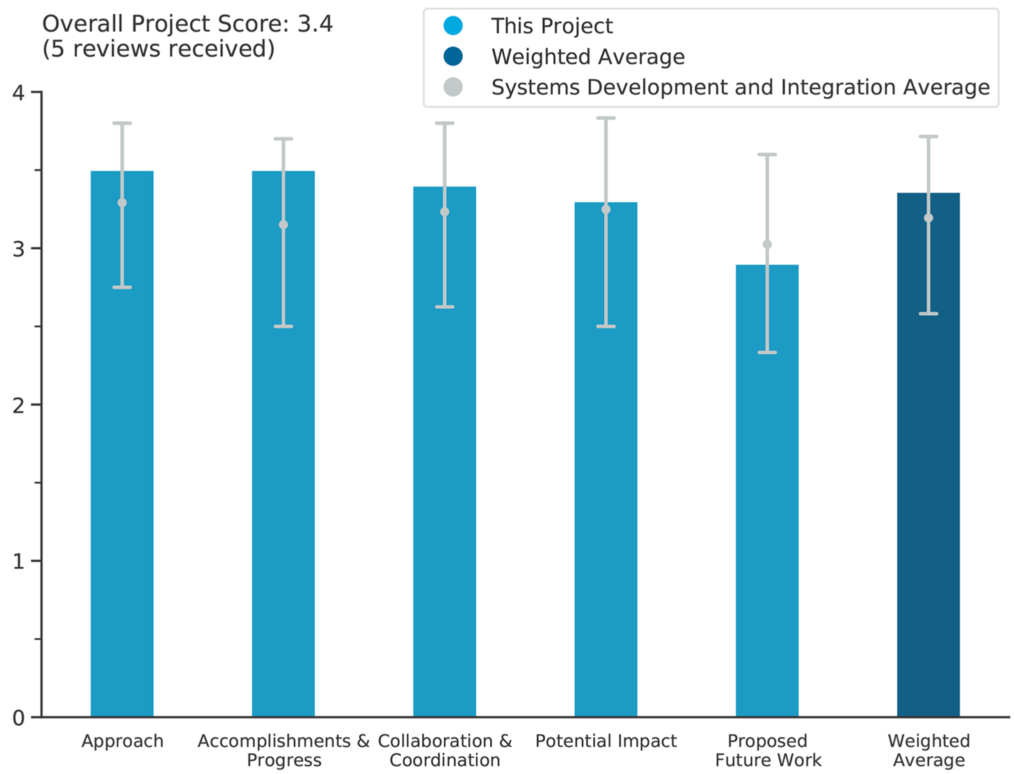
Paul Wang, Caterpillar, Inc.

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

- This project was the first of its kind to demonstrate and validate a 1.5 MW PEMFC system with liquid hydrogen storage for providing emergency backup power for a large data center. The demonstration was conducted on a Microsoft data center site. A key aspect of the team's approach was the deployment of a liquid hydrogen storage system instead of the more common gaseous hydrogen storage system, with the liquid hydrogen storage system providing sufficient hydrogen for at least 48 hours of continuous operation. The project addressed safety issues and concerns regarding liquid hydrogen storage on a data center site. The team engaged the Hydrogen Safety Panel (Center for Hydrogen Safety) and all subcontractors in all aspects of the hydrogen safety plan development and approval process. The team provided in-person and online job and safety training, documented process hazard analyses and lessons learned, and had zero reported safety incidents. Diversity, equity, inclusion, and accessibility (DEIA) efforts and a community benefits plan (CBP) were not addressed by the team and may not have been required of this project when it was awarded.
- The project team clearly stated the project objectives and barriers to successful demonstration of a backup 1.5 MW fuel cell power system for a commercial facility. Aside from not actually connecting to the site electrical grid, this project executed all operational aspects of an emergency backup power system, including cycling characterization and power quality measurements. The project team implemented a complete safety plan and included onsite safety personnel for the demonstration. As this four-year project is ending this September, neither DEIA efforts nor a CBP were mentioned or expected.
- The project team effectively communicated the goals, tasks, and work plan of the project. The project has come to a conclusion that satisfies all its stated goals.

- The principal investigator (PI) used a standard linear approach that consisted of (1) establishing requirements, (2) developing the design and concept, (3) building and testing at lab scale, and (4) integration and demonstration at full scale. The PI reports completing all major subgoals.
- The work to demonstrate a stationary hydrogen fuel cell for backup power to a data center was very focused and finished ahead of time. The approach was straightforward: to use a commercial fuel cell and liquid hydrogen system to operate a data center. The team overcame installation, safety, and environmental approvals for the installation, which is no small feat. There were also components to the project for meeting transient loads and durability testing. There are two downsides to the approach. First, the site for the demonstration was not permanent, so the whole system needs to be torn out. Although putting in a permanent data center was not part of the contract, it is still a waste. Second, the techno-economic analysis (TEA) seemed to be incomplete, as the team included primary batteries but not secondary batteries. While the TEA was in scope, it was not particularly useful. The team should have also updated the TEA for the final review and given a better perspective for how the demonstration fits in the puzzle of green backup power. Cummins should be commended for a very good slide on hydrogen safety. The team had no DEIA statement in the work.

Question 2: Accomplishments and progress

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

- All milestones and deliverables appear to have been completed on time and within budget. The team faced and addressed multiple technical, safety, and logistical issues in deploying both the fuel cell system and the supporting hydrogen storage system at the Microsoft site, including having to relocate from one Microsoft site to a different Microsoft site. Lessons learned are important in helping technology advance and increasing acceptance in the marketplace. The team demonstrated successful startups and operations to meet emergency backup power requirements.
- The three primary accomplishments include (1) demonstrating 48 hours of continuous run at 75% load, (2) exceeding performance of diesel generators for similar purposes, and (3) successful operation at elevations of >6000 feet and under freezing conditions. Other important accomplishments include a thoughtful safety plan, including engaging with the Hydrogen Safety Panel. The PI and team supported the training of first responders. The team was dealing with the potential for both hydrogen fires and battery fires, possibly at the same time, so safety was key.
- This project is a significant milestone for generating evidence on the viability of hydrogen as an energy vector for an industrial application. Using a fuel cell system to provide emergency power to an industrial site is one of many applications identified by DOE as viable. While all technical activities have concluded, it would have been beneficial to have had more than 48 hours of operational time and for the team to have actually connected to the site electrical grid to provide definitive evidence that electrons from hydrogen could support a data center. Other than those two points, this activity demonstrated all salient aspects of an onsite emergency backup power system. As this four-year project is ending this September, no DEIA or CBP was mentioned or expected.
- This project concluded, having demonstrated the use of fuel cells for backup power at a data center. The reviewer was pleased to hear that Microsoft had substantial involvement.
- The project team has done well making progress, with the demonstration having been completed in full and ahead of schedule. The only deficit to the project was the lack of details on what the team will do next. While it is understood that this could be business-sensitive, it would have helped to explain the overall impact of this $6 million investment. The team could have reported more on the transient response, because it is well known that hydrogen fuel cells can follow transients. The system was also hybridized, and it is unclear if the battery met some of the transient load. The project team did not report on any assessment of the impact of the data center transients on fuel cell durability, nor on their GHG emissions (e.g., presumably a diesel truck was used to haul the equipment and hydrogen to the demonstration site).

Question 3: Collaboration and coordination

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

- The participants included Caterpillar, the National Renewable Energy Laboratory (NREL), Microsoft, Ballard Power (Ballard), Linde, and McKinstry. This is a diverse team with diverse capabilities that are essential to success.
- Caterpillar built a top team for the demonstration, including Ballard, NREL, and Linde.
- The safety planning with multiple partners and multiple first responder groups, plus the buy-in from Microsoft, all seemed outstanding.
- The project team is excellent, including subcontractors Ballard (a major supplier of PEMFC systems) and Linde (a major producer of hydrogen and supplier of hydrogen storage systems), as well as Microsoft as host of the demonstration and a major owner/operator of data centers. The roles of NREL and McKinstry are not clearly described.
- This project is a strongly commercial effort that includes a limited cast with no explicit collaborations listed beyond the project team and NREL.

Question 4: Potential impact

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

- This extremely focused project provided empirical evidence toward the viability of megawatt-scale fuel cell systems for applications with high power quality requirements. The commercial and industrial sectors require this evidence prior to committing meaningful resources into procuring and deploying megawatt-scale fuel cell technologies.
- Emergency backup power for data centers represents a potentially significant market opportunity for fuel cell systems. The project's lessons learned from the perspective of the team at Caterpillar, which deployed and demonstrated the technology, and from the team at Microsoft, which is the customer, should prove significant and valuable to help advance the technology and increase its market readiness. Installing and demonstrating the safe operation of the liquid hydrogen storage system is critical for this and other applications that will transition from gaseous hydrogen storage to liquid hydrogen storage, thereby addressing the need for longer operating time requirements and less time between refilling the storage system.
- The PIs have been evaluating the potential to use hydrogen to back up data centers. This effort is currently performed by backup diesel generators. Replacing diesel with hydrogen assets is relevant to the decarbonization effort. Working with both batteries and hydrogen is laudable, and the degree of integration with the data center is impressive.
- The project is aligned well with DOE Hydrogen Program goals.
- Despite the excellent response of the team to the DOE Hydrogen Program metrics, the project has ended with no clear way forward. It would have been more helpful if Caterpillar had been able to make some sort of positive assessment of the system and the lessons learned. In the end, the system ran for a short time and then was torn out. It is unclear why Microsoft was hesitant to keep the system (i.e., whether the concern was about TEA, logistics, etc.).

Question 5: Proposed future work

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

- The project has ended on a high note, but the go-forward plan is not yet defined. This is fine, as many demonstrations end this way. The reviewer wishes the project team luck in finding a new home for the fuel cell and continuing to test and prove the technology.
- While this project does not end until September, all its demonstration activities have concluded. At the time of this review, the final disposition of the hardware was not reported, and no subsequent activities were mentioned. If additional work were to occur for this concept in the future, significant benefit would be derived from a multi-month demonstration actually connected to the demonstration site electrical grid.

Such a demonstration would provide critical evidence toward the commercial viability of this concept and would potentially expose the unknown unknowns requiring mitigation prior to implementing this concept in a permanent installation.

- The project has been completed. Unfortunately, the team at Caterpillar is decommissioning the site and is looking to commercialize the technology. Hopefully, the final report will contain Microsoft's perspective on the strengths of the technology, as well as the weaknesses/shortcomings that were not addressed in this project but that need to be addressed to enable broader deployment opportunities for fuel cell system emergency backup power for servicing data centers.
- The project is ending, with the only remaining task being to decommission the fuel cell. It may make sense to continue this work at NREL so the project team can collect more data.
- The project is drawing to a close, so there is no future work at this time.

Project strengths:

- The project team designed, built, and demonstrated a 1.5 MW PEMFC system, including the supporting hydrogen storage/delivery system for emergency standby power for a modern data center. The fuel cell system was built on the site of a Microsoft data center. The lessons learned, both from the perspective of Caterpillar, in terms of building/installing the system and ensuring safe operation, and from the perspective of Microsoft, as a potential client for fuel cell emergency power backup systems, are valuable to both companies. It is valuable for Caterpillar as it moves forward to commercialize the technology and for Microsoft as a potential customer. The team demonstrated multiple test cycles in excess of 4 hours/run, including one ~80-hour continuous run.
- This project provided hardware data from a megawatt-scale fuel cell power system supporting an alternating-current electrical bus. This project activity illustrated the successful integration of the components and subsystems necessary to support an industrial electrical grid with high-quality electrical power from hydrogen using a fuel cell.
- The project team reported completing their project objectives, which were ambitious. The thorough engagement with the Hydrogen Safety Panel and engagement in onsite training deserve extra kudos. The level of hazard and operability support across the team was simply exceptional.
- This project is a great demonstration of hydrogen and fuel cell technology for data center power systems. The project team accomplished what it set out to do.
- The project was completed on time, had no accidents, and reached all project goals.

Project weaknesses:

- No weaknesses are noted. Future efforts would be advantageous for improving the systems so that they could be used at data centers.
- While the testing schedule demonstrated one run of ~80 hours of continuous operation, which is substantially more than the 48-hour requirement, and the total run time of all test cycles was stated to be equivalent to 1–15 years of typical operation for a diesel generator, the lack of significant downtime between runs fails to address any issues that might occur due to periods of long inactivity. Diesel gensets typically operate for only a few minutes each month during the monthly test and are in shutdown mode the rest of the time. The project team did not address the question of the reliability of the fuel cell system and the supporting hydrogen storage/delivery system operating in such an operational mode, so it remains an unknown. The project is completed. While the project can be deemed a success, it is unclear how the knowledge gained and the lessons learned will benefit the broader fuel cell system backup power market for data centers. The transfer of this information is critical, as the number of data centers is expected to grow significantly in the coming years. The demand these centers will put on the electrical power grid is not totally understood, and there is a tremendous opportunity for fuel cell systems to serve as emergency backup power.
- This project did not continue long enough to provide actual operational costs or identify the unknowns that are revealed only by long-term exposure to reality. It would have been beneficial for the project team to connect to the site electrical grid, which would have provided significant evidence on any potential benefits from this concept.

- The project did not really answer the questions about the suitability of liquid hydrogen or stationary fuel cell power for data centers. The TEA was not updated at the end of the project, and there were no lessons learned. The role of the battery in the hybrid system was unclear.

Recommendations for additions/deletions to project scope:

- Ultimately, with this asset, it would be great to continue operating it at some demonstration site to learn more and prove out the technology over time. There are many more questions to address, and it would be sad not to see the asset repurposed. Longer-duration testing would be nice to see, maybe stressing the fuel cell under different conditions.
- It would be good to write a final report and publish it in a peer-reviewed journal to share more lessons learned and give a final assessment of practical strengths and weaknesses of the demonstration.
- This field is not applicable, as the project has concluded.

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

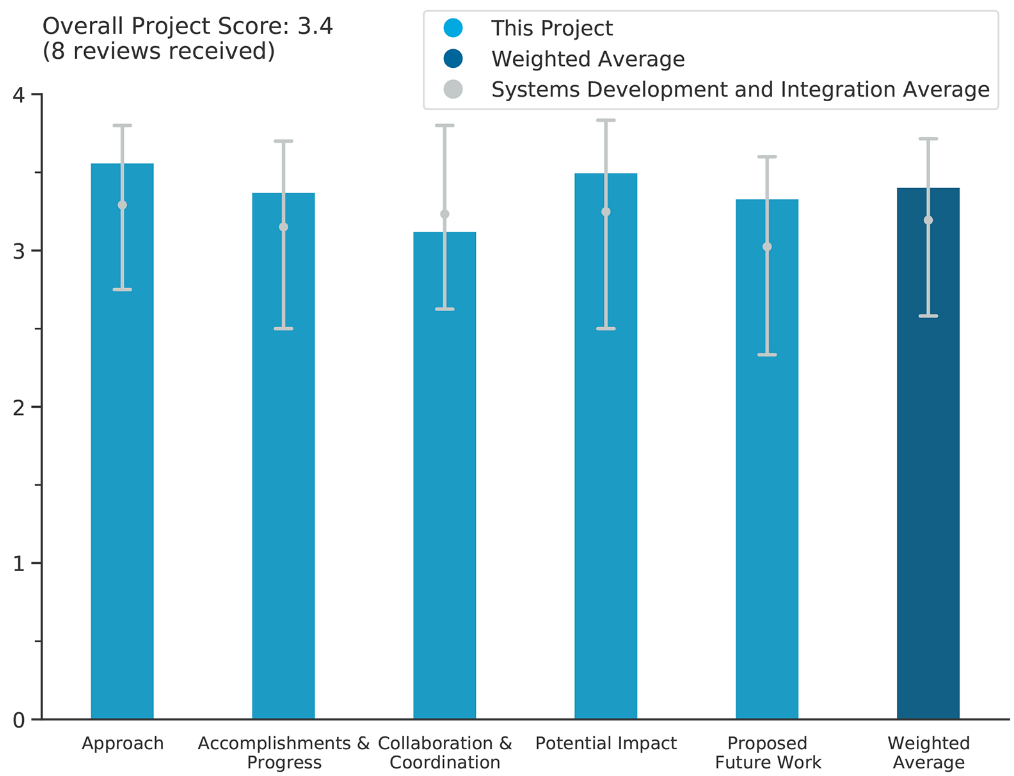
Daniel Leighton, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.9
Start and End Dates	5/6/2020–9/30/2024
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 (R&D) 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.

- The work focuses on the following three barriers: demonstration of electrolyzer and stationary fuel cell technology under real-world conditions, production of hydrogen using directly coupled zero-carbon energy sources, and hydrogen energy storage and grid stabilization for a high-penetration renewable electric grid. The work approach establishes a research capability within the DOE national lab network that is nothing short of outstanding. The approach focuses on demonstration of system integration at meaningful scales, specifically the coupling of electrolyzers with wind and solar, storage, and fuel cell operation, while also allowing the near-plug-and-play capability for future cooperative research and development agreement (CRADA) projects. Safety planning and culture are at the forefront and meet expectations.
- The project allows testing and integration of megawatt-scale renewable energy with a megawatt-scale electrolyzer, hydrogen energy storage, a megawatt-scale fuel cell, and control electronics and software at one site. Key benefits include the flexibility of the system the project team has built and its ability to reconfigure and switch between three grids to test integration of different assets, including wind and solar. The project de-risks testing of large-scale systems by having the potential to test systems on isolated grids. This can allow testing that you may not be able to perform on a commercial grid, owing to worries about impacting other grid customers.
- The project approach is well-defined and very relevant to the mission of the Hydrogen and Fuel Cell Technologies Office (HFTO), as the project supports the Hydrogen Shot. The work enables megawatt-scale testing of various configurations and equipment. The project complements the testing at NREL's Energy Systems Integration Facility and enables equipment manufacturers to move from a test stand to an integrated operation.
- The project approach is good, targeting relevant integration/operational challenges. The testbed will provide opportunities to evaluate technologies in a real-world environment.
- The project team has a good approach to building a platform, and it is good to see that there have been multiple projects that replicate parts of this one.
- This is a great renewable power–electrolyzer integration, as it is very meaningful to showcase successful integration. The project team did not discuss operating capacity when combined with solar and wind, and it is unclear if this project's hydrogen has a safety panel from industry. It would be more meaningful if the authors compared hydrogen storage with battery storage.
- This project presents a research capability to de-risk large-scale deployments, and its integration looks good. The project's hardware-in-the-loop, especially with the microgrid to understand grid impacts, is important. It is unclear how the project data will be shared with industry, the Regional Clean Hydrogen Hubs Program (H2Hubs), and other national laboratories.
- In the context of a response to a 2023 comment on this topic, it is still unclear how the project will address redundancy for the hydrogen production component of the project (e.g., multiple electrolyzers, other production methods, backup delivered liquid hydrogen storage). While there is collaboration with the electrolyzer original equipment manufacturer, there is only one hydrogen production method, and long-duration equipment malfunction of a single critical path component will disable the whole site for hydrogen-related activities. The project does not directly connect to wind and solar power sources, which, for an R&D facility of this scale, should be an option seriously considered because it is not done elsewhere at this point. It is unclear what the cost structure is for private industry to use this facility. As this project is publicly funded, it should have reasonable, non-prohibitive rates.

Question 2: Accomplishments and progress

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

- The project has successfully installed all major equipment. Data are being collected at the electrolyzer, and the resulting estimates of energy efficiency over time for both step function and simulated solar and wind curves are excellent accomplishments. The reporting of the fuel cell operation in grid-following mode is good, and it is impressive that the team was able to troubleshoot a filter clog rapidly and continue the operation. Estimating and demonstrating 50% fuel cell efficiency, as well as efficiency when accounting for parasitic losses and conversion with produced hydrogen, are excellent.

- The project's electrolyzers have been commissioned, and initial data has been captured. The project team was able to operate the electrolyzer to simulate wind and solar curves. As expected, the balance of power limits the electrolyzer response times. The response looks similar to the older wind connection to electrolyzer work done previously by NREL at a smaller scale. The round-trip efficiency demonstration confirms the projected round-trip efficiency used in the Energy Storage Grand Challenge cost estimates.
- Great progress has been made in validating the integration of wind or solar with electrolyzers. This is the first success of a laboratory-led integration project.
- The project team has completed installation and integration efforts. The team has achieved round-trip efficiency—for solar electricity to hydrogen, then back to electricity—of 35%.
- The project team has completed the planned equipment installation. The project is operating and producing results. The project is producing hydrogen at a megawatt scale with renewables. The project should have provided more analysis results. If the project did a complete analysis of the cost of hydrogen, it should have been presented during the Annual Merit Review presentation.
- The selected and implemented electrolyzer appears to have more unstable current at the point of highest operational efficiency. While efficiency is a factor, it is unclear how the project plans to put a value on the ability to store renewable energy.
- The site is operating.
- The project is complete.

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 has already identified an outstanding list of projects with valuable information and manageable plug-and-play opportunities for the campus. This is impressive, given the likely long waitlist and ambitious visions for work at the site. Balancing potential with practical first collaborations is key.
- The project team has collaborated with Toyota North America (Toyota) and Nel Hydrogen to commission the system and, more recently, collaborated with the Electric Power Research Institute, the Southern California Gas Company, General Electric, and the Gas Technology Institute.
- The project has engaged in broad national laboratory and industry collaboration.
- This project has good collaboration with an electrolyzer manufacturer (Nel Hydrogen) and a consumer of hydrogen fuel (Toyota). This project would have benefited from the inclusion of a utility such as Excel on the project team. The inclusion of a grid operator would also be beneficial since the commercial operation would most likely be connected to the electrical grid.
- The capability has potential to generate useful data to support industry and directly support H2Hubs. It would be helpful to know how the data and learnings will be made available to project developers. The initial projects look interesting.
- Collaborating with industrial partners (Nel Hydrogen and Toyota) is valuable, but information dissemination would benefit from additional partners.
- The project has limited collaborations because its focus is to establish NREL capability.

Question 4: Potential impact

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

- The project is directly aligned with three barriers that are essential for the advancement of wind and solar hydrogen. This alignment touches on confidence-building and efficiency in troubleshooting system integrations that can lower risk of investment for other megawatt-scale projects. There are many non-financial barriers that green hydrogen deployment faces, and this project can advance our understanding of genuine risks and challenges that may affect predicted performance and safety.

- The system will allow testing integration of fuel cells and electrolyzers with solar and wind energy to test devices in grid services, energy storage, and other applications. The project allows for proof at scale and for testing control strategies to optimize the larger integrated systems.
- The project is relevant to HFTO from the aspect of having a megawatt-scale renewable hydrogen test facility. This project will enable future testing of large-scale integrated projects with renewable resources.
- This project is a great example of renewable power–electrolyzer integration, and it is very meaningful to showcase this successful integration.
- This project is working on relevant challenges that need to be addressed prior to large-scale deployment of hydrogen systems.
- This is a very useful platform project on which future projects will be built.
- The project has good progress and impact that are long anticipated.
- This project supports the DOE H2@Scale vision. The impact will depend on how the data are shared and how the access to use the capability is done.

Question 5: Proposed future work

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

- The project to build the system has been completed, except for the compressor system. The project team plans to complete the compressor system and demonstrate storage of one week's worth of hydrogen. The project team also plans to produce data for four separate projects related to clean hydrogen, including studying dynamic response and direct alternating current (AC) grid coupling of an electrolyzer with photovoltaics and wind turbine. The system is now being used for testing for multiple CRADA projects, with more in negotiation.
- Future work is focused on finishing project scope regarding the three barriers listed. In particular, it is essential that the project directly couple the wind and solar power with the electrolysis unit. It would have been nice to see more comments on hydrogen energy storage and grid stabilization for a high-penetration renewable electric grid, as the sizing of the storage system is quite arbitrary based on physical constraints, and integration with the local utilities and grid is also missing. Still, it sounds like additional storage projects, both hydrides and subsurface, are under way.
- Some initial tasks have been started, and the project team is looking at dispatchable loads and grid tests.
- It may be valuable to consider direct-current-coupled (DC-coupled) systems in the future. The team should publish lessons learned around completed efforts (e.g., safety, integration, controls) and future efforts (microgrid stability with high penetration of grid-following resources).
- Storing hydrogen for longer than a week should not be an issue; how much is stored is more of a challenge.
- The project is ending.

Project strengths:

- The project team and leaders should be congratulated for successful installation of the equipment. The reviewer appreciates that NREL recognized the team and that the award summarizes the team's accomplishments well. The ability to bring together so many partnerships will help blaze the trail for others seeking to get megawatt-scale projects safely deployed in a timely manner. The project team also did an excellent job responding to past reviewer comments, particularly on water questions. The project is wrapping up, but it is encouraging to see future work target very critical aspects of the scope, as well as target selection of CRADA projects that will further tackle the original three barriers this capability-building project sought to address.
- The use of three parallel grids makes this system quite flexible and adaptable and allows for megawatt-scale testing in isolation from the local grid.
- The project is demonstrating hydrogen production from a megawatt-scale production system. The testbed will enable that testing and dynamic testing of connected renewable resources for hydrogen production.

- This is a great renewable power–electrolyzer integration, and it is very meaningful to showcase the successful integration.
- This is a very inclusive platform project done at the right scale.
- This project is the first at this scale for research, development and demonstration purposes.
- Understanding how electrolyzers respond to rapid signal changes is valuable to future operations.
- This project is well-funded by DOE. The NREL team has done a good job integrating the systems.

Project weaknesses:

- Further details on the procedure for allowing new campus personnel, students, workers, or CRADA partners would be helpful for further evaluating the safety plan and culture. It was not clear why the team used a simulated solar photovoltaic curve rather than the direct-coupled solar production. Additional details on sensors and monitoring would be helpful in understanding the ability for rapid response to issues (filter clog, etc.) and what can be expected for state-of-the-art response time. A more detailed visual of the round-trip efficiency and how it ties into expected solar and wind in that location would be helpful in understanding how the results in this project may be more generalizable to other sites and facilitate site selection for similar micro projects. Some of the future work proposed sounds very difficult to deploy in a plug-and-play manner—specifically, integration of natural gas hydrogen with wind and solar hydrogen or the integration of a pipeline or direct reduced iron unit. It would have been helpful to hear more consideration of the original footprint and design of the facility, with a nod to what might have been done differently, to prepare for much more complex system integration projects.
- The project team should have provided more analysis and understanding of the cost of hydrogen production. Also, the analysis should provide “tornado” charts of the impact of different variables. A waterfall chart of reducing the cost of hydrogen to $1/kg should have also been provided. One project limitation, given the Flatirons facility location, is the availability of water resources. While the project team plans to truck in water, the megawatt-scale facility will need large quantities of clean, deionized water. As a result, the delivered water will need to be purified, and impurities will need to be rejected/recycled. Some information or mention of how this project supports the DOE HFTO Hydrogen Shot should have been provided.
- While a safety review is not required for this scale, this project may benefit from having a review from the Hydrogen Safety Panel (HSP). The HSP has experience in larger systems that may benefit the project.
- The project would benefit from considering multiple hydrogen production methods and integrations (steam methane reforming, autothermal reforming, solid oxide electrolyzer cells, methanol reformation, ammonia cracking, etc.). The project is also lacking regarding the hydrogen pipeline component.
- Lack of high-pressure storage limits opportunities for vehicular refueling.
- Hydrogen storage is a little limited.
- The project would benefit from collaboration with other partners, mainly from industry.

Recommendations for additions/deletions to project scope:

- The project would benefit by engaging the long-duration energy storage teams at NREL, Sandia National Laboratories, and Pacific Northwest National Laboratory to ensure that the project system can simulate integration with the grid. The data-sharing plan needs to be improved to enable utilities and other national laboratories that model the grid to use the data that are generated to better simulate the grid. A community benefits plan should be added.
- The cost of the electrical infrastructure required to connect to the grid—i.e., electrical switchyard and transformer costs—should be extracted from the project. These costs should be considered first-of-a-kind costs, while Nth-of-a-kind costs could be projected and added to Hydrogen Analysis (H2A) models.
- The project team should resolve and/or conceptualize the integration of other hydrogen generation and supply options.
- It might be worthwhile to look at integrating hydrogen liquefaction and liquid hydrogen storage.
- The project should add high-pressure storage and DC-coupled electrolyzers.
- This project is over. If the project receives additional funding, longer durability testing should be performed.

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

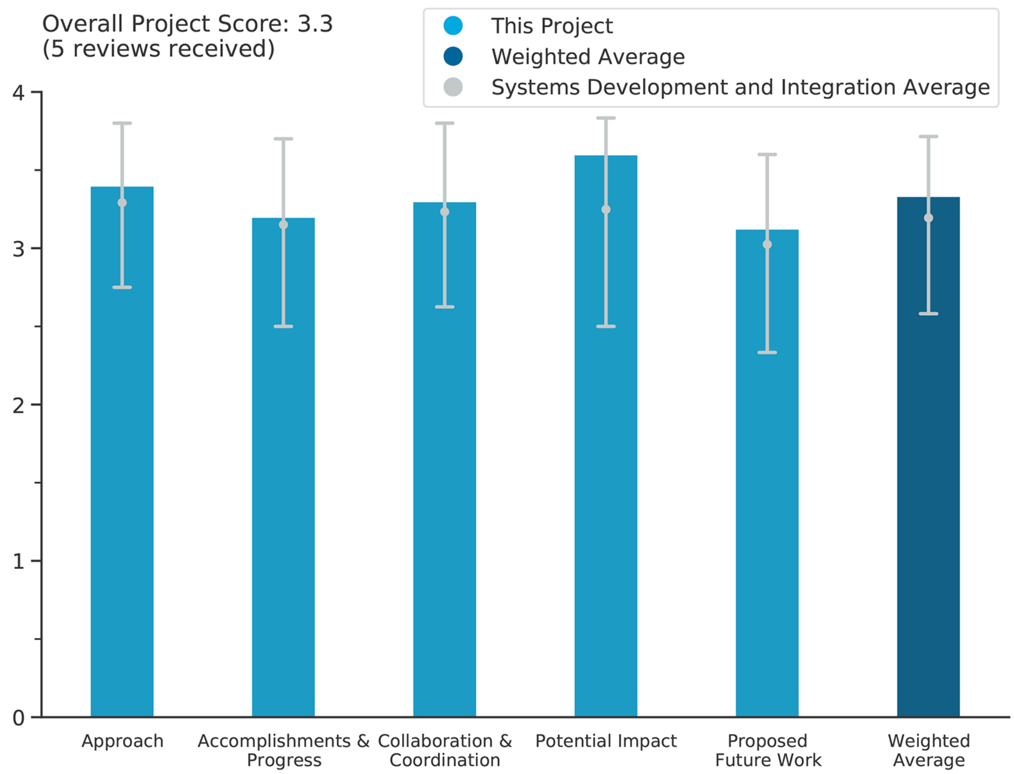
Jack Brouwer, University of California, Irvine

DOE Contract #	DE-EE0009249
Start and End Dates	3/10/2021–9/10/2024
Partners/Collaborators	University of Wisconsin–Madison, 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 electrolyzer cell (SOEC) module and a direct reduced iron (DRI) furnace, paving the way for production of clean 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/yr 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 analysis (TEA) 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 **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The purpose of this effort is to couple SOECs with DRI plants with the objective of producing green steel. The "green" moniker comes from either the use of hydrogen from green electricity or the use of carbon sequestration with natural gas. The effort is arranged around five work packages: system integration and thermodynamic analysis; SOEC module design and control; SOEC prototype design, construction, and testing; design and characterization of pilot-scale processes; and TEA of full-scale layouts.
- The demonstration of effective use of hydrogen for direct reduction of iron is a critical and outstanding approach toward integrating renewable energy into industry. The team takes on an ambitions scope, supported by industry partners and an impressive advisory board. Kudos to the principal investigator (PI) for setting out very clear targets for cost, production, emissions, technology readiness level advancement, and energy efficiency, highlighting the project's clear coupling of experiment with practical system-level targets. The approach to integrating SOEC with DRI is unique and poses very compelling opportunities for systems integration and heat management/top gas recycling that can only be truly verified with a demonstration.
- The project approach is excellent. It includes key industry collaborators. The project is inclusive and considers the impacts of contaminants that could affect the electrolyzer operation. A safety review was conducted and considered a high priority. The project could benefit by including a utility company and grid operator.
- Good progress was made on the project, and clearly much work is still to be done through the nine-month extension. A significant amount of information was shared, and it would be helpful to tell a higher-level, cohesive story. It was unclear if slide 19 was intentionally blank. It was great to hear that another $10 million was secured for a demonstration with Cleveland Cliffs. The assumptions behind the calculations and each line item in slide 13 should be clarified.

- It will be a long journey to implementing SOEC/DRI into steel manufacturing. Analysis work leading to hardware-in-the-loop simulation with SOEC demonstration is a reasonable approach as a first step in this journey. The approach for analysis in this project was solid. The approach for the SOEC demonstration is a work in progress. There does not seem to be any connection between the analysis work and the stack demonstration work with respect to defining stack requirements.

Question 2: Accomplishments and progress

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

- The PI and team made progress in several areas, including demonstration unit design and fabrication, electrochemical impedance spectroscopy, scale-up mass and energy balances, and capital expenditure (CAPEX) analyses. The PI and team performed simulations to consider thermally integrated systems. They also included a nice comparison of costs showing that there is a benefit.
- Accomplishments include outstanding progress on the development of a safe prototype design and logical series of experiments, despite supply chain issues. It would be good to see publications coming from this work as preprints to expedite the communication of critical data and insights learned from this project.
- The project analysis has been inclusive and identified key elements that affect the steel cost. It is suggested that a tornado chart be prepared to identify the impacts of variance of key variables. The project should consider including the use of oxygen from the electrolyzer to offset the costs associated with hydrogen. Oxygen is produced from an electrolyzer at a ratio of 8 kg O_2/kg H_2. Steel plants use a considerable amount of oxygen. The project conducted a safety review. The current operation has been delayed by the delivery of key equipment. The project will continue with a no-cost extension. The project has prepared a scaled-up design that will be beneficial for industrial partners.
- The analysis work was well-conducted and provides a solid basis for future demonstrations. The SOEC demonstration work is behind, apparently because of supply chain challenges.

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 collaboration involves coordination among several partners, including the University of California, Irvine, the University of Wisconsin–Madison, FuelCell Energy, Versa Power Systems, Hatch Associates Consultants (Hatch), Politecnico di Milano, Laboratorio Energia Ambiente Piacenza, and Southern California Gas Company (SoCalGas). The team has also arranged for an industrial advisory board that includes several of the leading companies in the DRI space, including Nucor, Tenova, ArcelorMittal, Midrex, Snam, Cleveland Cliffs, and the Electric Power Research Institute.
- There is outstanding collaboration between academia, industry, and international partners. Details on diversity, equity, inclusion, and accessibility were missing. It is unclear what SoCalGas's role is in this project is if there is only electric arc furnace (EAF)/secondary steel and not DRI in California. It is not clear what the role is of the University of Wisconsin–Madison in the project. The team may want to consider working with the National Renewable Energy Laboratory (NREL)/Lawrence Berkeley National Laboratory (LBNL) team to add this model to the GreenHEART model coupling wind with hydrogen production using DRI/EAF. There is no need for Hatch to reinvent the wheel on some of the modeling TEA and life cycle analysis work.
- The project has an excellent team and has collaborated with key steel companies. The project could benefit from including an industrial gas company and utility company. The project is handling hydrogen and could potentially include oxygen. The industrial gas company could provide insights about oxygen cost and the overall project impact.
- There are a great many participants and advisors in this project, although it is not clear that there has been a high level of coordination among these participants. Fuel Cell Energy and Versa Power are the same company, so they should not be listed as separate collaborators.

Question 4: Potential impact

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

- The data already produced through simulations, design, and initial TEA work are outstanding, as is the inclusion of key stakeholders to derisk investment. The field will benefit greatly from the kinetic data and thermodynamic analysis, and it will be important that the team provide insights on the scaling of such results to large deployments.
- The project supports goals of H2@Scale and Hydrogen Shot. The project should elucidate its impact on these efforts. The testing and demonstration operation will provide valuable data and information to the project's industrial partners and DOE.
- The PI indicated several potential impacts that could be met related to hybrid hydrogen direct reduction. Highlights include concepts for 2 Mton/yr and 8 GJ/ton.
- This project is an important first step toward decarbonization of one of the largest CO_2-emitting processes in our world. Thus, the potential impact is extremely high.

Question 5: Proposed future work

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

- The PI indicated that the next steps are experimental, including a hardware-in-the-loop demonstration with SOEC. The PI and team also intend to prepare articles. It would appear that a no-cost extension would be in order, if one has not already been approved.
- More focus is recommended on the intermittency of SOEC operation based on renewables. Details included on the storage (slide 18) were appreciated, but more detail on the simulation would be useful. The question of how this could affect the DRI capacity factor is concerning, and there must be a sweet spot between SOEC operation, storage, and conditioning. Perhaps the project could leverage the excellent simulation work conducted by NREL teams led by Dan Leighton and Genevieve Saur to simulate steady-state and wind/solar profiles and effects on electrolyzers (proton exchange membranes, in their case). It is unclear whether compressed gas is adequate for ~200–4,055 tons of storage. Carrier/toluene–methylcyclohexane (MCH) storage might also be considered. It is unclear what the impact and energy penalty of CO_2 capture from reducing would be. It looks like capture only from the furnace is proposed (slide 17). It is excellent to see continuation of funding and the active participation of Cleveland Cliffs.
- The SOEC stack demonstration is well behind where it needs to be. It is not clear that the analysis work defined conditions under which the SOEC stacks must be operated. It would be useful if this “connection” can be made as the stack testing plan is developed.
- The project will be completed through a no-cost extension.

Project strengths:

- The effort to integrate components was appreciated. A strength of this effort was the clarity that the $200/ton target has been taken out by inflation, even as the team works to find efficiencies to lower the cost. A particular project strength was the engagement of the Hydrogen Safety Panel early in the process.
- The project supports H2@Scale and the goals of the Hydrogen and Fuel Cell Technologies Office. The project will demonstrate the impacts of hydrogen on the steelmaking DRI process. Key vulnerabilities of the electrolyzer to contaminants will be assessed, and potential solutions will be studied.
- Project strengths are the very clear flow and integration of tasks and team members, outstanding progress on the development of a safe prototype design, and a logical series of experiments, despite supply chain issues. Off-design simulations are excellent.
- The analysis work is solid.

Project weaknesses:

- More details are needed on the SOEC fabrication related to whether any modifications were made for this work or these systems are “off the shelf.” It was unclear whether lessons were learned when going through vendor selection and skid fabrication design considerations. It was unclear how much variation in selection there was for the type of heat exchangers required. The CAPEX does not include handling equipment for the DRI, which is hazardous material and challenging to transport if it is delivered cold to an offsite EAF. The reviewer adds a note of caution when doing the TEA benchmarking with other systems. The details on slide 13 of CAPEX are a bit vague in general. Missing details on the measurement and verification process and associated sensors and controls made it hard to evaluate the data quality that will be generated and the level of automation vs. the manual measurements involved.

- The project would benefit from having industrial companies and utilities on the project team. The project should provide a sensitivity analysis of the impact of key variables and generate a tornado chart of these impacts. Also, a waterfall chart should be constructed to show the impact of various key efforts to reduce the cost.
- SOEC stack demonstration work is woefully behind. There is little evidence that the analysis work has defined stack requirements that will feed the stack demonstration test plan.

Recommendations for additions/deletions to project scope:

- Including impacts on cooling tower capacity/makeup water would be very helpful. The Elgowainy Argonne National Laboratory team and the Breunig LBNL team modeled impacts on water consumption in iron and steel for the NREL GreenHEART model; the results could be used for benchmarking.
- It could be very valuable for the team to perform additional analysis work to define requirements of the stack (steam/CO_2 utilization/selectivity, feed compositions, impurity tolerances, etc.) and to define specific goals of stack development work to reduce the burden on balance-of-plant components.
- The recovery of oxygen from the electrolyzer should be assessed and analyzed to determine the impact on the cost of steel and the break-even cost of hydrogen.
- The sensitivity analysis discussed in the presentation at the Annual Merit Review meeting should be included.

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

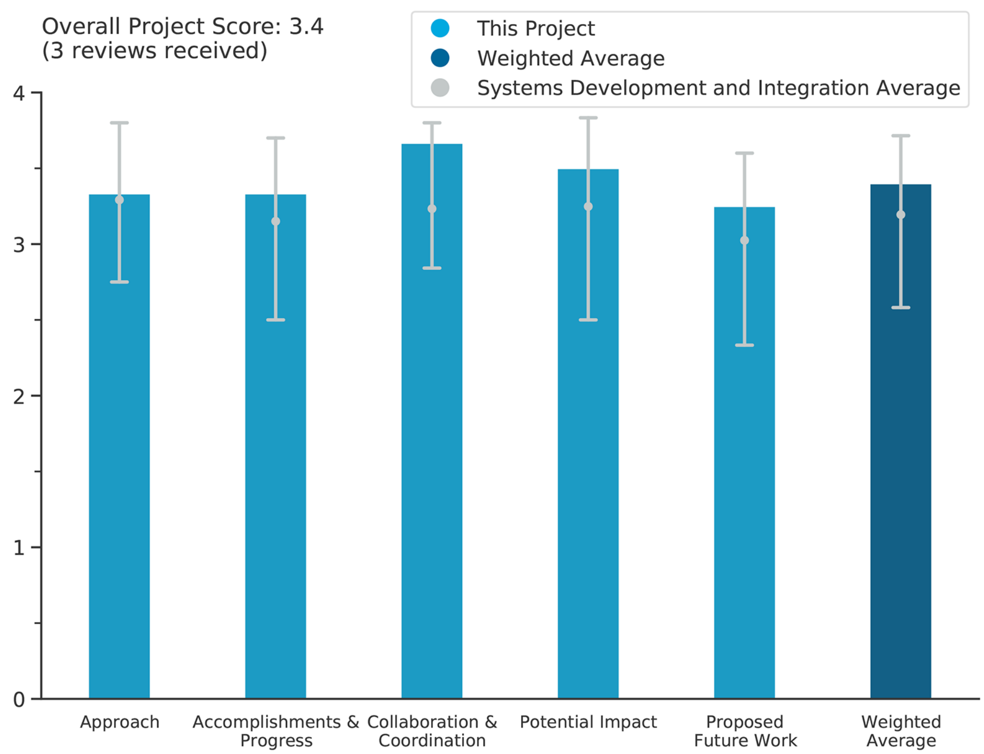
Ronald O'Malley, Missouri University of Science & Technology

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 derisk 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 (NG) 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 analysis (TEA) to quantify the economic opportunity of the project's 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 project seeks to address several critical barriers including rising materials and manpower costs, materials and construction delays, gas preheater design startup issues, and hydrogen safety approvals. Lowering the cost of low-carbon-emissions steel is directly related to the approach and scope of this project. Hydrogen safety approvals appear to have occurred in a previous year, and the team seems to have incorporated feedback from past reviewers. More than the project overview barriers listed, the project has major implications for the validation and demonstration of hydrogen use in iron and steelmaking. The approach takes on an ambitious scope of work through a combination of pilot experiments, simulation, TEA, and industry feedback. It was not clear whether the inlet hydrogen was delivered at a pressure, temperature, and purity to simulate proton exchange membrane (PEM) electrolysis (prior to gas heating) and whether the system was operated at steady state. Some hydrogen may be needed from storage, unless it is assumed that during times of power scarcity for running PEM electrolysis, the system is run on NG only.
- The principal investigator's (PI's) approach combines experimental aspects and modeling aspects. The two support each other in complementary fashion. The effort is organized around ten tasks that address the process to varying degrees, as indicated at the bottom of slide 4 in the provided slide deck. However, slide 6 indicates that there are only eight tasks, leaving some lack of clarity regarding the approach. The team is complimented for engaging the Hydrogen Safety Panel (HSP) in this effort. The presenter could have indicated things that the project had changed because of engagement with the HSP.
- The project supports DOE Hydrogen and Fuel Cell Technologies Office efforts for H2@Scale. Decarbonizing iron and steel will require large volumes of hydrogen. This project provided the details of the addition of hydrogen and helps derisk the industrial application of hydrogen. The approach should include incorporating utilities to support the use and integration of renewable electricity and grid power.

Question 2: Accomplishments and progress

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

- Huge congratulations are due to Professor O'Malley and the whole team for overcoming the previous years' supply chain issues and directing the project to successful and safe collaboration, data collection, and initial results. Critical accomplishments include kinetic modeling of reactor operation/reduction with different mixes of H_2 and NG, analysis of melting and validation with industry, troubleshooting some of the preheating issues of the demo, demonstrating the pilot plant production of direct reduced iron (DRI) at an impressive 1 ton Fe/wk, and initial TEA evaluation. No information on diversity, equity, inclusion, and accessibility was provided. It would have been helpful to provide more information about the student intern programs, one of which was noted by ArcelorMittal.
- The PI and team reported several accomplishments. For example, the team has been evaluating the swelling and shrinkage of pellets and found catastrophic swelling at 950°C. The report work is in a publication. The team used a plasma furnace to perform reduction and found plasma to be helpful. The project's third campaign achieved 94% metallization and produced 1 ton of H_2. The researchers found the gas preheater to be a challenge. The team explored the break-even price for both hydrogen and NG, and the TEA suggests that NG may be cost-competitive but that hydrogen costs still need work to become cost-competitive.
- The project identifies specific details of the impacts of hydrogen application on iron and steel production. The work benefits industry with understanding the impacts on kinetics. An extensive safety review and program was used for the project, which benefited the project and enabled higher flow. The analysis should provide a tornado chart of the impact of variables on the cost of iron production. The project provided a break-even analysis for the cost of hydrogen. However, incorporating the oxygen benefit from an electrolyzer would potentially change the break-even hydrogen cost.

Question 3: Collaboration and coordination

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

- The PI and team have assembled an impressive list of partners, including the Missouri University of Science and Technology, Arizona State University, Danielli USA, ArcelorMittal, Steel Dynamics, Gerdau North America, Nucor, Linde, Air Liquide, and the National Renewable Energy Laboratory (NREL). These partners, including ArcelorMittal, are participating in helping validate performance in Task 5. On one slide, the presenter indicated that Voestalpine was a partner, but the company was not listed consistently.
- The project has an excellent team, especially with the steel manufacturing companies. Inclusion of the industrial gas companies helps the project understand the impact on hydrogen supply. These companies should be engaged to understand the potential recovery of oxygen from the electrolyzer. The project should include utilities and grid operators since the project plans to be grid-interactive.
- The project has very impressive collaboration that brings together key stakeholders in industry, as well as strong research teams.

Question 4: Potential impact

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

- Some of the highlights of the potential impact include providing a pathway to curbing one of the largest CO_2 producers that will otherwise be challenging to decarbonize. The team was responsive to previous concerns around impurities and dirty materials in the process streams. The team's work highlights the need for both NG and hydrogen approaches to allow a smooth transition as the hydrogen economy grows.
- This project supports H2@Scale and Hydrogen Shot objectives. The project should identify its impact on H2@Scale and Hydrogen Shot. This project will support large-scale use of hydrogen and reduction of the cost of hydrogen. The project identifies risks and impacts for industry in using hydrogen for decarbonizing the steel industry.
- The data collected and produced in this study have a significant value in better understanding the coupling of hydrogen with DRI and the impact on DRI product quality and energy efficiency. The results not only are going directly to key stakeholders but also are being disseminated in conference talks and papers.

Question 5: Proposed future work

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

- The proposed future work is clear and focused on derisking relevant industry-scale systems (5,000 ton/d). The type of scaling analysis approach being used by the NREL team was not specified, but that should be straightforward if the team follows chemical engineering guidelines. It would be great to see the final report define remaining uncertainties beyond which the current operating pilot cannot address. It would be helpful to see more analysis on the safety around handling the DRI product in a situation where there is no hot link to the EAF (vs. having a hot link to the EAF). The team is tasked with addressing safety, and the transport of DRI to offsite EAF/secondary steel manufacturing facilities is potentially a very challenging aspect. The field is lacking data on the hopper, cooling, and processing/transport of DRI, and it would be good to see the entire team come together to add more details on this aspect.
- Next steps include experimental switching between hydrogen and NG and modeling/TEA analyses.
- The project is ending and getting a no-cost extension.

Project strengths:

- The project has completed excellent research investigating the impact of hydrogen on iron and steel production. Industry will benefit from the excellent research and analysis of this project.
- A strong publication and presentation record ensures results are shared with industry and the research community quickly.

- Strengths of this effort include strong modeling and industrial trials. The team achieved many of the planned results.

Project weaknesses:

- No weaknesses are noted at this time. Previously, setting up the experiment was a challenge, but many of those challenges have been overcome since last year.
- Context for the use of plasma rather than alternative proposed hydrogen DRI systems would be useful, as the overall benefits, risks, and technology maturity of the plasma approach were not clear. Without further context and breakdown of methodology and assumptions, the TEA is impossible to evaluate. The numbers sound too low, and the lack of time spent on presenting this important task is concerning. There are many parameters in the TEA that can drive changes in results, from ore cost and pretreatment, to heat integration, to labor assumptions. It is not clear what the hydrogen break-even price is. If it is the price at which hydrogen can be competitive with fossil-based pig iron production, then that should be clarified; or perhaps it is the price at which delivered hydrogen needs to be without increasing costs at the noted NG prices.
- The project should include a utility to integrate with grid impacts since the project plans to be integrated with the grid and use renewables. The analysis should include tornado charts of the evaluation of variables' impacts on the cost. The project should include the oxygen benefit produced from the electrolyzer to improve the break-even hydrogen cost for the project. The steel industry uses a significant amount of oxygen, which could be supplied from the electrolyzer. The industrial gas partners should be engaged to help with the analysis.

Recommendations for additions/deletions to project scope:

- The project should include the analysis of oxygen from the electrolyzer to reduce the cost of the supplied hydrogen. The cost of an electrical switchyard and transformer for the project should be assessed. This is needed for the NREL Hydrogen Analysis (H2A) model cost analysis.
- The TEA team should align with Argonne National Laboratory for a first-order life cycle analysis with the Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) model.
- No additions or deletions are recommended at this time.

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

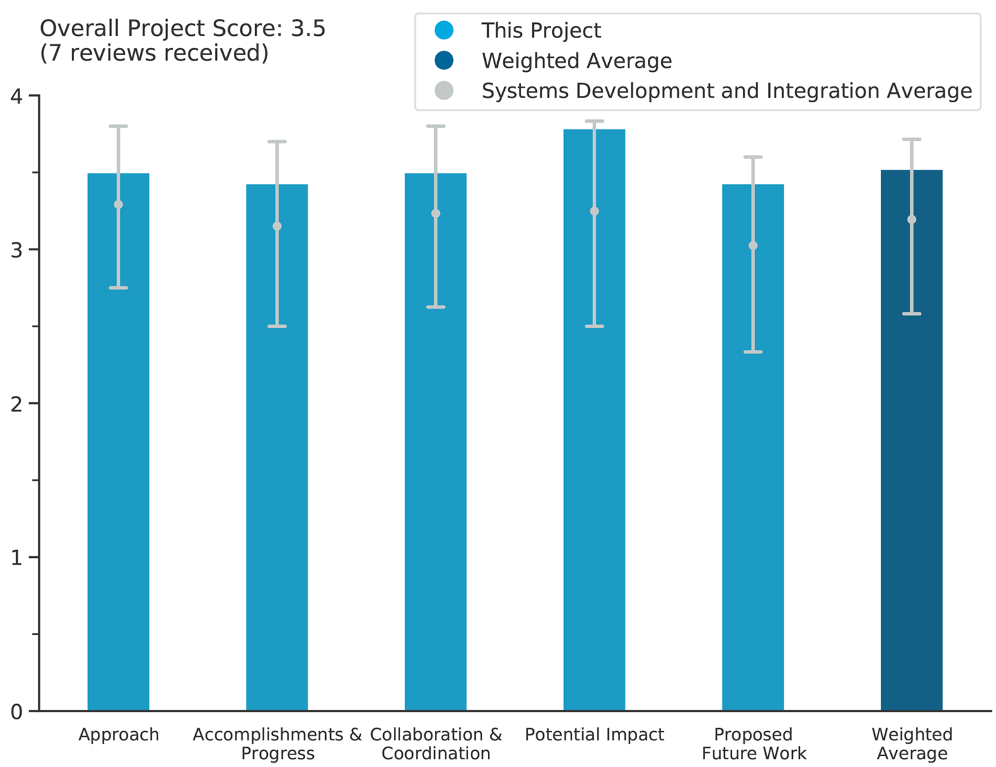
Darek Villeneuve, Daimler Truck North America

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 H_2 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 (HD) 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 **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Critical barriers and specifications are clearly identified, with emphasis on cost and payload, using integration data from earlier vehicles with liquid hydrogen (LH2) systems. The thought was compression will get things running on the B-sample faster. Third-party safety training is a good plan. The community benefits plan (CBP) is good for the funding level, and it is clear that the funding of this project directly leads to increased benefits to disadvantaged communities in the area, both through hiring underserved individuals and with science, technology, engineering, and mathematics (STEM) in their schools. Suppliers are doing meaningful work and seem to be well-managed within the project.
- Developing and demonstrating a viable LH2 Class 8 truck is key to understanding whether LH2 will provide the appropriate total cost of ownership (TCO) for the Class 8 segment. LH2 has much momentum for long-haul applications, but many challenges inherent to LH2 remain. It remains to be seen if the market will accept this approach. Demonstrations like this one will give the industry key insight into the viability of such an approach. Thermal challenges of the powertrain will be some of the biggest challenges and are understood by the principal investigator. It will be interesting to watch the development of an evaporative cooler for the trucks, and while the systems provide significant performance benefit, they are not simple systems to design and maintain.
- The project objectives have been clearly identified, along with a work plan to address challenges to meeting objectives. The safety plan and diversity, equity, inclusion, and accessibility (DEIA) plan/CBP have been clearly covered. The project deliverables tie in nicely with Daimler Truck activities in HD trucking.
- There are excellent, relevant, and transparent metrics. This is a high-impact project with an industry-leading original equipment manufacturer (OEM), and the approach of testing and evaluating high-density LH2 storage is critical for long-haul trucking.
- The project has a clear goal and appears to be well-planned, with clear milestones in each of the five budget periods and appropriate go/no-go decision points.
- The project is properly defined as proof of hydrogen fuel cell HD long-haul trucks. It is recommended that the project show the design requirements of the battery hybrid system and LH2 onboard storage. The current selection of energy type vs. power type seems to be based on availability of the battery module. Systematic system design is required for this battery hybrid system. For the design of sub-cooled LH2 onboard storage, the estimated energy consumption of the sub-cooled system should be shown for its feasibility for long-haul trucks. The metric and method of durability assessment should be addressed.
- The approach is solid. It is not clear why the first design used a longer wheelbase; the standard wheelbase requirement should have been defined upfront.

Question 2: Accomplishments and progress

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

- Aside from supply chain delays related to the battery, the project appears to be moving forward according to the project plan. The use of subcooled liquid hydrogen (sLH2) fuel is a technical challenge, so it is good to see the progress made to date on that part of the project. In particular, the use of waste heat from the fuel cell to heat and vaporize the fuel is innovative. The project emissions goal is aligned with the DOE goals, and the efficiency results obtained so far on the dynamometer are encouraging.
- Project progress is on track.
- There has been really good progress. The fuel cell for the B truck tests out. There was good recovery when the specified power battery was not available; the team used a double-energy-level (2×) commercial-off-the-shelf (COTS) battery, which should suffice to demonstrate proper power levels, as long as its energy use is limited to what would be used in a 100 kWh battery. Facility updates are in place to support truck testing and development. The project demonstrated future LH2 fueling dynamics and controls. The project is using a novel evaporative cooling radiator, using the water produced by the fuel cell for cooling—cooling being a key issue.

- The progress appears to be slightly behind schedule, but nothing appears out of the norm for these projects. There is good progress on a safety plan (it would be good to hear more about how the safety plan/failure mode and effects analysis has affected design, training, manuals), and powertrain development appears to be on track. There are challenges with the cooling system, long wheelbase, and battery supply for power modules.
- System design and selection of partners are complete—that is a significant challenge, from experience. Parts of the system (stack) are already built, and vehicle assembly has started.
- Progress is good. As usual, a design spin is needed but not fully planned for in the timeline.
- It is necessary to show what outcomes from B-sample design verification would be leveraged to design the demonstrator's design.

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.

- Excellent collaboration seems to be happening, given the comprehensive nature of the project. In particular, the tires, cooling system, fuel storage, and electronics collaboration seem very effective.
- There are partners listed in tires, subsystems, national labs, fuel suppliers, and truck fleet purchasers. There is a very good set of collaborator types. The collaborators all seem to be carrying out critical jobs.
- There is very good collaboration across both public and private groups, particularly on the sLH2 with industry leader Linde.
- There is strong collaboration, with all the appropriate and strong stakeholders.
- Collaboration with partners is effective in supporting project objectives.
- Collaboration is laid out with industry, academia, and national lab partners, and the objectives for the partners are clearly articulated and appear balanced among the partners. The presentation could provide more specifics as to what work has actually been done by the partners.
- There seems to be more space to leverage academia (national labs) for fuel cell hybrid system modeling and failure mode analysis for durability validation.

Question 4: Potential impact

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

- The project is directly relevant to the critical DOE goal of hydrogen HD transportation by making a hydrogen-fueled truck that meets the needs of Class 8 truck drivers and fleet owners. If successful, the hydrogen-fueled truck would produce a zero-emissions, lower-maintenance tractor that meets current vehicle specifications for range, payload, and power. That and equivalent TCO are required to start a hydrogen transport system. Also, this work is relevant in that the project is working on 10 kg/min fill, which is certainly an enabler and could easily be a requirement for market penetration. This capability will be needed in other venues of hydrogen storage and use.
- This project will provide direct and valuable information on the feasibility of LH2 and fuel cells in Class 8 and other mobility sectors. Many eyes are watching the outcome of this project—whether all the known issues will be addressed and the fleet customers will accept the systems—as LH2 is currently the favored approach for Class 8.
- Potential impact is significant, with Class 8 fuel cell truck development coming from a major OEM, particularly for adoption of high-density hydrogen fueling.
- The project is well-positioned to support emissions reduction and decarbonization of HD freight transportation. It is hoped that the project will demonstrate (especially for fleet partners) that fuel cell propulsion for Class 8 trucks meet their payload and economic/TCO needs. A careful approach to evaluation of the fueling approach with sLH2 needs to be taken, as sLH2 represents yet another variant of infrastructure; at least in the foreseeable future, the use of sLH2 probably limits use to a defined corridor or point-to-point model where fueling could be set up and see a high level of utilization in order to manage cost.

- Hydrogen HD long-haul is a high-impact area. The project adequately covers necessary items to develop for HD long-haul application.
- This is a flagship project for HD fuel cell truck demonstration.
- Successful execution of this project is expected to meet the specific performance targets given during the Annual Merit Review.

Question 5: Proposed future work

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

- The plan is well-laid-out, and assuming that the build and commissioning of the final demonstration truck can be accomplished in roughly the planned time, then the optimization and testing in budget period 5 will provide very valuable information to inform the expansion of fuel cell transport.
- Moving to actual truck mileage testing is a huge step.
- The plans to execute future work are sound.
- The future work is well-planned and appropriate.
- Future work is planned on critical systems, cooling system development, energy storage sizing, and sLH2 validation. The long wheelbase needs to be addressed, and cooling system work for fuel cell system heat rejection should be optimized for efficiency across all other cooling/heat transfer systems.
- The project is still in early stages—completing the vehicle builds is clearly the most important next step.
- The metric and method of fuel cell system durability validation should be addressed.

Project strengths:

- Overall, the project strengths include a good fuel cell truck development plan, transparency with regard to project execution and metrics, dedication to address onboard hydrogen storage capacity, and collaboration. This appears to be a model development project.
- This SuperTruck project is highly relevant to the Hydrogen Program objectives in the sense that it deals with a Class 8 truck designed for hauling freight. Additionally, the project makes use of mature technology, along with a market-leading truck platform. The data analysis provided is very strong.
- The project is well-organized and -funded, and the lead company (Daimler Truck) has the key resources to execute the build and test of the trucks. The project management also appears to be a strong point and so far is keeping the project mostly on track.
- The strength of this project is the comprehensive nature of the technology under development, i.e., sLH2 storage, tires, and the evaporative cooling system.
- The stakeholders and management structure are strong. The project will answer important questions on feasibility of LH2 for the Class 8 segment.
- The project has experience with the previous vehicle. There is an understanding of customers and a strong team and partners.
- There is an understanding of the HD long-haul application.

Project weaknesses:

- There have been no weaknesses identified at this point.
- Battery sourcing is an issue, and the only project weakness is the difficulty of achieving penetration into the market, which is a hard market to break into.
- The coupling of sLH2 fueling (which is rather more experimental than the rest of the technology involved) adds risk to the project, and if problems are encountered there, this could jeopardize the schedule and time for gathering data toward the end of the project. The compressed hydrogen gas fuel system of the B-sample truck does potentially provide a fallback in the event that sLH2 runs into problems.
- Thermal management may prove to be the Achillies heal of this propulsion system. The success of the project will hinge on creative and prudent management of thermal control systems.

- A project weakness is the understanding of fuel cell system durability and failure mode to address fuel cell system durability validation.
- The initial design with the extra-long wheelbase seems like a misstep.

Recommendations for additions/deletions to project scope:

- The stated target of six miles/kg H_2 is specific to a Daimler Truck real-world route. This is difficult to translate to the freight efficiency target. It would be useful to provide fuel economy targets for common operating conditions for HD trucking, for example, flat grade, full load, full speed cruising, or hill climbing.
- For the HD long-haul application, powertrain system durability is key. It is recommended that the project involve a fuel cell system expert for failure mode analysis and develop a validation method for system durability.
- The team should consider non-standard suppliers for power cells for this demo (obviously not for the product).
- It would be good to see the updated truck design with the shorter wheelbase. It would be helpful to know what the standby time limitations are when using the sLH2 tanks.
- It would be helpful to see a test plan for the two vehicles that is better described, with more detail. It is unclear what tests will be run, what data will be gathered, or how the test plan ties back to the project goals.
- There are no recommendations for additions/deletions to project scope.

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

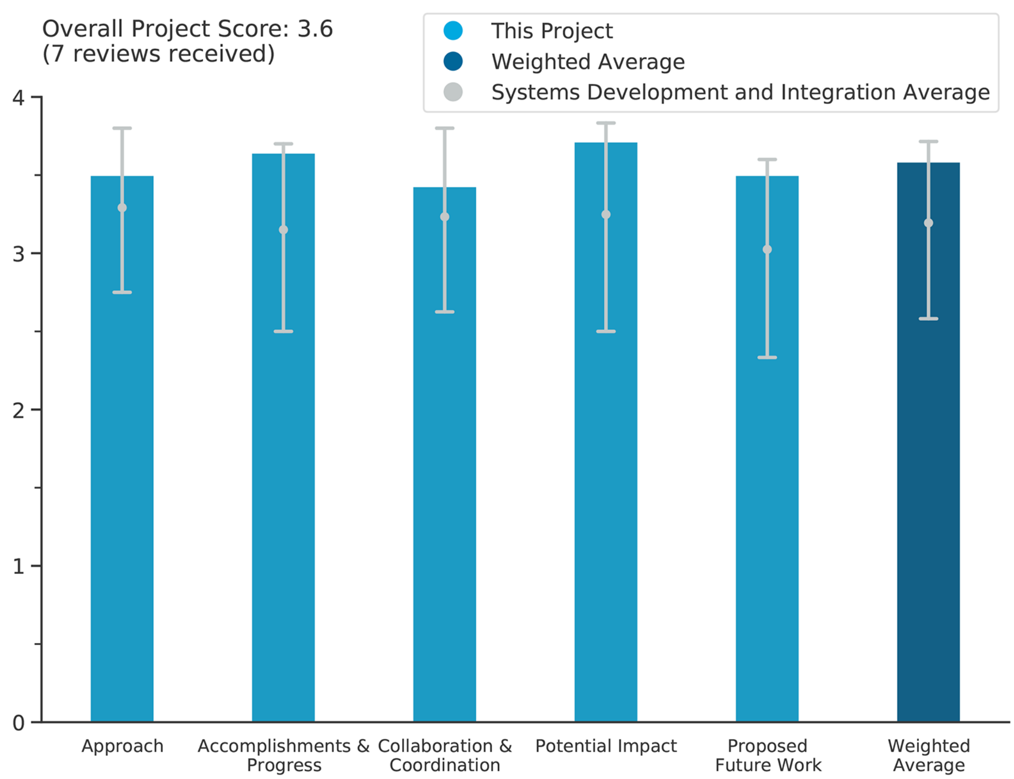
Stan Bower, Ford Motor Company

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 the development of a zero-emissions vehicle (ZEV) 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 (TCO) 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 **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Medium-duty (MD) truck focus is critical for the fuel cell vehicle industry; the project has good focus on application challenges: multishift operation/range, harsh conditions, and payload capacity. Collecting duty-cycle data and simulating performance across various vocations and locations is a good approach. The use case and duty cycles are broad across the MD truck space.
- Project objectives are clearly identified. The safety plan and diversity, equity, inclusion, and accessibility (DEIA)/community benefits plan are complete and of high quality. The project is feasible, and output will integrate nicely with Ford's MD vehicles.
- The approach seems excellent.
- This project will develop and evaluate fuel cell powertrain technologies for commercial vehicles in three different operating environments that have operational demands that cannot be met with today's battery technology. Three barriers and challenges are identified: hydrogen infrastructure and cost, commercial vehicle lifetime durability, and capability in extreme cold environments. The reviewer agrees with the second and third challenges, and the customer demonstration plans are designed to address these challenges. With regard to the first challenge, it is true that mobile refueling solutions are required to enable this technology (as stated in the presentation), but it is unclear how this project addresses the challenge (hydrogen infrastructure and cost). The project has a sound and comprehensive safety plan that leverages Ford's 30+ years of experience in conducting research into hydrogen vehicles and hydrogen storage technologies. The safety plan was approved by the DOE Hydrogen Safety Panel. Safety analysis and training considers failure mode and effects analysis, standard operating procedures, operator safety training, safety reviews, incident reporting, and emergency response. The project includes DEIA and community benefits plans. Ford's Global DEIA activities are highlighted. Pilot vehicle deployments are selected for underserved or disadvantaged communities such as Bakersfield, Californica (Southern California Gas Computer [SoCalGas]) and Flint, Michigan (Consumers Energy). The primary benefit of the project is to reduce/eliminate GHG emissions. When hydrogen trucks are deployed in underserved or disadvantaged communities, it helps to reduce health issues suffered by those residents due to GHG emissions from diesel trucks.
- Class 3–6 pickup truck applications will be a very important part of the hydrogen ecosystem; these vehicles are now under the heavy-duty (HD) ZEV mandate, and the nature of their vocations precludes use of electric vehicle or liquid hydrogen propulsion systems. Currently, the only viable options are 700 bar systems. Ford's approach of packaging tanks under beds for payload-restricted vocations and then adding backpack tanks for towing vocations makes great logical sense from a customer perspective. From a towing perspective, Ford is committing only to the minimum SAE Davis Dam specification at 40 mph. While this specification is required to make towing capacity claims in advertisements, typical real-world requirements for towing are driving by the 0% grade at 80 mph; this requirement is the hardest corner case for both the fuel cell system (it gets too hot) and the hydrogen storage system (it gets too cold) where the propulsion system will struggle. No customer will be happy with a 40 mph maximum towing speed.
- The project is attacking cost and efficiency and recognizing the value of durability and extreme environments. Range is planned to meet the diesel benchmark. The safety plan is as good as one would expect from Ford's experience in the area. The project is using analytical methods and customer data to figure out what will satisfy. The team is looking at extraordinary day requirements and meeting them, so the results are sure to satisfy virtually all customers. The project is doing climate cell testing to look at cold weather operations. Real-time telematics are built in. The DEIA and equity and environmental justice plan is largely that Ford will follow normal hiring processes and will test the vehicles in disadvantaged areas, but of course, those actions will have non-measurable impacts. This project has no direct benefits to individuals.
- The project appears well-organized, with appropriate phases/budget periods and goals for each phase. The safety plan seems to be based on saying "Ford has a lot of experience," so it would be helpful to see at least the steps taken to develop and review the safety plan and the designs. The safety plan was reviewed by the Hydrogen Safety Panel.

Question 2: Accomplishments and progress

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

- The project appears to be meeting all requirements and targets during the design and construction phase and is on schedule. Truck design and sizing are intended to meet critical mission requirements such as 10,000 lb. payload and 20,000 lb. towing capacity, as well as to meet or exceed the performance of 7.3 L gas performance feel, 300-mile range, and refueling time of 10 minutes or less. The design appears to meet all of those requirements. The pilot system met or exceeded five quantitative metrics for fuel cell system performance, including continuous net power in excess of 140 kW. The project passed the go/no-go to proceed to Phase II. The vehicle appears to meet the 300-mile range, based on analytical projections calibrated with experimental surrogated data. However, this result needs to be validated in real-world customer testing. The project completed 15 years' equivalent operation in accelerated stress testing with no membrane failures observed, no catalyst failures, and voltage degradation of 57% of the lifetime budget. (However, it is not clear what the lifetime budget is in terms of voltage degradation.) Vehicle assembly is on schedule for May 2024 completion. Preliminary TCO was calculated assuming "a representative day" model. Subsequent work targeted integrating "days that matter" (i.e., days the battery electric vehicle does not meet owner operational requirements) into the TCO. The preliminary TCO for the fuel cell truck looks to be cost-competitive with that of diesel and better than batteries, based on the data presented.
- The team has figured out the base architecture for the platform to optimize the fuel cell/battery issues and heat management. The fuel cell is validated to meet all targets. The team has done some projections work to show a range similar to that of petroleum fuel (more on some tests, less on others, the same on the base test). Customer needs and use data are being used to predict key areas of stress, do accelerated tests, and iterate to gain confidence the results will satisfy consumers. The project is claiming 15-year catalyst durability, which will improve TCO.
- Progress appears to be on track, with approximately 40% of the work completed across the four-year project. It appears that component specification and validation are complete and a truck is being built. The project has great focus on logging real-world customer data to get power and energy requirements for modeling and simulation, subsystem testing, and breadboard validation. The reviewer appreciates the transparency with respect to vehicle specifications, key performance indicator (KPI) achievements, etc.
- The first build already has a cab mounted onto the propulsion system—a major milestone in any truck build. The location for additional cooling modules is innovative (it looks like a ram air module); this solution will be more appealing to traditional truck buyers than other systems the reviewer has seen in this space.
- The project appears to be proceeding according to the plan presented and is approaching completion/ commissioning of the first vehicle. The direct linkage to the DOE goals was not stated in the presentation, but the project goals for the vehicles are clearly stated and appropriate.
- The project has made excellent progress building the truck.
- Progress toward objectives is very good.

Question 3: Collaboration and coordination

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

- The project leverages critical expertise, capability, and experience of subcontractors. The National Renewable Energy Laboratory (NREL) is working on TCO, commercial vehicle partner fleet system analysis, battery lifetime modeling, and hydrogen fueling rate. FEV Group is working on fuel cell system development and testing services, vehicle testing facilities, and functional safety engineering services. The project made an excellent choice of three customers to demonstrate different operating requirements and environments for fuel cell powertrains, with each customer located in a different region of the United States, which addresses the fuel cell system's ability to perform under vastly different climate conditions.
- There is good incorporation of TCO analysis from NREL. FEV Group development of fuel cell system and testing is impressive. There is a good operator user base, especially with SoCalGas, which has a good history of demonstrating alternative fuel vehicles and zero-emissions technologies.

- The project has a good panel of collaborators, including the very important fleet operators who will be the eventual buyers of these initial fleets of vehicles.
- FEV Group is building and testing the fuel cell. Three potential customers are also participating with design, testing, and input.
- Ford has effectively engaged project partners to improve the likelihood of success.
- Collaboration with FEV Group is critical; collaboration seems to be good.
- The project appears to have appropriate collaborators (industry and national labs). It would be helpful to see more information about the specific contributions to date and planned for FEV Group and NREL, as not much was said about their contributions in the presentation.

Question 4: Potential impact

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

- This project (and Super Truck as a whole) has the potential to have high impact, as the products being developed would replace vehicles that have pretty poor fuel economy and high usage in their current internal combustion forms. There is also a very broad array of applications/duty cycles in the MD/work truck space, so demonstrating that fuel cells work well in those applications is very important.
- Class 3–6 pickup truck applications will be a very important part of the hydrogen ecosystem; these vehicles are now under the HD ZEV mandate, and the nature of their vocations precludes use of electric vehicle or liquid hydrogen propulsion systems. Currently, the only viable options are700 bar systems.
- Development of an MD fuel cell chassis from a major original equipment manufacturer (OEM) and industry leader across MD truck classes has potential for a major impact to the industry. There is a high level of need for this type of vehicle.
- The project is developing a ZEV technology for applications that cannot be met with current battery technology. Thus, the project is strongly aligned with the Hydrogen Program's goals of developing fuel cell powertrain technology for HD on- and off-road vehicle applications.
- The project is very well-aligned with DOE goals and in the hard-to-decarbonize MD/HD vehicle market. The project is collecting a good deal of data that will serve DOE as well.
- The MD truck segment is very relevant to DOE goals.
- The project deals with MD vocational trucks, which makes it difficult to quantify impact on freight efficiency objectives.

Question 5: Proposed future work

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

- Phase II go/no-go milestones appear to be on track, with the 140 kW net power capability having been achieved with the complete development builds needed for completion. End-of-life testing on fuel cell systems will provide valuable information to ensure fuel cell systems meet durability and lifetime requirements. The project is targeting vehicle deployment to the customers by the end of 2025.
- The remaining work in the project is well-planned, and no high-risk areas/delays were reported. The upfitter modifications to the trucks will be a critical phase. It would be helpful to see more information on how the project will carry out that integration. There was some discussion of what upfitters want for power take-off (PTO) characteristics, but that was in the context of a reviewer question and was not really discussed in the plan, per se.
- Future work is as planned and makes sense. Several deployments with customers will get third-party data.
- Planned future work includes appropriate elements to effectively execute the project.
- The project is very close to attaining actual mileage data.
- It would be good to hear more about the decision to do 700 bar storage and designed-in ability to adapt to future higher-density onboard hydrogen storage technologies. It would be helpful to understand more about the approach to driving PTO and auxiliaries. Presumably, that million miles of customer data included PTO power and energy consumption that was included in duty cycles. It would be helpful to understand more

about the design for cost reductions of the fuel cell chassis. The price point will be critical for mass market adoption; it is unclear how cost is addressed in the early stages of development.

- The project needs to complete vehicle builds, deliver to customers, and begin collecting real-world data. It would be good to see a bit more information on the infrastructure readiness and planning going into the project (similar to how the General Motors project is looking upstream from the dispenser). The plan to support the fleet customer from the infrastructure side is unclear.

Project strengths:

- The project is developing zero-emissions fuel cell powertrain technology for commercial applications that cannot be met by current battery technology. Fuel cell powertrain technology will be evaluated by three different potential customers with different operational requirements and that are located in three different climate regions. Results from the commercial demonstrations should be extremely valuable for accelerating the commercialization of fuel cell powertrain technology for markets in which batteries cannot meet the requirements. The project is on schedule and making excellent progress.
- Ford is well-positioned and -resourced to execute the design, build, and testing of the project. The project demonstration phase will potentially provide excellent data on a variety of usage profiles; the use of three differently configured vehicles with three “customer” companies is definitely a strength of the project.
- Project strengths include significant involvement and progress by MD truck OEM Ford in the development of a fuel cell chassis. There is great transparency from the OEM on activities, progress, target objectives, and KPI results. The project has good focus on safety and coordination with industry groups. The involvement of disadvantaged communities and DEIA practices are also appreciated.
- The team has vehicle experience, knows the customer well, and has the analytics to characterize customer needs.
- Ford has done a very nice job with vehicle-level analysis and integration of advanced fuel cell technologies.
- Strengths include the project’s logical targets and propulsion system vision/plan.
- The team is able to execute on a complex fuel cell truck build.

Project weaknesses:

- There are no apparent project weaknesses.
- There are no major weaknesses.
- This is a very hard market to penetrate. This is no fault of the principal investigators, but it may be the biggest barrier they face.
- The project presentation does not detail the contributions of the partners very well. Also, while it appears that there is a plan for fueling the vehicles at each user site, it looks like there is some risk there if the fueling solutions do not have high reliability/uptime.
- Application is limited to MD vocational applications. There is very little opportunity to understand the potential impact on freight efficiency.
- Lack of project visibility on the infrastructure side is a weakness.

Recommendations for additions/deletions to project scope:

- The researchers are asked to share as much performance data and planning data as they can with DOE to inform their models.
- As the project moves toward the commercial demonstration phase by the three customers, the team is asked to provide some information on how the customers plan to utilize (evaluate) the vehicles and how their utilization provides the data/information required to move the technology forward.
- For next year’s Annual Merit Review, it would be good to see more information on infrastructure readiness. The project should plan to address real-world towing duty cycles (80 mph at 0% grade—continuous).

- It would be useful to discuss efficiency numbers in terms of work performed to allow conversion to the freight efficiency target.
- The presenter should discuss in more detail how FEV Group and NREL contribute to the project, as well as PTO/upfitter integration.
- More discussion on TCO analysis is suggested.
- There are no recommendations for changes 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

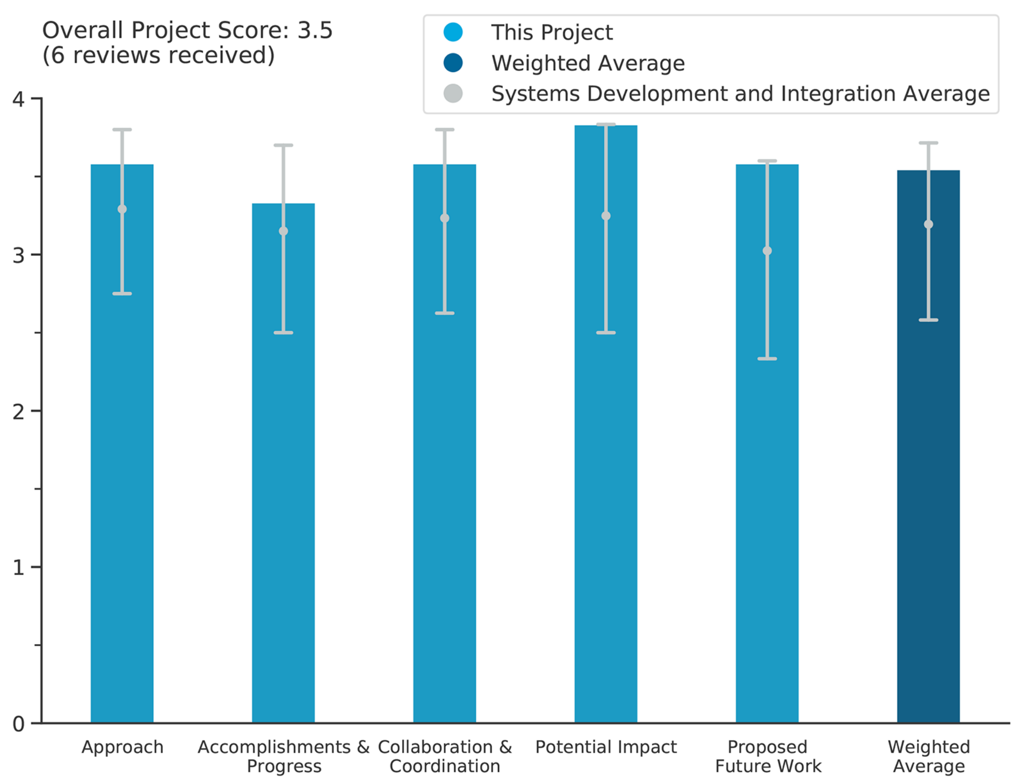
Jacob Lozier, General Motors, LLC

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 • Heavy-duty vehicle 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 (TCO) 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 project has a commendable vision for fuel cell system (FCS) and electrolyzer durability testing. The project appears to have much bigger focus than other truck demonstration projects on FCS development, drive cycle definition, and accelerated test protocols that the industry can potentially adopt.
- The project approach is adequately defined. This project includes onsite hydrogen production and a mobile refueler. It is necessary to pursue techno-economic analysis for onsite hydrogen production, central hydrogen production and delivery, and mobile refuelers for these mid-duty commercial vehicle usage profiles.
- All aspects of the approach are well-thought-out and clearly conveyed. The diversity, equity, inclusion, and accessibility and community benefits plans are clearly articulated. The project approach is feasible and reasonable, and safety is an essential part of the effort.
- This is a holistic project that evaluates upstream impacts on infrastructure beyond the dispenser, which is extremely important to helping the eventual buyers of these initial fleets (fleet operators) understand new TCO models that will be necessary to the success of these fleets. To improve the business case for these initially expensive and limited fleets, fleet operators will need to take advantage of upstream grid services to capture revenue streams not currently included in most TCO calculations from either vehicle original equipment manufacturers (OEMs) or fleet operators. The General Motors (GM) team's work to understand/develop an accelerated stress test for electrolyzers is an important and often overlooked detail, as it will likely not look like traditional grid services (i.e., significant variation could happen based on the vocation and location of the fleets used). It is not clear that the truck goals really cover 99.8% of vocations and duty cycles. For example, the toughest corner case, high-speed towing (for which these vehicles are currently primarily designed), does not seem to be covered with the propulsion system proposed. If it is covered, fuel cell power, cooling capacity, etc., have not been discussed, so it is hard to define what hardest duty cycles are considered.
- The project approach is broad-based, with hydrogen production and zero-emission vehicle truck demonstrations.
- The presenter covered the approach in detail. The reviewer appreciated all the slides presented by the team.

Question 2: Accomplishments and progress

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

- The project's distinguished outcomes are seen in FCS durability validation with the newly developed test protocols. These protocols enable the team to save development resources and time. It seems that these test protocols are specific to this project's MD application. These test protocols can be modified for heavy-duty regional-haul and long-haul usage profiles. This is addressed as a remaining barrier and could be included in the future work.
- The project team clearly presented the project accomplishments, which are tracking well for the overall project. The team is on target to hit the DOE goals targeted in this effort.
- The project vehicles will be on-road soon, and pulling together all the necessary components and assembling/testing is a monumental task. The reviewer notes that their company, Forvia, is involved in this project by providing the hydrogen storage tanks. Forvia has contributed to the delays in providing GM parts, so this reviewer's notes on project progress must be considered with this context.
- The project provided an excellent summary, but there is still room for improvement. All the engineering results should be summarized in simple indicators (e.g., percent complete and targets for next year).
- The project team appears to have spent very little funding (<10% of budget) compared to the project duration, which may be an indicator of lack of progress. The fuel cell design is complete. The team has made good progress with duty cycle characterization in work truck application with Southern Company. It is unclear what progress has been made with safety planning and integration into design, test, training, and manual processes, as there is little information on progress or description of system integration or design results. Regarding slide 9, it appears that the efficiencies for battery electric vehicles (BEVs) and fuel cell

electric vehicles (FCEVs) are transposed. Unless something groundbreaking has been done with this project, BEV propulsion system efficiency is 85%–90%, and FCEV is 50%–55%.

- The project is two years in with only 10% of the funds spent, so it appears the project is behind plan.

Question 3: Collaboration and coordination

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

- The project has close, appropriate collaborations with other institutions. The project partners are full participants and well-coordinated.
- This project has excellent collaborations with multiple organizations, including Argonne National Laboratory, Nel Hydrogen, and Southern Company. Slide 7 effectively tells the story for overall development with partners. The team has good collaboration with Southern Company, a utility with a history of hydrogen and fuel cell research. However, the team needs to identify a freight partner.
- This project includes great collaborations with upstream utilities and OEMs. The team should prioritize securing another fleet operator, as fleet operators are ultimately the ones that need to purchase these initial production fleets. A thorough understanding of fleet operator needs and TCO considerations is crucial.
- This project has a strong project team and appears to have strong participation. The project team is seeking a replacement partner, but this has not impacted the project negatively yet.
- The project's collaboration is well-coordinated among industry and academia. The team should add a techno-economic analysis partner.
- The team at Nel Hydrogen is supplying an electrolyzer, but there is not enough information available on how this electrolyzer is new or low-cost.

Question 4: Potential impact

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

- The overall impact and relevance of the effort are outstanding. This well-rounded project is targeting an ecosystem of hydrogen support, not just a targeted hydrogen fuel cell platform. This effort will provide a great deal of data that will be impactful and inform future investment.
- The project is strongly aligned with the Hydrogen Program's goals and objectives and is likely to significantly advance progress toward its performance targets.
- These are the types of projects that eventually lead to successful large-scale deployment of hydrogen vehicles on the road. The new understanding of the full ecosystem requirements will provide valuable feedback to all stakeholders as to where gaps remain in the technology.
- The potential impact is significant, ensuring that FCS durability and reliability are on par with traditional diesel engines, especially coming from major OEMs. The approach is similar to electrolyzers.
- This is a very relevant project to demonstrate the practicalities of hydrogen supply and use in the transportation sector.
- This project can have significant impact regarding the use of hydrogen in commercial vehicles. The project focuses on MD freight usage, but this technology (e.g., FCS, hydrogen production) could be used for other applications, including heavy-duty long-haul, which is one of the highest-impact areas.

Question 5: Proposed future work

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

- In the future, the project team should provide more details on the actual vehicle build, powertrain packaging, specs, etc. and the reasons for design decisions.
- The project team appears to have a good roadmap for iterative testing and demonstration with project partners. The trucks are to be delivered and evaluated in 2024, with a good iterative plan for FCS development and integration.

- Plans clearly build on past progress and are sharply focused on critical barriers to project goals.
- Proposed future work is reasonable and logical in the next steps of the project. It will help the effort achieve its overall goals and metrics.
- The future work proposed makes good sense.
- The project's workplans for 2024 and 2025 are well-defined and relevant.

Project strengths:

- The project team has a very good approach to FCS development, durability testing, and iterative demonstration. The team has good collaboration with experienced partners and major OEMs.
- The project's main strengths are its sustainability highlights. The team's accomplishments on efficiency and other indicators clearly align with DOE goals. There is more to be done in the future, and the future looks optimistic for this team.
- The project team has a deep understanding of proton exchange membrane fuel cells and water electrolyzers, including failure mode, to develop universal test protocols. The team has in-house development capabilities.
- The project's ecosystem approach will be able to inform future work and get real performance data to feed models and cost metrics.
- The project's holistic ecosystem approach is a strength.
- This is a broad-based project with many moving pieces.

Project weaknesses:

- The project team has done amazing work. The collaboration with GM engineering can enable the project to prove more and bring more. It would be helpful for the team to elaborate more on, and have a strong plan to overcome, heavy-duty vehicle FCS durability. The presentation should include a slide on how GM can achieve the 75% reduction in greenhouse gases to clarify the current status on how much reduction can be achieved.
- The project has no significant weaknesses.
- The project has a critical blind spot regarding the lack of current fleet customers.
- The project has a heavy focus on FCS development, which is important, but the team should include more transparency about vehicle-level integration, testing, and commissioning plans. The team should also include more information about how the onsite hydrogen production microgrid deployment evaluation ties to FCS and vehicle development, if at all. The project team should include more information on electrolyzer key performance indicators and test results.
- It appears that the funds are not being spent at a rate that reflects the grand ambitions of this project. The project team may need to bring in more resources to complete the next phase. The electrolyzer portion of the project is unclear regarding what is new and why it will be low cost.
- One project weakness is vendor instability.

Recommendations for additions/deletions to project scope:

- The durability test protocols that are developed in the project can be universally used for FCS and water electrolyzers. It is highly recommended that the team propose the developed test protocols to the fuel cell/water electrolyzer development community.
- The project team should have more transparency around vehicle integration and design, such as the level of hybridization, component sizing, and thermal management approach. The team should also have more transparency around electrolyzer test results, challenges, and key performance indicators.
- The project should add a fleet customer for critical feedback toward purchase considerations.
- The reviewer-only slides could have more summary content.
- No changes are recommended.

Project #TA-059: Identifying Medium- and Heavy-Duty Applications for Fuel Cell Electric Trucks

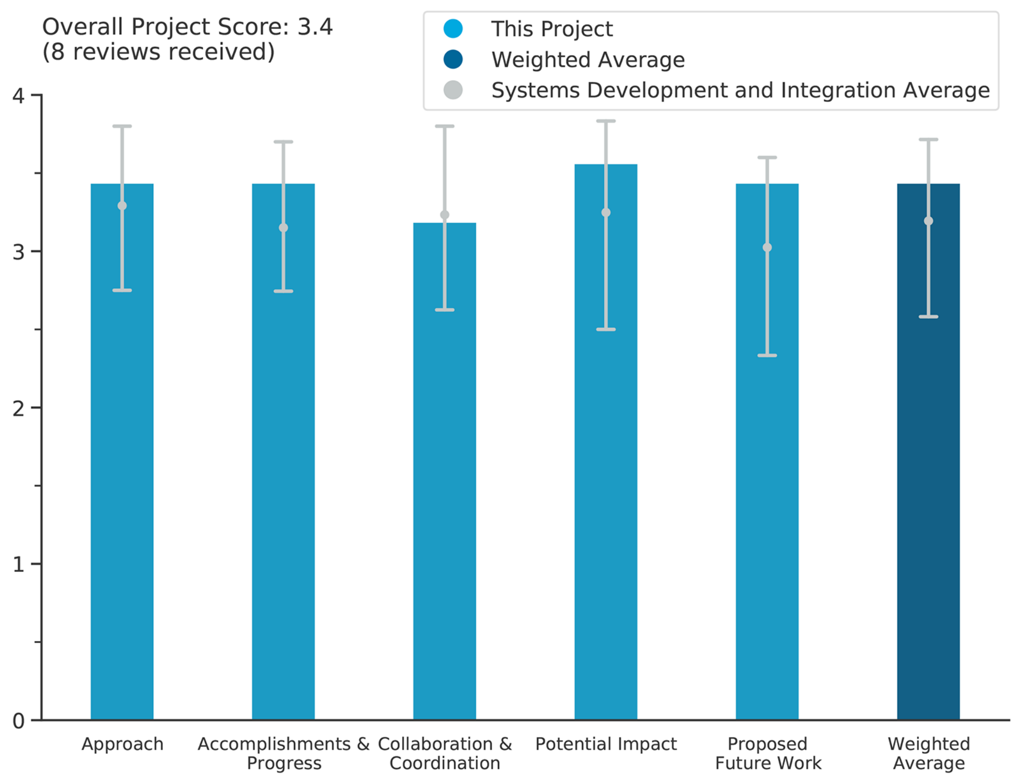
Ram Vijayagopal, Argonne National Laboratory

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 objective is to support the development of fuel cell electric trucks (FCETs) for medium-duty (MD) applications by evaluating the trucks' 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. FCETs 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 **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Objectives are clear and logical, and the approach covering all classes, from Class 3 to multiple Class 8 truck types, is very thorough and equipped to uncover where hydrogen and battery electric powertrains are best applied. The strategy to evaluate electric- and hydrogen-powered vehicles was comprehensive and very thorough, providing the right level of technical detail for a complicated subject. By the time the technologies become widespread, it is likely that electricity prices will be higher and hydrogen prices lower. Showing targets side by side is important for the learnings and outcome use scenarios for the different energy storage options. The capacity factor and use of the vehicles will have a significant impact on the results for the type of vehicle (battery or hydrogen) that should be used. The approach to identifying trucks of interest was very thorough in reviewing the full number of truck types. There are likely fleet logistics, real estate, and final use cases that may be missed in this initial high-level analysis. It will be up to end users to fully understand the limits of the results and how they would apply to individual companies.
- The project includes a great premise and well-thought-out approach. It is nice to see meaningful results halfway through and then spend time on validating the model with refinement of input data. The project also includes a good approach to having a high impact by collaborating with industry groups to use project results in their activities. It is unclear how extensive the Fleet DNA data are or whether those data are being maintained. Modeling on this dataset will heavily affect the results.
- The work is clearly articulated and backed up by quantitative analysis. Results are communicated clearly. Use of quantitative analysis tools, such as Autonomie and Techscape, makes the input assumptions explicit and the results rigorous.
- This project provides a good approach to making a comprehensive comparison between battery electric vehicle (BEV) and FCEV technologies while leveraging established modeling tools from Argonne National Laboratory (ANL) and outside sources (the National Renewable Energy Laboratory [NREL], 21st Century Truck Partnership [21CTP], and DOE HFTO targets).
- The project has a clear plan organized in four stages over the planned project duration, with specific milestones and deliverables for each period.
- Project objectives are clearly identified and addressed. Analysis is closely integrated with several other developed tools.
- This is an important but difficult-to-characterize space for FCEVs because of the many vocations covered in this segment. It will be difficult to capture all the powertrain configuration and drive cycle permutations. The project team is advised to cover two major vocations for the Classes 3–6 pickup truck options. Classes 2–4 tend to be more dominated by towing, whereas Classes 5–6 are usually more payload-constrained. Unless another zero-emission propulsion system can satisfy the high power requirements of towing (diesel equivalent today needs 200–250 kW for Classes 2–4), the team is encouraged to exercise caution regarding reducing power requirements (for ultimate targets). The project may still need a mid-power and high-power fuel cell configuration (akin to gas and diesel engines or high-output options offered today on trucks). It should be noted that these lower-power options may only be suitable for limited fleet applications, which typically account for <15% of truck sales. Original equipment manufacturers (OEMs) will be reluctant to design/launch a propulsion system for such a small segment of the customers.
- Both electricity and hydrogen price assumptions are optimistic, considering the upward trend in cost components (including transmission/distribution infrastructure). It would be better to represent these price assumptions in 2020 dollars. Many models do not consider “one vehicle that can do it all” decision parameters for fleets acquiring new vehicles. Instead, the assumption is that a vehicle with specific technical specs will address niche use or that fleets will change fleets’ make-up (more vehicles) and their logistics. It is unclear how this model addresses this.

Question 2: Accomplishments and progress

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

- Results provide clear guidance on the utility and economic feasibility of using BEV and hydrogen vehicles in various scenarios. Results are comprehensive across a range of truck classes and use cases. Special cases, such as towing, are examined to understand the impact of user-expected performance in those special cases. These results are helpful for DOE efforts to make investments in hydrogen- and battery-electric-powered vehicles pay off by indicating which truck classes and use cases can benefit most from each technology from an economic perspective.
- The project has made good progress and contributed value for being 60% through the overall budget of $300,000. The project has produced meaningful and reasonable results comparing TCO for dominant zero-emission technologies over all medium- and heavy-duty (MD/HD) classes of trucks.
- The milestones and deliverables are logical and were readily accomplished for Quarter (Q)1 and Q2 2024. It was very good to see buses also included with this, as they are a good "canary in the coal mine" for learning about high-throughput stations, as well as early challenges of hydrogen or electric charging at scale.
    - The TCO is a good preliminary screening tool but will need some review for practical application to fleet decisions.
    - The transition range is important for sharing uncertainty around range, fleet logistics overhead, and other inputs that do not show up as clearly in traditional TCO analysis.
    - The justification for long-range vehicles from 21CTP and other data is an important message to stakeholders and end users of the project outputs.
    - Fleet size and grid upgrades or hydrogen delivery may dramatically affect outcomes of the analysis as the advantages or disadvantages of each energy supply are compared. Many demonstrations have gone very slowly or failed when the real-world use case is much more demanding than modeled use cases. Additional range (at additional cost) will mitigate some of the maturity risk of fleet infrastructure. There was an explicit mention of this, which is a critical takeaway for the project.
- There has been very good progress toward DOE goals.
- In picking duty cycles, it is recommended that the project team pay close attention to Stan Bower's comment of "Days that Count" or "Design Determining Vocations." There are a few days a year in which a truck needs to prove its worth. This is usually some extreme cycle that may happen only a few times a year, but it is the reason why the truck is purchased (emergency response scenario, large load, etc.). Trucks are designed for extremes, never averages. While averages are useful, they do not sell trucks. It would behoove the modeling team to work in some of these extremes. For example, today's diesel powertrains are designed to achieve 80 mph at 0% grade at maximum towing combined gross vehicle weight. This cycle will put maximum stress on the fuel cell power and cooling capabilities (the system cannot reject the heat) and freeze the 700 bar hydrogen storage system (the system cannot keep the temperature high enough—it will drop to ≤-60°C). These considerations need to be kept in mind if significant market penetration is to be achieved by FCEV trucks.
- The results of the study are informative and provide valuable information for the comparison of BEV and FCEV truck applications. Utilizing gravimetric energy density for hydrogen storage estimates is somewhat confusing, as this method does not provide clear insight into what onboard vehicle storage entails (i.e., pressure class of gaseous or liquid hydrogen [GH2 or LH2]). Using volumetric energy density would provide more useful insight into how storage type relates back to vehicle range and cost. Also, the gravimetric measurement at 2 kWh/kg seems low.
- The team should consider including a factor that reflects insufficient grid capacity for choices made and resulting TCO. Grid capacity is already a major cost issue, and solutions that focus on hydrogen-powered trucks/FCETs and hydrogen for generating power for charging are being implemented.
- The project has identified most of the factors impacting vehicle range, energy consumption, and usage. The project has its own defined objectives; however, the presentation did not specifically tie them back to the DOE goals.

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.

- Overall collaboration on this project appears appropriate for the scope. The project is referencing outside sources of information from NREL and 21CTP, as well as working closely with DOE HFTO on associated Hydrogen Program targets.
- The team has shown an openness to reaching out and including operational data from other entities working in the MD/HD zero-emission vehicle space.
- The right team members are involved. 21CTP is technically the right partner to help gather OEM feedback. However, the OEMs seem reluctant to reveal their true internal key design criteria for propulsion systems to a partnership that includes their competitors. The OEMs are providing 21CTP and ANL with generic SAE-driven targets that are usually 15%–25% below actual internal targets. It is unlikely that approaching the OEMs separately will yield more accurate information, but it is safe to assume that every OEM has internal targets that are tougher than SAE or regulatory targets in order to provide a margin of safety and/or provide a competitive edge vs. the competitors.
- While there is engagement with the 21CTP roadmap and review by working groups, there appears to be limited engagement with fleet owners and end users, which would be most informed by this project and interested in the results. Discussion with end users will be important to ensuring the government-funded tool gets the most widespread use.
- There is some collaboration with NREL through the use of Fleet DNA data but not much collaboration with other institutions. However, the team appears to have some collaboration with 21CTP and the MD/HD action plan.
- The presentation states that "DOE and industry feedback serve as the starting point," but more detail is needed about the source of those data. (The Vehicle Inventory and Use Survey is mentioned, and more information is given in the backup slides.) Also, it seems like the lack of industry partners to provide (or at least confirm) the usage data weakens the project.
- The team is collaborating with other groups in DOE by using tools such as Autonomie and Techscape. The extent to which organizations outside DOE are involved is unclear.

Question 4: Potential impact

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

- This study addresses a key and large segment of the FCEV market that, until now, has not been well-characterized by Autonomie, the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model, etc. The team is highly encouraged to continue this work to improve understanding of (and to prioritize, etc.) the countless and often extreme vocations in this space. This work will present new challenges but also identify new opportunities.
- This work is incredibly important to the DOE transportation decarbonization strategy. There are key issues regarding temperature impact on range, long lead times, and dependence on the utility that can be harder to control. The wide range of vehicle platforms further boosts the significant relevance and impact on future transportation fleet make-up between hydrogen and electric energy storage options.
- The potential impact for this study can be significant if the results are ultimately extended to MD/HD industry stakeholders and decision makers. Future development of this model, in addition to the information flowing through industry groups, can help fleets plan and operate mixed approaches for using a combined approach to zero-emission technologies (i.e., using all-electric MD trucks where their operational efficiency is optimized and using fuel cell MD trucks where it makes financial sense).
- These results can guide DOE investments in hydrogen-powered and battery-electric-powered vehicles by identifying the truck classes and use cases that can benefit most from each technology from an economic perspective.
- The project is providing very useful information regarding the comparison of BEV and FCEV technologies in terms of vehicle type, range, TCO, and energy cost.

- This is an important topic to sort out in a way that reduces industry discomfort with making a change to alternative propulsion for commercial trucks of all types, especially with regard to TCO. While an argument can be made for TCO, upfront cost needs to be considered as well, as it can be a significant barrier, especially for small businesses. Commercial transport is very sensitive to both cost and disruption of current practices.
- The project has very good impact and relevance to support progress toward targets.
- The team is encouraged to continue this work.

Question 5: Proposed future work

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

- The project has a great approach to future work to continue to improve modeling in areas of need, primarily with cost component inputs. Also, dissemination of results through 21CTP and the MD/HD action plan is critical to creating real utility and impact from the work. Fleets need to be able to use this information in purchasing and decision-making processes.
- The proposed work to inform 21CTP and the roadmap is very important. Near-term cost assumptions are very challenging when considering the next five years and the expected increase in fuel supply and component cost reductions. The future work outlined in the five bullets on slide 15 is logical and a good step forward.
- The proposed future work is consistent with the project objectives and goals while advancing the work already completed on the project.
- The planned future work is very thorough.
- The team should consider adding other TCO considerations such as maintenance, training, spare parts availability, and deferred payload costs. The team should also account for OEMs needing multiple platforms, whereas one diesel system covered all in the past (e.g., the Southwest Airlines model). It should be noted that these are hard metrics to gather and model, but all these considerations are what truly make up a TCO analysis for a fleet buyer. What is being modeled now is really a levelized $/mile calculation. Although that is still very useful, it cannot be called "TCO."
- The project has a list of future work, so it is well-organized in that sense. However, it would greatly increase the value of this work if the TCO of contemporary internal combustion engine (ICE) commercial vehicles can be included as a baseline. In addition, it is important to add the impact of heating, ventilation, and air conditioning (HVAC, specifically heating loads) to the analysis, as they have major impacts on cost and usability and currently are specifically excluded from the analysis.
- The proposed future work makes sense in the context of the current effort. There could be some difficulties in the scale-up to the regional and national levels if assumptions break down or become so significant that the analysis results are less certain.
- The team should consider bringing up freight refrigeration energy consumption, both on vehicle (MD/HD box truck) and trailer.

Project strengths:

- The project provides a good comparison of BEV vs. FCEV technologies in terms of vehicle type, vehicle range, and TCO. The project appears well-aligned to help determine the most suitable applications for BEV and FCEV MD/HD vehicles. The project leverages legacy modeling tools from ANL and brings in other sources of information from outside analyses and DOE HFTO targets. The project appears to have met the major metrics with some clear goals for future work.
- The project is clearly worthwhile and is producing actionable recommendations for DOE and commercial investment in hydrogen-powered and battery-electric-powered trucks. The project is well-organized and backed up with quantitative analysis. Sensitivity analyses to understand the impact of assumptions (such as hydrogen price) are good for assessing the range of results.

- The project includes great analysis using current methods, tools, and data to establish TCO for zero-emission MD trucks. The process of engaging in the TCO study inherently creates opportunities to learn and advance the technology. The reviewer is eager to see what else comes out of this project.
- The project addresses a key issue with the transition to alternative propulsion and has the potential to be an important tool in informing the decarbonization roadmap and in clarifying the transition for commercial vehicle operators.
- There is clear and logical review of TCO and impact of range and use. Especially impressive is the opportunity for users to adjust inputs to tailor the use case to their scenarios.
- This project is an excellent start in understanding and addressing the needs of the MD segment. There is a need for the team to keep building on this momentum.
- The project includes a broad and considerate approach, using as much operational data as possible to come to results.
- The project includes very good analysis and integration with other developed tools.

Project weaknesses:

- No project weaknesses were noted.
- Some of the assumptions made in the project are difficult to follow in terms of hydrogen storage technology applications. For example, utilizing gravimetric energy density for hydrogen storage estimates is somewhat confusing, as this method does not provide clear insight into what onboard vehicle storage entails for FCEVs (i.e., pressure class of GH2 or LH2). Using volumetric energy density would provide more useful insight into how storage relates back to vehicle range and cost. Also, the gravimetric measurement at 2 kWh/kg seems low.
- Analysis relies heavily on assumptions around cost, production rates, use cases, etc. Such assumptions are necessary and reasonable; however, they must be communicated clearly, along with results, to ensure they are understood.
- More discussion of fleet logistics and real-world infrastructure costs could be explicitly called out as a benchmark for assumptions. It would be good to see an explicit list of other companies ANL is working with; the term “working group” is quite broad.
- The analysis and results really need more context to be as useful as possible. The usefulness of the data would be increased if the analysis included HVAC loads and an ICE TCO baseline.
- The project lacks some key extreme case vocations that could be useful in establishing ultimate targets that truly achieve diesel equivalence and thus high market penetration.
- It is difficult to cover all analysis approaches with a finite set of assumptions (sizing, heat rejection, etc.).
- The project is a modeling exercise.

Recommendations for additions/deletions to project scope:

- It is recommended that the team add a particular case study for Classes 3–6 pickup trucks at maximum tow weight, 80 mph, and 0% grade continuous operation. The team will find this is the most stressful scenario on FCEV propulsion systems. The study will reveal that 700 bar systems will need to be capable of -60°C gas temperatures and beyond for tanks and balance-of-plant auxiliaries. Hydrogen storage system suppliers are having a difficult time convincing the auxiliaries manufacturers that this situation is real and that OEMs are asking for it. This project’s modeling can provide public and credible awareness of this need to the broader hydrogen community.
- It would be interesting to look at fueling time (GH2 pressure class and flow rate) compared to BEV charge time as an added metric to the project scope. This is an important factor that separates the two EV powertrain technologies and may help drive technology acceptance for fleet owners. Fueling time also relates back to a previous comment regarding using volumetric energy density to distinguish which hydrogen storage system is being used. This information would be very valuable to DOE and industry right now, as MD/HD vehicle manufacturers are debating the uses of various GH2 pressure classes and/or LH2 use.

- Where there is bandwidth and sufficient funding, it is recommended that ANL choose a few key fleet end users with recent experience with hydrogen or battery electric fleets. It would be good to ground the researchers as they walk users through the model as a scenario trial for real-world experience to calibrate or adjust the presentation of the results of the model. This could rapidly lower the learning curve for wider distribution and provide a quality check that the model is aligned with end-user priorities. This strategy may be a significant ask and outside the scope of the project, especially considering the model is suited to some longer-term timeframe when targets are met, e.g., in 2030.
- Expanding on the idea of using 2030 as the target and inputs could create a method for sweeping through technology readiness projections (from public reports and literature) to provide a fuel cell TCO for MD trucks over time. Perhaps this is already planned with and through 21CTP coordination. The project could parameterize the inputs to the model and create a tool for public use, particularly for hydrogen cost and electricity cost.
- It would be good to see more explanation of the sensitivity analysis around varying the cost of fuel and electricity. It would be very helpful to understand why the crossover points of TCO vs. mileage move to the right as the costs of electricity and hydrogen go down. This could be due to the higher relative capital cost of the FCEV, but that is just a guess. The result is not intuitive.
- More discussion on fuel-cell-sizing and battery-sizing approaches would be helpful. It would be interesting to perform a sensitivity analysis on the hydrogen and electricity cost assumptions. TCO can be based on miles traveled/work performed/freight miles. The team should consider evaluating usage profile dependencies.
- The team is encouraged to continue this work.
- No recommendations are noted for scope changes.

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

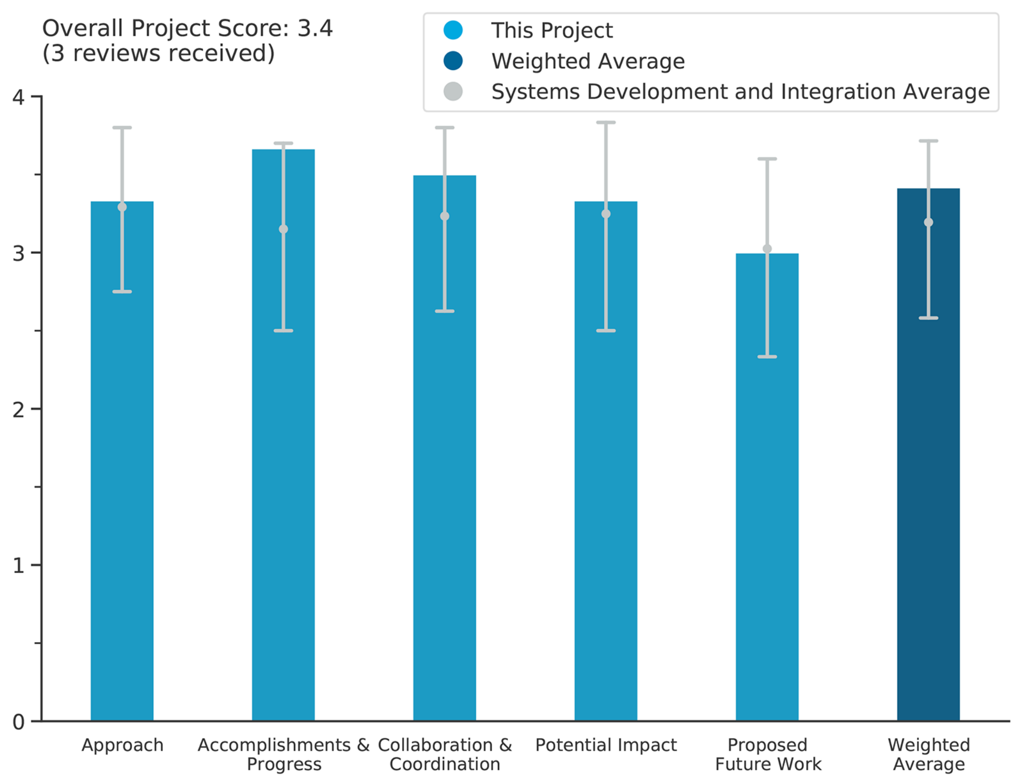
Genevieve Saur, National Renewable Energy Laboratory

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 excellent for addressing the barrier of dynamic characterization of stack response and degradation effects. The approach is excellent for demonstration and performance evaluation of an electrolyzer system coupled with an offshore wind turbine. The facility setup tackles several key data gaps but could be improved upon with additional data collection on heat management, corrosion, or overall unique cost and operation conditions of operating offshore.
- The project plans are presented well and appear complete.
- The impact of dynamic operations on electrolyzer durability is an important aspect to identify.

Question 2: Accomplishments and progress

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

- The project team has made excellent progress generating critical data on the performance of the stack under steady-state and wind simulated conditions. The team developed and applied a clear framework for modeling the system and collecting data, and the reviewer appreciates the clarification regarding past reviewer comments (e.g., the simulating power output across wind speeds to evaluate stack profiles and develop empirical power to the current model). Potential degradation via water effluent is not well-understood, and its monitoring has high impact on research.
- Progress to date is excellent per the scope defined at the outset of the project. There is more research that can be done in the future, but that does lie outside the scope as the project was defined.
- Identification of degradation due to highly dynamic operation is a valuable first step.

Question 3: Collaboration and coordination

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

- The project has significant levels of involvement from various partners, including international organizations.
- This is a great team with great collaboration. In the future, there could be opportunities to partner with other research groups, labs, or universities using these assets.
- It is unclear how collaborators will contribute to data analysis and what confidential data will prevent publication and enhanced learnings for the broader community outside the 2022 publication. That said, the reviewer sends congratulations to the team for successfully coordinating so many industry team partners while also involving experts from the international community.

Question 4: Potential impact

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

- This project has produced a significant amount of interesting and excellent data to advance Hydrogen Program goals. The capabilities of the system provide a fast data collection sample rate that could help inform questions around the technology that can be explored with future work.
- The team’s modeling and simulation of the system looks good.
- Overall, it is not very clear what interpretation of experimental data will lead to, and this could have a big effect on the overall impact of the project. It would be nice to see a flow of data or data management plan and how that will align with collaborations. It would be nice for the team to summarize further how the work here is unique to offshore wind and not just wind in general. It is unclear how the results are different from what is being simulated and collected at the Flatirons Campus.

Question 5: Proposed future work

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

- Sizing considerations should be evaluated in terms of the electrolyzer and wind energy rated power levels. A smaller electrolyzer would result in less dynamic operations but also additional curtailed/lost energy, unless the wind array was also connected to the grid. Since the project is concluding, this may not be accomplished as part of the current effort but could be included in different studies.
- The project team should provide insights on the scaling of 30-cell stacks with 225 kW input power to expected deployment stack sizes. It is unclear if the data being collected on the proton exchange membrane electrolyzer operation are useful data irrelevant to offshore wind coupling. It is also unclear how this is being shared with other groups developing water-splitting technologies. It is encouraging that the team is planning on publishing the project results.
- The project has outlined a plan to wrap up the work, but it would be helpful for the team to develop future work plans and scope to address other issues and opportunities for electrolyzers on the grid.

Project strengths:

- The project team successfully reached a point of system setup and data collection to evaluate key aspects of electrolyzer performance based on steady-state and offshore wind performance, including power to current, potential stack degradation, and stack response. The project team has done an excellent job collaborating and bringing in industrial partners and international interest.
- The data collection sample rate speed might be the best part of this project, as it will provide valuable insights for electrolyzer operations and durability. The team is also a highlight of the project—they have done great work.
- This project includes good simulation efforts and interesting results with respect to the fluoride release.

Project weaknesses:

- There were no real weaknesses, only future opportunities to explore.
- It is unclear what ambient conditions or added protection is required for the system to operate offshore—or perhaps electricity is being delivered onshore to electrolyzers. The publication suggests direct coupling is economically advantageous, but the project approach is not addressing the conditions of the ocean on the facility. It is unclear how priorities were set for this simulation and data collection. Also, overall, there is a lack of context to the project approach and results. Several points are unclear: how the PlugPower system compares with other systems, with literature, and with the targets for electrolyzer performance; how the lab conditions compare with the system that will be offshore (or perhaps it is onshore); and how this compares with onshore wind and the data generated from the Flatirons Campus.
- The project could include electrolyzer/wind energy system sizing considerations.

Recommendations for additions/deletions to project scope:

- The project team should seek to continue work in this area, leveraging this test setup and system. There is a need for electrolyzer operations directly with wind power, as this project addressed, but there are many other opportunities for electrolyzers on the grid that this hardware could explore.
- The project team should evaluate the impact of different electrolyzers on dynamic operations.

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

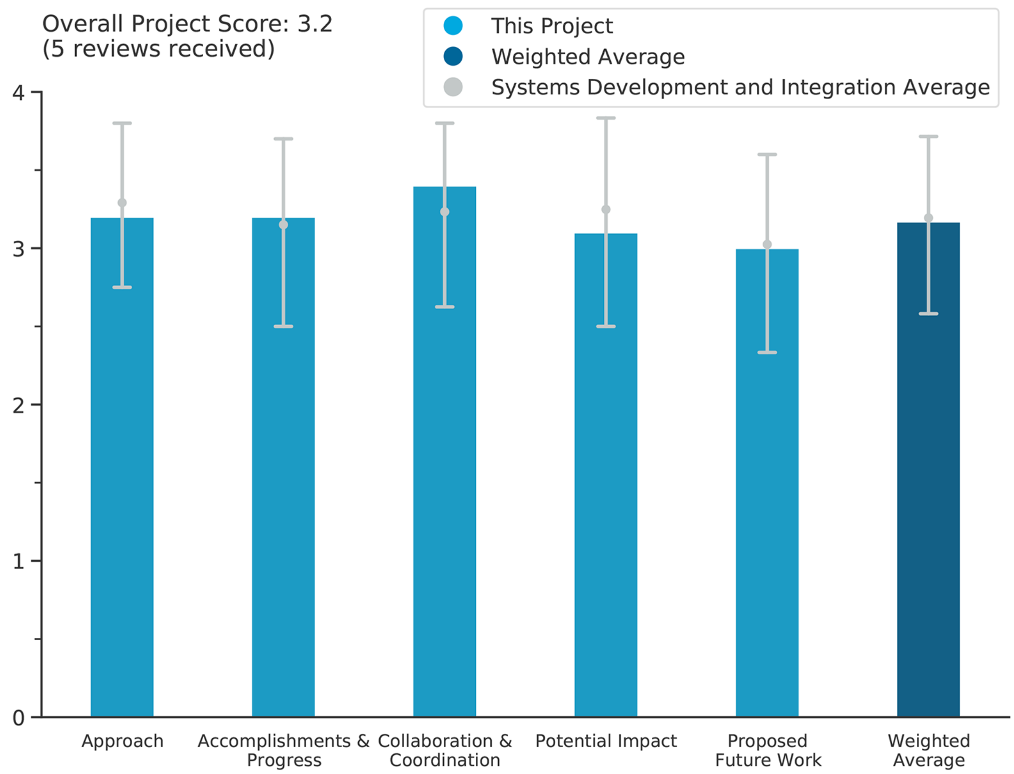
Kumaraguru Prabakar, National Renewable Energy Laboratory

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

- The work looks to inform current codes and standards through modeling and simulation. Verification through a planned demonstration will work to confirm the proposed changes and updates. The approach is well-thought-out and outlines a path to improving what is on record today for the community.
- The modeling approach is solid and provides good tools for new projects. The outreach activities are good, giving K-12 students exposure to science and engineering. The standards activity is also important and should be maintained beyond the project's end, if possible.
- One of the key challenges to renewable microgrids is how to operate the electronics that govern microgrid operation. This is particularly challenging when baseloads are not available and the energy sources are highly intermittent. This effort is centered around interconnection and interoperability of GFM inverters, with a focus on proposing updates to existing standards. The goal of the project is not to create new standards or requirements but to propose updates to existing standards. The principal investigator (PI) has a clear plan of attack for this work. This project appears to be significantly underspent.
- The focus is on proposing new interconnect and interoperability standards. It would be helpful to identify potential areas where these standards could be updated specifically for fuel cells. While the relevant standards have been identified, it remains unclear which aspects of these standards should be modified for fuel cells.
- The approach makes sense, and the project is in the final budget period.

Question 2: Accomplishments and progress

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

- The PI reports completing power hardware-in-the-loop (PHIL) testing with a GFM fuel cell inverter, publishing methodology at an Institute of Electronic and Electrical Engineers (IEEE) conference, procuring microgrid controllers to work with the microgrid model, and extending the modeling of microgrids beyond the initial test system. Additionally, the PI has been collaborating with Oak View, a disadvantaged community with aging electrical infrastructure.
- Significant progress has been made. Outreach activities have been conducted with multiple educational groups, and presentations provided on the work have been delivered. Modeling work has been completed for several sites, and onsite solar and battery resilience has been demonstrated.
- The science club provides hands-on opportunities for students to engage with various scientific principles, which should help maintain their interest. Two modeling cases were demonstrated, showing how the model predicts battery usage and the need for additional backup.
- The project is in its final stages and is nearing completion. PHIL experiments with the GFM fuel cell inverter have been completed, and the results have been disseminated to communities of interest, including IEEE.
- The transient response of the fuel cell to a step change in load should be presented. While the zoomed-out view shows good response, a sub-second view of the transients from fuel cell operations would provide valuable insights.

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.

- This effort was designed as a collaboration between the National Renewable Energy Laboratory (NREL), the Southern California Gas Company (SoCalGas), and the University of California, Irvine (UCI). The PI has been extending the effort to include multiple vendors that provide controllers to grid operators (ETAP, OATI, PXiSE Energy Solutions, S&C Electric Company, and Siemens). The PI reports receiving requests from others about using intelligent electronics device capability description (ICD) files. This increased collaboration is laudable.
- Comments from last year regarding collaboration appear to have been addressed. Certainly, UCI students have actively engaged in the community outreach, and multiple utilities are involved in the microgrid efforts. It is still not completely clear how the fuel cell and electrolyzer community has contributed to the project beyond getting data for the electrochemical device for the model, but generally, engagement appears to be good.
- Great collaboration between academics, national institutions, and industry provides robust research.
- The team appears to have good partners. It would be good to include an electric utility to confirm the interconnection standards are appropriate.
- While there appears to be a good list of other institutions involved in this project, it seems to be primarily an NREL project. It is hard to see the tie-ins with the diversity, equity, and inclusion work in UCI and SoCalGas. It feels slightly connected but not really tied to the main task of providing more information on GFM fuel cell inverters. It is not clear how Triangle Microworks is contributing. Previously, it was suggested that a major fuel cell manufacturer with stationary offerings provide input, but this does not seem to have taken place.

Question 4: Potential impact

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

- The work here is intended to reduce the cost of the installation, operation, and control of GFM fuel cell inverters and enable them to functionally replace traditional generation, resulting in greater market potential and installation at scale. The outcomes of this work directly aim to reduce the costs—specifically interoperability and interconnection costs—of integrating hydrogen assets into the grid. All of this will aid the adoption of these technologies by improving cost in these sensitive applications.

- The codes and standards have to be science- and fact-driven. Having the labs support this goal by providing analysis reports is needed. Also, with the mistrust of science in some regions and the demand for staff in growing industries, it is vital to expose children and students early. Additionally, if used properly by the community after the project, the model development can also provide good impact.
- Updating interconnection standards for GFM fuel cell inverters is important, particularly given the potential differences in response between a fuel cell and a battery. Defining interoperability standards is very important to ensure compatibility across multiple vendors and sectors. It would be good to get a sense of the potential soft cost savings.
- This effort is relevant and will have impact because standardizing interoperability and interconnection has to potential to reduce costs that may not be captured in initial techno-economic analyses. Improving standards is key to both safe operation and reducing some (but not all) of the costs of implementation.
- The project provides information to the wider community on GFM inverters for fuel cells. There are existing standards, and the project adds to these—but without necessarily changing or adding significant breakthroughs to performance targets, etc. The dissemination of information will, however, help with further deployment of assets that can support and firm the grid.

Question 5: Proposed future work

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

- Future work will finalize testing and code update suggestions, which will undergo peer review for acceptance. Future work aligns well with the project scope and is well-planned.
- The PI intends to complete standards recommendations documentation, submit the document for review and dissemination, and execute the test plan using an integrated experimental setup. This is a significant amount of work that may require a no-cost extension. It appears that there is budget remaining.
- Proposed future work makes sense and is cohesive with the rest of the work and effort so far. It is important to focus on the planning and execution phase of the testing for the final leg of the project.
- It was not totally clear what the test plan was for the integrated setup, nor what continuing outreach will be performed going forward, if any. Documenting the demonstrations in a way that can be reproduced with future students would help ensure impact beyond the current project.
- A "test plan" is referenced, but there was not much description of the actual effort involved. Additional details should be provided.

Project strengths:

- he presenter is clearly well-versed in the research he is supporting. The collaborations provide confidence that inputs are being considered from the researcher all the way to the end user to ensure all stakeholders are included.
- Strengths include the amount and variety of outreach activities, the codes analysis, and the model demonstration.
- Perhaps the most important project strength is working on the problem of intermittency, which is a key technical challenge in the development of green hydrogen.
- Partnerships with original equipment manufacturers is key to ensuring adoption of updated standards, and this project has included good industrial members.
- Strengths include developing and testing the GFM inverter and disseminating knowledge in relevant communities.

Project weaknesses:

- No weaknesses were noted at this time.
- It is not clear what will be done to leverage the educational materials already developed or who the model will be distributed to. These questions seem to be relatively easy to address.
- Not much has been presented to frame the soft cost savings. Although this may not be well understood for the fuel cell industry, perhaps leveraging existing technology experience (e.g., batteries) could help frame the costs.
- It is not clear how much a new “standard” is created if there are already established standards, such as the ones listed on slide 5, already available. The project proposes only “updates” to existing standards.

Recommendations for additions/deletions to project scope:

- It is necessary to ensure a mechanism for the tools to survive beyond the project performance.
- It would be good to focus on sub-second transients during load changes.
- Some cybersecurity considerations should be added in the final documentation.

Project #TA-063: High-Efficacy Validation of Hydride Mega Tanks at the ARIES Lab (HEVHY METAL)

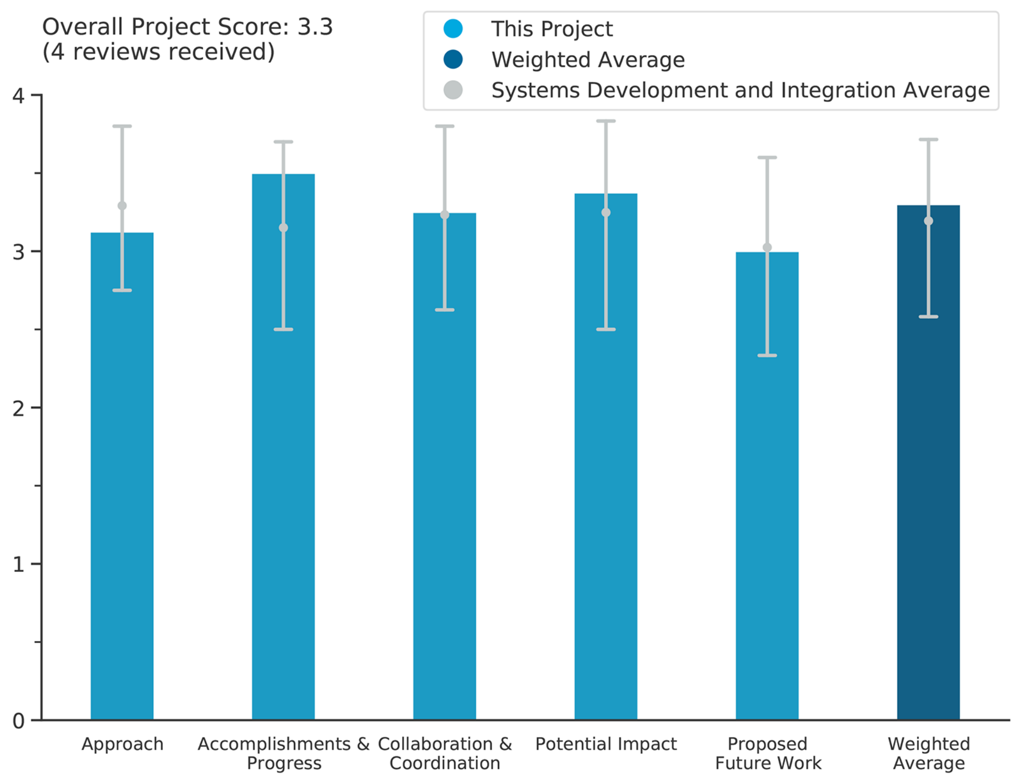
Katherine Hurst, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.17
Start and End Dates	7/01/2023–12/31/2025
Partners/Collaborators	GKN Hydrogen, Southern California Gas Company
Barriers Addressed	• Need for sufficient infrastructure • Need for technology advancements • Demonstration of technology at scale • Need for long-duration energy storage

Project Goal and Brief Summary

The project aims to advance materials-based hydrogen storage technologies through large-scale demonstration and identification of deployment pathways. This project focuses on validating new metal hydride (MH) technology integrated with megawatt-scale hydrogen systems and renewable energy infrastructure. By presenting a new MH technology with advantages in storage vessel size, efficiency, and safety, the project seeks to enhance resilience and energy security while supporting remote/rural communities and contributing to workforce development in the green hydrogen 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 **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project addresses the following four barriers: need for sufficient infrastructure, need for technology advancements, demonstration of technology at scale, and need for long-duration energy storage. This is accomplished by evaluating a highly promising emerging storage system that relies on MH material, offering an aboveground storage technology for smoothing wind- and solar-powered hydrogen production with end users that require steady delivery of hydrogen. The project leverages the new capability at the Flatirons campus to couple the storage system to electrolyzers driven by the grid, or onsite wind or solar, as well as couple the system with a fuel cell and waste heat generation. The commitment to safety planning and culture is outstanding. It is hard to vet the diversity, equity, inclusion, and accessibility (DEIA) activities without business names, but efforts appear to be heading in the right direction. The project's DEIA efforts would be strengthened by gathering information on the actual needs and operation of rural and isolated systems for communities.
- The project is integrating MH (from GKN Hydrogen [GKN]) and compressed storage into a system of clean generation, compression, and use. The project provides suitable facilities for attacking materials characteristics and demonstrations, which are critical barriers. The implementation plan is good and under way. The project has good safety planning in design and implementation, with reference to correct sources. The project will use fuel cell waste heat to release MH hydrogen where possible, increasing efficiency of the total system. So far, the project has no tangible benefits to the community (the bid went to the regular supplier); hydrogen discussions are about best practices, not community issues or benefits to the community.
- The consideration of infrastructure needs to acknowledge the rate at which hydrogen may be needed, especially in scenarios for which hydrogen is serving as a resilient energy supply. The project should also consider the potential round-trip thermal integration, i.e., the absorption of hydrogen onto the storage media releases heat that can improve electrolysis efficiency.
- This project has great potential. The use of MHs could be very helpful in a number of locations. The potential to use these systems for long-duration storage is strong. The principal investigator's (PI's) approach includes system integration and demonstration of operation (e.g., to hold 400 kg over 72 hours), optimization of performance, demonstration of a use case (desorption of 1 MW within 20 minutes), and a techno-economic analysis (TEA) to determine what makes the most sense for this technology. Perhaps the most concerning aspect of this work is the assertion that these systems require no safety distancing. Even if the MH required no separation distance per se, safety distancing should be required when the hydrogen flows out of the CONEX. An unexpected runaway thermal event has the possibility of releasing and igniting hydrogen catastrophically. If these boxes are placed too close together, one box could ignite the next, leading to a much larger accident. Furthermore, the hydrogen in the CONEX is in equilibrium with that on the surface, so there is always some free hydrogen. These are serious concerns that have not been adequately addressed by the PI and team A member of the Hydrogen Safety Panel (HSP) was consulted to see if these concerns were unwarranted. Unfortunately, that panel member had additional concerns that are not adequately captured here. This project specifically should not be exempted from review by the HSP. It only takes one safety incident for this technology at scale to be rejected and for the DOE investment of taxpayer dollars to fail.

Question 2: Accomplishments and progress

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

- The team is congratulated for the successful and safe delivery and placement of the GKN system. The team's awards from the National Renewable Energy Laboratory (NREL) are well-deserved. The coordination between the industry partner and the campus, design of measurement and verification controls, and electric utility planning are well-thought-out and appear to be on track. This is a very large demonstration with many novel aspects, and the researchers are doing what they can, despite issues with supply chains.

- The PI and team indicate that they are making steady progress toward overall project goals: the site preparation has been completed, the MH CONEX has been delivered, and efforts to connect the systems are in progress.
- The project team has designed the site and started construction with key components onsite. The team has also designed and started construction on the thermal handling system. The electrical package has been pre-certified and will be arriving onsite. All safety aspects have been completed and are in force. The project team is working with the National Fire Safety Council to improve codes. The team is working on pre-certification of European parts so the parts can be used with less certification and inspection occurring onsite. The team is also creating a communication/control system.
- The project has made great progress toward its goals, including physical deployment.

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.

- Collaboration and coordination are suitable, especially with Southern California Gas Company (SoCalGas), which may be a user or a beneficiary of users. SoCalGas also provided economics, so the partners have been used well.
- The project team is very collaborative with industry/original equipment manufacturers.
- The PI and team have arranged for able collaborators. These collaborators include GKN, a technology supplier that provides technical expertise, and SoCalGas, which performs the TEA and identifies preferred ways to deploy. The PI indicated a collaboration with National Fire Protection Association 2 (NFPA 2), though that seems to have led to an invalid safety conclusion, which is highly concerning.
- The value of the partnership with the SoCalGas team is unclear. It is unclear what information SoCalGas is contributing, what SoCalGas' concerns are with physical storage, and where SoCalGas sees material-based storage playing a role. This interest has major implications for the value of the Hydrogen Materials Advanced Research Consortium (HyMARC) program but is unclear beyond its evaluation of hydrides for trucks. The TEA benchmarking can commence regardless of time delays, and the NREL team should work closely with HyMARC, which already has established process models and cost assessments of hydrides in power applications to expedite the process and to guide the operation cycles of greatest relevance.

Question 4: Potential impact

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

- Materials function, compatibility, and development are critical aspects of the entire hydrogen economy effort from production to use. As such, this project is relevant. GKN mega tanks could serve remote communities, and the material is recyclable, which is a future issue all hydrogen economy technology will need to address.
- This project is properly aligned, and the results will be very informative.
- The impact provided by this project is potentially significant. The PI and team are demonstrating an Fe-Ti MH at scale, with the potential to number up. The PI indicates that this approach does not require a compressor with its complexity because of control of the desorption process. This could provide the means for providing as-needed energy to remote/rural communities.
- Overall, the potential impact of this project is outstanding; however, the proposed future work is so limited (understandably, considering budget and time) that some of the most critical data may not be gathered. The project team notes that the HY2MEGA platform is 100% recyclable. It is unclear whether the plan is to replace the entire system or only certain material components when the material degrades past a certain uptake. It is also unclear what the recycling pathway is and what effect it will have on the cost and life cycle of the system. Mr. Leighton clarified that part of the safety of the system was that the hydride was stable and that only 3% or so of gas in the storage vessel would have to be released during an emergency event (versus complete venting of a compressed gas or liquid tank). It is unclear if there is any way to verify the actual gas phase in the storage system and that potential venting loss. Overall, this does indeed seem to be an extremely safe system with very low hydrogen loss potential. A major aspect of this

technology is the thermal unit and use of waste heat from the fuel cell. The concept of using waste heat is often reported in literature with little to no process modeling or validation. Coupling variable heat demand with steady heat sources is very difficult; in this case, the fuel cell is operating along with the storage system, but caution should be taken to extrapolate that potential coupling to industry with waste heat. This will affect the levelized cost of storage (LCOS) of the technology as a whole and should only reflect this case study. The lack of discussion on cooling is puzzling. In presentations from GKN, different strategies for cooling are shown depending on whether the material is pellet, disk, etc. It is unclear what the energy penalty of cooling is or how that was avoided.

Question 5: Proposed future work

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

- The project has a suitable and timely plan for future work.
- Deployment and commissioning of the storage systems is reasonable future work.
- Future work includes electrical work to connect the systems, activation of the tanks followed by commissioning, and the beginning of efforts to determine the metrics of system performance. These are key steps in progress performance. Steady progress like this is important to large-scale deployments. It is concerning that safety issues have not been adequately addressed, which is why this score is lower than it otherwise would have been. In general, the reviewer really liked this project and sees strong potential if important safety issues can be accurately captured and responsibly managed.
- The project suggests the storage system is low-cost. It is quite hard to vet the truth of that statement, as there is no preliminary TEA benchmark reported and no sensitivity of that statement to changing prices of material or availability of waste heat. Future work on the comparison with compressed gas is eagerly awaited. It would be important to have these data from the demonstration campus and not just from an Aspen model of the compressed gas system. Information gained regarding the charging and discharging of the system is critically important; however, the team should also think carefully about the value of information related to storage duration. It is unclear what the effects are on round-trip efficiency of frequent cycling versus long (10+ hours) duration storage, as well as what the depth of discharge is. The energy balances all change, depending on the use case. Any sampling of the material after different cycling would also be very valuable.

Project strengths:

- r. Hurst, Mr. Leighton, and the whole NREL team are congratulated for their continued excellent work advancing demonstrations and building capabilities for the national laboratories in hydrogen. It was very impressive to see how the team demonstrated flexibility and strategy when considering the added challenge of activating the material onsite. Insights gained regarding the safety and siting requirements of the material-based storage system are extremely valuable. It would be great to see that information shared. This is an outstanding project for its ability to generate a wealth of data for the field of material-based hydrogen storage. The NREL team has an excellent track record of accomplishing demonstrations, and there is confidence that the team will work to ensure the data generated benefits the research community at large, not just the utility partners.
- A key project strength is the demonstration of an MH system, which has the potential to eliminate the need for compression.
- The project is on the last step prior to initial deployment—so close to starting to serve the hydrogen economy.
- The project has good demonstration of emerging hardware technology at a platform test site.

Project weaknesses:

- Coupling with rural or remote community power end use is a bit weak; there is no evidence that the solar or wind profiles, storage duration, or end-use scale and operation patterns to be used in the project reflect data or a prototypical end user in this category. Yes, microgrid systems are on the megawatt scale, but more can be done to represent this use case. The charge and discharge rates seem somewhat arbitrary but are exciting, nevertheless. It is important to clarify to the field that these storage systems may be allowed multiday charging and that the depth of discharge may be much less. Slower charging allows for the use of smaller electrolyzers and smaller balance-of-plant conditioning compressors/heaters. It is unclear how this slow charging can be achieved for systems with large electrolyzers. It will be important that the team goes beyond charge/discharge validation and provides context-setting on impacts of LCOS. This is needed in the field to develop technical targets for storage materials. GKN already has demonstrated systems at different scales. It would help to understand the value of this scale of demonstration and the risks being targeted that lead to addressing the key barriers listed.

- The key project weakness is an inadequate safety review, particularly around safety distancing. Perhaps the Hydrogen and Fuel Cell Technologies Office should review whether NREL's prime contract should exempt projects like this from HSP review.
- This project is likely to have good deal of proprietary information and so is less generally helpful.

Recommendations for additions/deletions to project scope:

- A key barrier this project is supposed to address is demonstration of material-based storage at scale. This can be done only by benchmarking with market-ready competing technologies, such as compressed gas or cryogenic storage, to validate whether the material-based storage system does better on any or most technical, safety, workforce, or economic metrics. The presentation did not clarify what "other storage tech" would be evaluated. The HyMARC team has models of stationary storage of hydrides and other materials for this scale of power applications and could help expedite this benchmarking. It is unclear how the TEA will take the data gathered with this project and advance the understanding of hydrides in this space. If the project reveals the hydride does not operate as well, it is unclear what levers GKN has to improve upon the system. It is also unclear if there are opportunities for iteration. Providing this information would greatly strengthen the project's value. It is unclear how the round-trip efficiency of this project will be compared with the data being generated by Mr. Leighton's team using the 600 kg compressed gas system. It is also unclear if the system will be run only on simulated solar and wind and how the use of waste heat will be measured and integrated into the round-trip efficiency. From an exergy standpoint, the compressed gas system is wasting that heat, but maybe it could be used for something else. This project should receive additional funding to further the impact and scope of work.
- It is recommended that scope be added to understand the influence of channeling. In large-scale systems, distribution of fluids is non-uniform, which can affect performance. Sampling the materials spatially and characterizing their absorption/desorption performance postmortem could provide a pathway to further optimization of these systems.

Project #TA-064: Hydrogen Production, Grid Integration, and Scaling for the Future

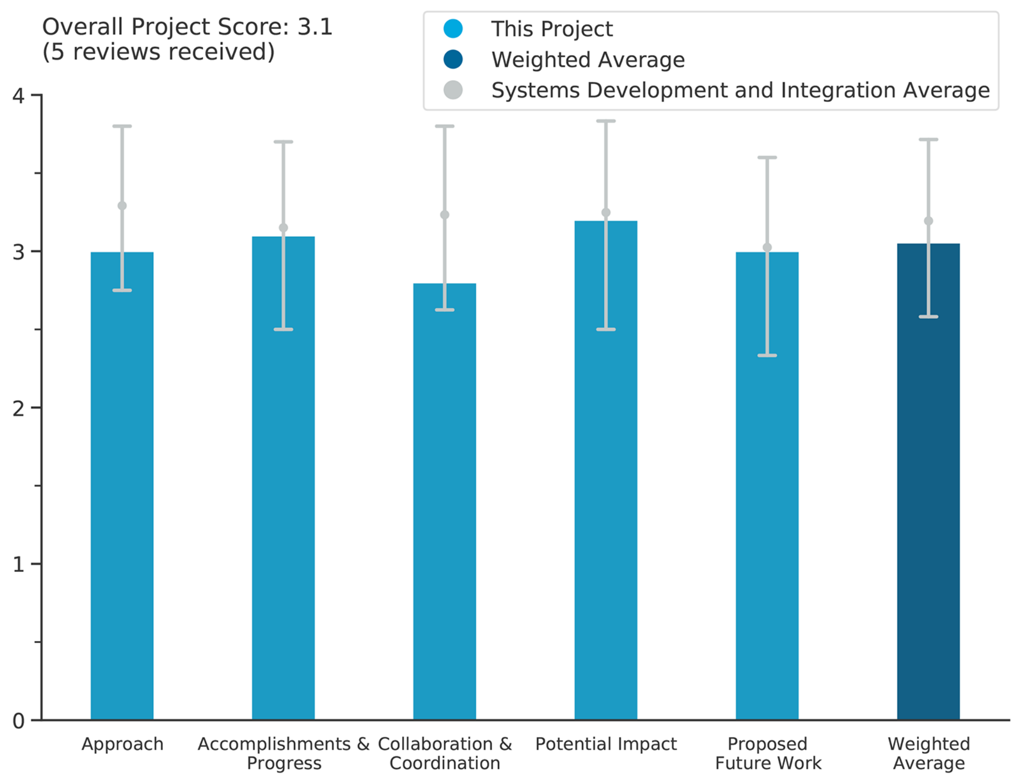
Sam Sprik, National Renewable Energy Laboratory

DOE Contract #	WBS 7.2.9.18
Start and End Dates	8/1/2022–5/31/2025
Partners/Collaborators	Electric Power Research Institute
Barriers Addressed	• Lack of system performance understanding to guide commercial deployments of electrolyzers with renewables and the grid

Project Goal and Brief Summary

The project seeks to explore near- and long-term pathways toward the commercialization of grid-integrated electrolysis systems. This will inform deployment strategies across the planning, procurement, and operation stages of hydrogen production on the grid. Leveraging the National Renewable Energy Laboratory's (NREL's) 1.25 MW polymer electrolyte membrane electrolyzer system, the project's goal is to characterize system performance under various relevant scenarios, create a digital twin for emulation in the Advanced Research on Integrated Energy Systems (ARIES) virtual environment, and perform hardware-in-the-loop testing of pilot-scale, decentralized, and centralized hydrogen systems. Through these efforts, the project hopes to promote hydrogen production from renewable sources, reducing greenhouse gas emissions and criteria pollutants, and to generate workforce in hydrogen facilities.

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.

- Identifying operational impacts from a variety of dispatch scenarios will help inform future deployments and provide direction to electrolyzer suppliers. This project will provide valuable information for developers as they look to integrate electrolyzer systems with different use cases.
- This project is in its beginning stages and has a clearly defined scope and plan. The project team's additional work through continued testing and creation of a digital twin should help overcome the listed barrier of "lack of system performance understanding."
- The project plans were communicated effectively, with initial operations having commenced. In the future, the team should speak more directly to the safety plan during presentations, rather than just referencing prior presentations. This will serve as a reminder to the reviewers and audience. The team should not assume the audience saw the prior presentation, as this assumption can communicate a lack of respect for safety on the project. That is likely not the case, but it could be interpreted that way by other audience members.
- The principal investigator (PI) and team are doing performance testing on large-scale electrolyzers. They intend to capture what is happening in the box, and they are designing metering and monitoring to capture performance to inform performance standards. This information can be used to plan for meeting contracting requirements and inform industry-wide performance reliability standards. The presentation at the Annual Merit Review (AMR) left some questions regarding whether hydrogen safety and hydrogen safety culture had been adequately considered in the planning and execution. All members of the team should fully understand safety, as relying on others without fully engaging in safety is often what causes issues to arise. A core safety principle is to evaluate every hazard every time.
- The described project approach is to use an electrolyzer system at ARIES, but unfortunately, NREL has had significant delays in commissioning the electrolyzer. The objective is to use the digital tools available at ARIES and then build out additional tools, such as a digital twin. These are all excellent ideas, but the team has made little progress on any of the tasks because of the delay in the electrolyzer commissioning. The team should have developed an approach that was less reliant on the electrolyzer commissioning. For instance, the digital twin work could have been developed on surrogates.

Question 2: Accomplishments and progress

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

- In this relatively new project, the PI and team have established a preliminary design; begun making key sensor measurements, albeit with some ongoing refinement; and completed initial electrolyzer shakedown tests. The team is likely going to need a no-cost extension, given the apparent delay in starting.
- The project's data collection has already started, even at this early stage. Calibration of the mass flow meter should improve data collection. The project team should identify a method to track the vented hydrogen gas (i.e., during the period where the dew point is dropping).
- The team has done great work on getting to this stage and through all the supply chain issues. This project is very exciting, and the reviewer is looking forward to the future work.
- The project is in its beginning stages, and there will be more accomplishments coming soon.
- The schedule for the electrolyzer commissioning was delayed significantly, so the project is very far behind, with only about 15% of funding spent, despite being 66% through the project timeline. There seemed to be significant progress in 2023; then work seemed to stop in 2024, perhaps due to uncertainty about the electrolyzer. It seems that the team could have progressed on the digital twin, research on system boundaries, etc. during this time.

Question 3: Collaboration and coordination

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

- This project has a great team and great collaboration.
- The PI and project team have constructed a collaboration between NREL, the Electric Power Research Institute (EPRI), and the Gas Technology Institute (GTI) via the Low-Carbon Resources Initiative (LCRI).
- The project team is developing demand scenarios, but it is not clear how those scenarios will be determined. It appears that EPRI will help define them, but it would be good to request input from utilities directly or from electrolyzer suppliers for additional options.
- There appears to be a good connection between the presenters and clearly defined contributions from NREL and EPRI. It is not clear what LCRI/GTI has contributed to the project.
- There seems to be limited collaboration in practice, with the team mainly waiting on the electrolyzer commissioning. Perhaps others on the team could have pulled forward other tasks to help.

Question 4: Potential impact

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

- This project intends to evaluate multiple scenarios and hardware testing that combines a 1.25 MW electrolyzer with hydrogen support equipment. The project is useful, as it will provide stakeholders with insight into how deployments of clean hydrogen production can work. The results from this project will inform entities looking to build clean energy projects.
- The dissemination of the information gained from the project, and creation of a digital twin, will enable further understanding of the commercial deployments of electrolyzers with renewables and the grid.
- This project will help decrease costs associated with new electrolyzer deployments by identifying new controls and dispatch scenarios.

Question 5: Proposed future work

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

- he project is in its beginning stages, but the plan is well-laid-out and achievable. The reviewer is looking forward to continued progress.
- The proposed future effort is commensurate with the current status and stated project goals.
- The proposed work as outlined appears to be fine. The PI and team are really at the early stages of this project, so additional results will be expected at the next AMR.
- The project presentation was rather weak on the next steps. “Revise scenarios and test plans” was about all that was stated without more information on what those might be or what they would look like. It was great seeing the initial data and runs, but it is unclear what comes next.
- The project has a go/no-go decision point on whether to use the electrolyzer in June 2024, and the project hinges on that decision. If the team cannot move forward, it should develop some generic tools of use to the community.

Project strengths:

- The Flatirons campus is ready, with an electrolyzer fully commissioned. The reviewer is looking forward to the execution of a well-laid-out plan.
- Getting the system running and commissioned is a great milestone. The team is to be congratulated.
- This reviewer appreciated the combined presentation of senior and junior members of the team. Training and mentoring the next generation are key to deployment of the growing hydrogen economy.

- Work at ARIES with EPRI focused on the response and effectiveness of using an electrolyzer on the grid, which is a key question for H2@Scale.
- Performance data from real-world demand scenarios with real-world equipment is valuable.

Project weaknesses:

- The team should continue to work with GTI, EPRI, LCRI, and other industrial entities as more data are collected to obtain feedback and suggestions.
- It was unclear what testing would be performed next. Though the team surely has a plan, it was not presented clearly.
- One project weakness is the increased partnership with potential end users to develop new demand scenarios. It would be good to see a stronger connection to how performance data help reduce ultimate production costs in the future.
- There are some concerns around safety that the PI and team can address.
- The team has been unable to use the electrolyzer, and little progress has been made on the supporting parts of the project, such as sensor development, digital twins, and other modeling components of the work. However, this may all change quickly if the team is able to use the electrolyzer.

Recommendations for additions/deletions to project scope:

- Progress on this project will hopefully change quickly once the electrolyzer is commissioned for use. The team can then catch up quickly on the project tasks and deliver useful information to the community about the important problem of connecting the electrolyzer to the grid. DOE should support this project to get it operational as soon as possible, providing extra funds or resources as required. The NREL/EPRI team should be encouraged to publish the results broadly.
- The team should consider quantifying hydrogen loss through venting and providing water consumption data. These are both hot button topics around hydrogen with communities and environmental groups, and it is imperative to collect these data.
- The project team should add any other input from stakeholders that will be involved in the commercial deployment of similar systems, which will be beneficial to the output from this work.
- Additional utility partners should be included in an advisory role.

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

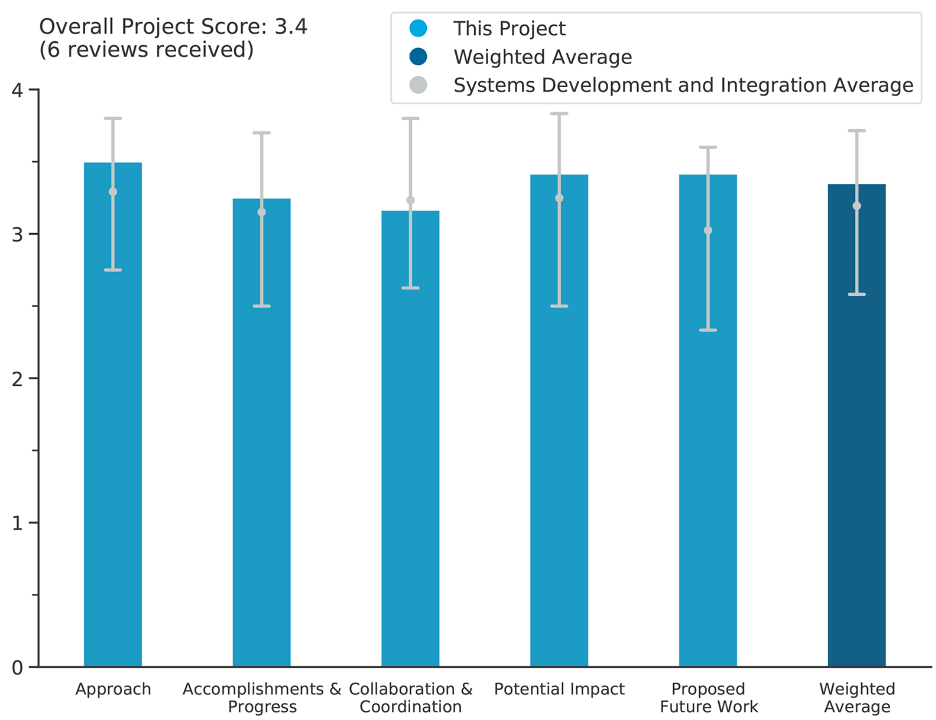
Rajesh Ahluwalia, Argonne National Laboratory

DOE Contract #	WBS 9.3.0.6
Start and End Dates	10/1/2020–9/30/2024
Partners/Collaborators	University of Illinois Urbana-Champaign, 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 (FCSs) being developed for heavy-duty (HD) 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 **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is well-thought-out and very detailed and specific. There is no overall diversity, equity, and inclusion plan or community benefits plan (CBP), as the project is being purely model-based work. The project objectives and critical barriers are addressed in detail throughout the project brief, and it is clearly well-organized.
- The goals are very relevant to decarbonizing hard-to-abate sectors such as mining vehicles and aviation. There is a detailed quantitative analysis for the duty cycle admission requirements that lead to the results. High-temperature fuel cells may be more applicable than low-temperature fuel cells and their associated weight of cooling.
- This project is a comprehensive attempt to understand the options and potential advantages/disadvantages of hydrogen-fueled commercial aircraft. The project seems to be well-integrated with other DOE efforts in hydrogen production and transportation. The scope was unclear and seems rather broad for a project of this scale; however, that was not communicated well.
- The approach is excellent**.** It is effective and contributes to overcoming most barriers. More summary slides can help. There was no information on diversity or a community benefits plan (CBP).
- GHG reduction for the aviation sector is large, and its reduction is high-impact. Analysis should be pursued among multiple kinds of propulsion systems to clarify the benefit of hydrogen use (for example, hydrogen versus sustainable aviation fuels [SAFs]). Among hydrogen propulsion systems, this project focuses on the low-temperature proton exchange membrane fuel cell (LT-PEMFC) and electric propulsion system, but fuel cell versus hydrogen combustion turbo fan could be first in order to narrow down the hydrogen propulsion system selection for the analysis. It is necessary to analyze the effect of hydrogen emissions, such as the GHG effect and fuel cell efficiency. The FCS emits hydrogen gas from anode purges, and hydrogen emissions from a high-power FCS would not be negligible. Boil-off gas from a liquid hydrogen (LH2) tank or subcooled system should be counted as well.
- The approach was confusing because of the tie between traditional off-road and aviation; however, it appears the foundational evaluation methodology is being applied to both. Both are very hard-to-decarbonize industries that should not be written off as applications for zero-emission technologies, including hydrogen. The methodology appears to be sound, and the principal investigator was knowledgeable and passionate about the subject.

Question 2: Accomplishments and progress

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

- The identification of redundancy requirements for fuel cells and additional reserve fuel are key points. The compressor–burner–expander module (CBEM) and the FCS compressor–expander–motor module were important archetypes to give a reasonable side-by-side comparison. Air temperature at high altitudes is a significant challenge for long-range aviation. The detailed comparison of the air and thermal management systems for the CBEM is very important for understanding the impact on fuel consumption. The comparison table for the two power train approaches is very interesting in showing the very limited change in efficiencies. The other details for number of components and reliability and weight are key takeaways. Slide 5 was helpful, as it provided a detailed comparison for speed, fuel consumption, and total range to ensure that the cruise and takeoff power assumptions are realistic. The comparison of the CBEM and the fuel cell compressor–expander–motor module is critical. Unfortunately, it was somewhat difficult to follow the exact weight and power and efficiency trade-offs between the two systems within the limited time of the presentation.
- The principal architecture and thermodynamics were dense and naturally hard to follow in a brief presentation (even by the reviewer, an ex-propulsion engineer), but the work appeared to be thorough. On the surface, packaging 6 x 6.25 MW FCSs (including balance of plant) with hydrogen storage on a commercial aircraft seems to be difficult to impossible, from both weight and volume perspectives, particularly when the only existing system that is being removed is the fuel tanks in the wings. Analysis needs to be carried out to truly understand the challenges and identify novel approaches to overcome those

challenges. It is also unclear whether modern electric fans (assumed to be 18 MW each for a twin-engine aircraft) can carry the load and be housed inside the turbofan.

- The amount of work and number of accomplishments over this rating period were well-documented. The project targets were accomplished and well-presented. The criteria against which the project measures itself were well-defined and applicable to overcoming barriers.
- Informative outcomes from the LT-PEMFC propulsion system are seen.
- It was difficult to understand the tasks accomplished and the results. What system topologies were examined and how they were analyzed were both unclear. It seems like a significant amount of complex simulation and analysis was done; however, the presentation lacked sufficient detail to understand whether the analyses made sense or what the significance of the results was. Responses to questions posed after the presentation did not help. It was unclear what role the fuel cell played—whether it is producing electrical power that is consumed by a motor augmenting the turbine engine, whether it is being considered independently, and what the assumptions are. A basic slide explaining the goal(s), scope, and approach would be helpful. There is a top-level goals slide and an approach slide, but they do not make sense without a clear explanation of what the project is actually doing.
- Significant progress has been made, but there are weaknesses that need to be addressed to improve the rate of progress or improve the clarity of the project's objectives and performance indicators. For example, engineering performance indicators could be better summarized. The project contributes to overcoming some barriers.

Question 3: Collaboration and coordination

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

- The coordination with the University of Illinois Urbana-Champaign (UIUC) is done well.
- There was extensive collaboration with UIUC, but it would have been good to see both smaller startups and established companies listed as collaborators for inputs and fact-checking assumptions. (Slide 17 provides details.)
- There are a limited number of partners, including Argonne National Laboratory and UIUC. The project could use an aircraft engine original equipment manufacturer partner like General Electric, Pratt and Whitney, Rolls Royce, or Boeing for both third-party verification of principals and technology transfer of the results of the analysis.
- There is a possible space for an aviation propulsion system expert to compare with hydrogen combustion propulsion. The off-road heavy-duty area is also a possible space for an industry expert.
- A list of collaborators, both within and external to DOE, was provided.
- The project has appropriate partners and leverages from internal partners but would benefit from a commercial partner for enhanced success in coordination.

Question 4: Potential impact

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

- This effort is clearly aligned and provides excellent information that can be used to advance and target applications for future investment.
- The project is strongly aligned with the Hydrogen Program's goals and objectives and is likely to significantly advance progress toward its performance targets for off-road applications.
- Understanding the feasibility of electrifying propulsion loads for aviation could have a significant impact on a sector that has traditionally been overlooked.
- Finding technically and economically feasible ways to use hydrogen for aviation promises to have a significant impact on carbon emissions.
- Reducing GHG for aviation and off-road heavy-duty applications is a high-impact area.

- The total CO_2 avoided is a key impact and relevant to decarbonizing the hardest-to-abate sector of aviation. It would be helpful to have a chart showing how the regional jet models might be compared to emissions for SAF, and conventional jet fuel, perhaps by looking at a few different hydrogen pathways.

Question 5: Proposed future work

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

- The identified future work is critical for the analysis, particularly packaging, weight penalty, and mitigation methods. The reviewer is excited to see the results.
- Most future work looks to be refining or improving TCO analysis. This is a great focus for the project, as the more accurate the data are, the more benefit they will provide. A commercial partner may be able to provide some of the information needed for refinement and accuracy improvements.
- Feasibility of the hydrogen fuel cell propulsion system is adequately addressed.
- The separate slide for remaining challenges and future work was good.
- Slide 16 has a series of bullets for future work. More details should be provided for reaching a storage vessel of 70 wt% gravimetric density. Hopefully, high-temperature PEMFCs can be studied by comparisons to results from this LT-PEMFC study in the future.
- Future work was discussed. General topics to be addressed make sense, but it is unclear how they will be approached.

Project strengths:

- The study methodology and knowledge base of the principal investigator and researchers are strengths of the project. The ability to develop and study the physics, thermodynamics, and cost is a difficult undertaking for a notional system, but the team appears to be managing it.
- Strengths include the capability of FCS analysis based on the experience of on-road heavy-duty FCS analysis.
- Performance of air and thermal management systems for the CBEM is well-described and has potential to improve further.
- The project provides a very good comparison for the initial TCO, with a breakdown of component contributions. It would be good to review these assumptions and projections with stakeholders.
- There is a significant amount of quantitative analysis. The project has worthwhile top-level goals.
- The analysis is excellent and thorough.

Project weaknesses:

- More information about the chosen cruise speed and power, and the ratio to takeoff, would be helpful in understanding the justification for the right system balance of plant and other details. A more detailed comparison would be helpful for the expander–burner system and the conventional fuel cell motor–compressor system for weight, cost, and practical implementation details. A better overview of emissions avoided by the regional jet under consideration for a variety of fuel pathways would also be helpful.
- The project could use a third-party validator from industry. The design and material are technically dense and could use an outside party to verify practicality. This could also be used to improve the utility of the study by providing technology transfer to a potential system manufacturer to allow justification of investment into a system.
- Key indicators in simple terms are missing when going through air and thermal management systems and the integrated thermal, air, and propulsion system. The team is asked to highlight this information in the slides.
- It is unclear what systems are being analyzed.
- Commercial input is needed.
- The lack of industry involvement is a weakness.

Recommendations for additions/deletions to project scope:

- It would be good to have a high-level overview and review of the challenges for bringing large-scale LH2 fueling to an airport. A quick overview of technologies required for fueling the aircraft would be helpful; wet hose, nozzle, vent management, and other technical challenges could be briefly addressed. California Fire Code appears to prohibit mobile LH2 fueling, even as the state funds research, development, and demonstration projects.
- Hydrogen usage for the aviation sector is still controversial. Recommendations include analysis of the cost to reduce GHG emissions, including TCO benefit, among multiple kinds of propulsion systems to clarify the benefit of hydrogen use (for example, hydrogen versus SAFs, or small versus large airplanes). Among hydrogen propulsion systems, this project focuses on the LT-PEMFC and electric propulsion systems, but a study of fuel cell versus hydrogen combustion turbo fan could be first to narrow down the hydrogen propulsion system selection for the analysis. It is recommended that the project add analysis of the hydrogen emission effect for both GHG impact and fuel cell efficiency. FCSs emit hydrogen gas from anode purges, and hydrogen emissions from a high-power FCS would not be negligible. Boil-off gas from an LH2 tank or subcooled system should be counted, too.
- The project should analyze work being done by commercial fuel cell aviation companies such as ZeroAvia.
- The only recommendation for addition is the third-party industry partner review cycle.
- An overall summary slide can be added as a reviewer-only slide.