2018 – Technology Acceleration and Hydrogen Infrastructure R&D Summary of Annual Merit Review of the Technology Acceleration and Hydrogen Infrastructure R&D Sub-Program

Summary of Technology Acceleration and Hydrogen Infrastructure R&D Sub-Program and Reviewer Comments:

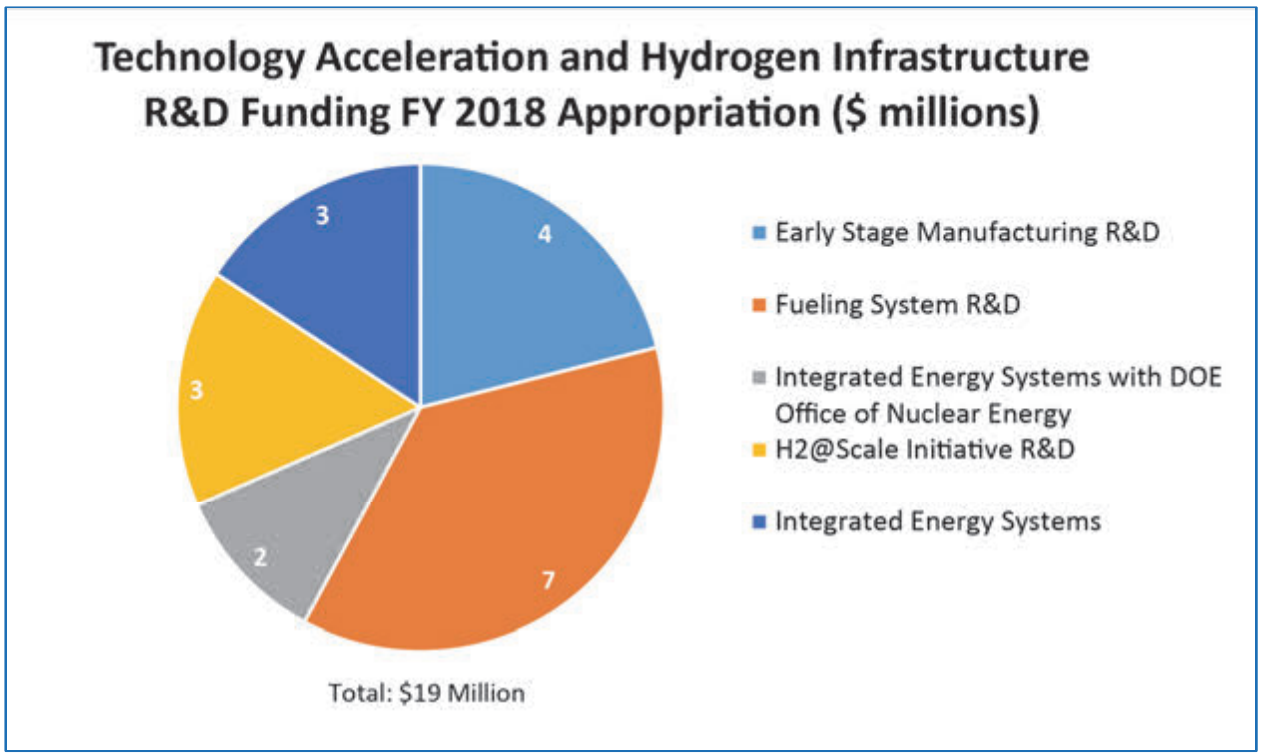
The Technology Acceleration and Hydrogen Infrastructure R&D sub-program aims to enable hydrogen technologies that support hydrogen infrastructure development and hydrogen production from diverse domestic resources such as solar, wind, and nuclear power through innovative research and development (R&D). The goal is development of reliable, low-cost, and safe hydrogen infrastructure technologies for multiple applications. The sub-program's portfolio of early-stage R&D activities support the H2@Scale concept, including R&D to identify and develop technologies that provide significant cost reductions in hydrogen storage, use, and transport. R&D focus areas in 2018 included (1) refueling station R&D (compression, storage, and dispensing), (2) hydrogen transport R&D (liquefaction, bulk hydrogen carriers, and storage), (3) materials compatibility R&D, and (4) integration with diverse generation sources and end-use applications (e.g., integration of hydrogen technologies with nuclear generation and the grid, advanced material and component fabrication technologies and processes, and system validation). The sub-program also collaborates with state and local organizations and other federal offices and agencies (such as the U.S. Department of Defense, National Science Foundation, U.S. Department of Transportation, and the DOE Offices of Science, Fossil Energy, and Nuclear Energy) to leverage outside activities, coordinate efforts, and build opportunities for new technology applications and deployment.

The Hydrogen and Fuel Cells Program (the Program) reviewers commended the Program's focus on H2@Scale and the prioritization of hydrogen production and infrastructure R&D to lower the cost of hydrogen production and increase hydrogen supply. They included the H2@Scale launch and grid integration activities among the Program's top accomplishments in 2018 and suggested that a consortium approach would be useful to encourage coordination and collaboration among the many stakeholders in grid integration. Reviewers recognized the importance of government funding for early-stage R&D for innovation and breakthrough science, but they emphasized the critical need for continued government support of applied R&D in the implementation and validation of new hydrogen and fuel cell technologies. Also recognized as a key Program strength was stakeholder collaboration, including the Program's work with international agencies and organizations, other federal and state agencies, the Hydrogen Council, and other industry stakeholders. Reviewers suggested an increased focus on medium- and heavy-duty vehicle fueling, high-volume manufacturing technologies, demonstration of H2@Scale in the field, and first-of-kind questions about how to successfully manage energy sector transitions. Reviewers also recommended continuing and broadening coordination with outside stakeholders important to H2@Scale, including the nuclear industry, fuel production and distribution industry, and state and regional utility regulators, as well as increasing participation of the manufacturing industry as suppliers to the fuel cell industry.

Project reviewers also were impressed with specific project highlights and accomplishments, as detailed in the project review reports that follow.

Technology Acceleration and Hydrogen Infrastructure R&D Funding:

The fiscal year 2018 appropriation for the Technology Acceleration and Hydrogen Infrastructure R&D sub-program totaled $19 million. The funding was focused on early-stage manufacturing, integrated energy systems, H2@Scale concepts, fueling system R&D, and integrated systems with nuclear hybrid energy systems; this breakdown is depicted in the figure below. Future work in the sub-program is expected to focus on applied early-stage research and technology for the H2@Scale initiative related to hydrogen production and storage, hydrogen energy storage, materials compatibility, and innovative hydrogen carriers.

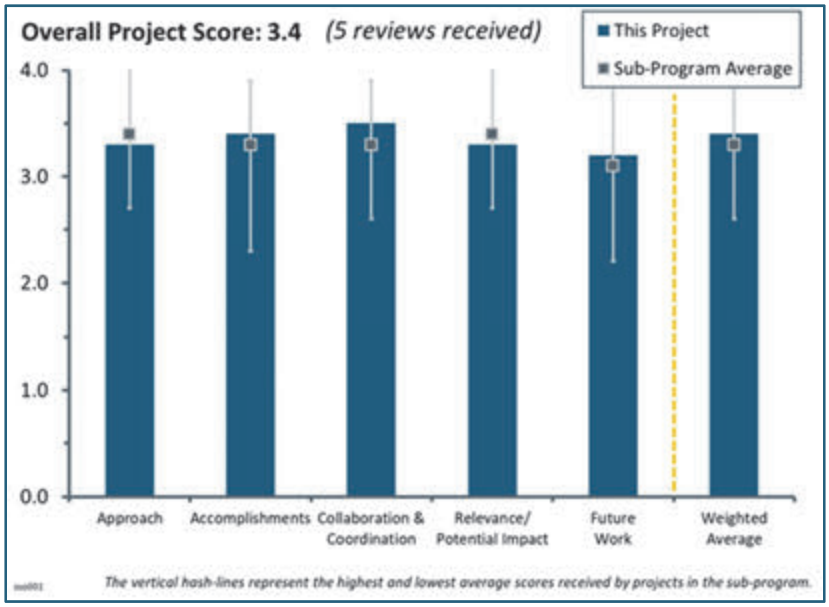

Technology Acceleration and Hydrogen Infrastructure R&D Funding FY 2018 Appropriation ($ millions)
4
7
2
3
3
Early Stage Manufacturing R&D
Fueling System R&D
Integrated Energy Systems with DOE Office of Nuclear Energy
H2@Scale Initiative R&D
Integrated Energy Systems
Total: $19 Million

Project #MN-001: Fuel Cell Membrane Electrode Assembly Manufacturing Research and Development

Michael Ulsh; National Renewable Energy Laboratory

Brief Summary of Project:

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



Question 1: Approach to performing the work

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

- The National Renewable Energy Laboratory's (NREL's) approach, focused on early-stage technique development coordinated with industry, is excellent. NREL's actual development of diagnostics and validation in-line on actual membrane electrode assemblies (MEAs) is far superior to merely doing an analysis.
- NREL is doing some fine work in this project. The collaborative approach to this project is exemplary, and the project team is working on technology that will be essential for ultimate large-scale manufacturing of polymer electrolyte membrane fuel cell (PEMFC) MEAs.
- This project is a continuation of an enduring effort to expand technology in fuel cell manufacturing. Certainly during the last years when this activity was underway, commercialization of fuel cell technology continued unabated. NREL has had the freedom to "pick their battles." Fuel cell technology has morphed into another engineering discipline. There is excellence written across the NREL activity. However, as is necessary, many of the activities have been accomplished under secrecy agreements, and while what is presented is finished work, it is clearly not all the finished work. Such an arrangement is essential. Even so, the "work" is not fully described, and thus judging on "performing the work" has to remain fuzzy.
- The approach to performing the work appears to be strong. This is validated by the partnership with Mainstream to commercialize vision-based scanning for defects.
- This project's approach is speculative on types of defects that could be significant. It artificially introduces the defects into a MEA/membrane manufacturing line, then manufactures the product to see whether those defects could be detected in the manufacturing line. The approach should be to scan commercially produced MEAs or membranes and look for manufacturing defects, study the impact of the discovered defects on fuel cell performance, study ways to quickly screen MEAs and/or membranes for those existing manufacturing defects, and work with the manufacturer to identify the cause of manufacturing defects that have an impact on performance.

Question 2: Accomplishments and progress

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

- The NREL team completed multiple demonstrations of in-line QC methodologies, all of which have potential for use in future manufacturing lines. As the scale of PEMFC manufacturing expands multifold over the next several years, these tools will be available for adoption. For example, the ability to find and localize pinholes in the membranes in an in-line (continuous) manner has enormous potential for reducing manufacturing cost and improving reliability.
- The project emphasizes the analysis of starting materials used in roll-to-roll (R2R) processing, processing like 3M uses to make Scotch Tape. During the duration of the NREL activity, very significant improvement in fuel cell performance happened. For instance, a 75-kW stack suddenly morphed into a 100-kW stack with no apparent change in weight or volume. The presentation covers some rather simple experiments, such as looking for pinholes in membrane materials. This is elementary. It is impossible to know how much NREL contributed to the success of the existing fuel cell industry, but it is apparent that the amount is *not* zero. As in many situations, it is impossible to fully understand individual contributions in a huge endeavor. General Motors (GM) claims they invested $2.2 billion in fuel cells to date, but there have been many people, with NREL in the middle of it. This is a good investment.
- The project presents numerous data examples of defect detection using a variety of approaches. Demonstration that defects can affect cycle performance yet have no impact on initial performance is a key finding. The project uses Lawrence Berkeley National Laboratory modeling to predict the impact of using a cooling jet for the through-plane reactive excitation approach, but actual test measurements would be more convincing.
- Many good defect scanning tools were developed. The defect impact in cell performance was studied. The DOE goals and barriers "E" and "H" identified on slide 2 should be done upon receiving MEAs at the stack assembly site.
- The team has reported progress on the various inspection methods investigated, including demonstration that the approach works. The project did not directly include what impact those methods have on the identification of defects. For instance, it was unclear how many defects were missed prior to development of these techniques and how many defects are now identified that were previously passed along to downstream manufacturing steps and allowed to be assembled into the product. Additionally, it was unclear what impact the implementation of these techniques would have on product quality and cost.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- The collaboration is broad and deep, including huge corporations, startups, universities, and foreign governments. It would take a principle investigator like Ulsh to pull this off; certainly this is not a one-man show, but there is one person in the middle. There are many things happening, but there are also many secrets to keep. There is the necessity of keeping proprietary data safe and protected, as well as having a staff that understands the details of protecting information. Fortunately, NREL has established a facility where this can happen.
- NREL uses an excellent plan that includes laboratories, academia, and industry to explore concepts and quantify diagnostic abilities. The project seems to blend several disparate collaboration and technology transfer interactions (Small Business Innovation Research Phase 2, R2R consortium cooperative research and development agreement, Work for Others). This is commendable.
- The level of collaboration is the strength of this project. NREL is working with a membrane manufacturer, a fuel cell manufacturer, and a potential QC equipment manufacturer. NREL also has established meaningful collaborations with other national laboratories and universities, as well as two foreign laboratories.
- There is a good cross-section of partners, including industry, academia, and national laboratories.

- The project team has had much collaboration with industry and laboratories; however, more collaboration should be done with original equipment manufacturers (OEMs) that receive MEAs and build stacks. The team should screen existing manufactured MEAs and develop screening tools.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The contemporary fuel cell engine is pretty simple. There are no high temperatures, many plastic parts, and a performance that is better than that of an internal combustion engine. Even so, the engineering is demanding, and many issues needed solutions. This project was run parallel to the global effort of making continuous, timely advances. The project successfully addressed manufacturing issues. There is no question about relevance. There is obvious impact, but, as with all technical advances, it is always a team effort. Many advances are created simultaneously in different places because such advances result from smart people getting together. It is unclear whether NREL really was responsible. However, this one project certainly did have an impact on the technology.
- In-line diagnostics at high speeds are highly relevant, as noted by the several non-Fuel Cell Technology Office groups cited (Hydrogen and Fuel Cell Technical Advisory Committee, National Academy).
- The large-scale commercialization of PEMFCs will not occur without low-cost and high-reliability manufacturing, which will be possible only with appropriate QC tools. To this reviewer's knowledge, this project is the first major effort funded by the Office of Energy Efficiency and Renewable Energy that focuses on this critical need.
- The project has potential for some impact and relevance; however, it is not as significant when compared to many other projects.
- The improvement in manufacturing processes clearly has an impact on cost and performance. Given the difficulty in demonstrating a quantitative impact on these two metrics, it would be good to attempt to quantify the impact these various solutions can have on the immediate defect being investigated. It was unclear how many of the specific defects were previously produced (how these targeted defects were selected), what the scrap rate was or what the suspected quantitative impact on product cost or performance was, and what impact these processes would have if implemented.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- There are plans for the future. With the rapidity of technical advances, those plans can change. Hopefully they will change. What is proposed is solid and worthwhile, but timely action is also essential. Sort of like with an emergency room doctor, it is important to judge the project on what it does, not on what the project team proposed to do. It makes sense to give Ulsh and team a good amount of rope. This team has a good history of using freedom well, using freedom to make broad strides.
- The proposed future work is fine. A comment from last year's review suggests that more focus is needed. NREL seems to agree with this comment and plans to focus their future work now that their toolset has been established.
- Demonstrating a prototype system for in-line membrane thickness measurement is a key goal. Further study of defects on cell performance should be continued.
- Much future work was identified, and some priority should be placed to increase the relevance of the work. For example, the work on platinum-group-metal-free catalyst or anion exchange membrane manufacturing diagnostics should not be done. It is not even clear that these materials can meet performance targets. More work should be done to identify needs of OEMs that are building stacks.
- As the various portions of the project are technically proven, it is unclear how the project team decides if the process is useful and effective for solving a specific problem or need. For instance, the detection of pinholes seems to be well investigated by this team, but it is unclear what data the team has to validate the

usefulness of that work. Additionally, it is unclear if the team will continue to further develop this process or put it aside and move on to another manufacturing challenge, or how the next challenge will be identified and folded into the project. Given that it is very difficult to obtain detailed input from many industry partners, perhaps there is a way to garner confidential or anonymous defect data from industry to help steer the project to very well-targeted and highly relevant topics moving forward. The project team should let the data guide proposed future work.

Project strengths:

- The team has developed at least one process or solution that is being pulled to commercialization. This validates the applicability and purpose of the project. There are bound to be developments that do not prove to be useful, but if the team can continue and even improve its ability to garner information from many industry partners, the project will build in importance. Ensuring that the project is focused on real challenges with commonality among the industry may be one of the biggest challenges.
- The development of in-line diagnostics is needed by the entire industry. Development at a national laboratory for all to share is appropriate. The project has demonstrated a long list of accomplishments, and the progress is impressive. The work is methodical, quantifiable, and well-thought-out.
- Three project strengths were the quality of demonstrations, the level of collaboration, and the importance and long-term applicability of the work.
- The NREL team is excellent and experienced. They tend to focus on tough problems and make good progress.
- Many diagnostic tools were developed. The team has excellent capabilities.

Project weaknesses:

- Learning what is happening in the People's Republic of China would be a good addition to the NREL tasks.
- Data showing why these specific defects were investigated would help verify why the team has focused on them. It is not clear if these defects were the most frequent problems or if the performance hits associated with the defects were the top manufacturing-related problems. If the data are available, this should be stated, and the impact of implementing these solutions should be shown. If the data are not available, the project team should develop a means to obtain data to ensure future work is aligned with high-frequency defects, performance hits, or other challenges that are limiting the industry's ability to achieve cost and performance targets.
- There could be more feedback (discussed) from industry as to what kinds of defects are likely to be made by production equipment. There needs to be a final assessment as to the size and/or type of defect that affects performance. This is being done now, but there does not appear to be a distinct study of how small a defect that can still affect performance might be.
- The project needs a bit more focus on the key barriers "E" and "H" identified on slide 2, using existing manufactured MEAs, not MEAs that the team makes.

Recommendations for additions/deletions to project scope:

- The issue, of course, is not just the cost of hydrogen. Rather, it is the value added by the hydrogen system—i.e., a system that includes hydrogen and the things that hydrogen permits to happen. Today, refineries do not stand alone. Almost all of them are also electrical generators, converting waste heat into electricity, which adds much value to the operation. The next step would be looking at integrated operations, such as an "electrolyzer plus." The project team could consider several questions, such as the following: what operators do when the hydrogen tank is "full" (presumably they do not just turn it off); what options occur if prices are changed to match the market demand curve; what is to be done with the co-produced oxygen; and whether it makes sense to integrate a hydrogen generation plant with a sewerage system. As with any big capital expenditure, the real question is not cost but payback. If the hardware creates more value than the mortgage costs for that day, that is all that is necessary for success. Therefore, the real issue to address is whether, when a system is implemented, the overall system creates more value than the system's cost, regardless of what that cost is.

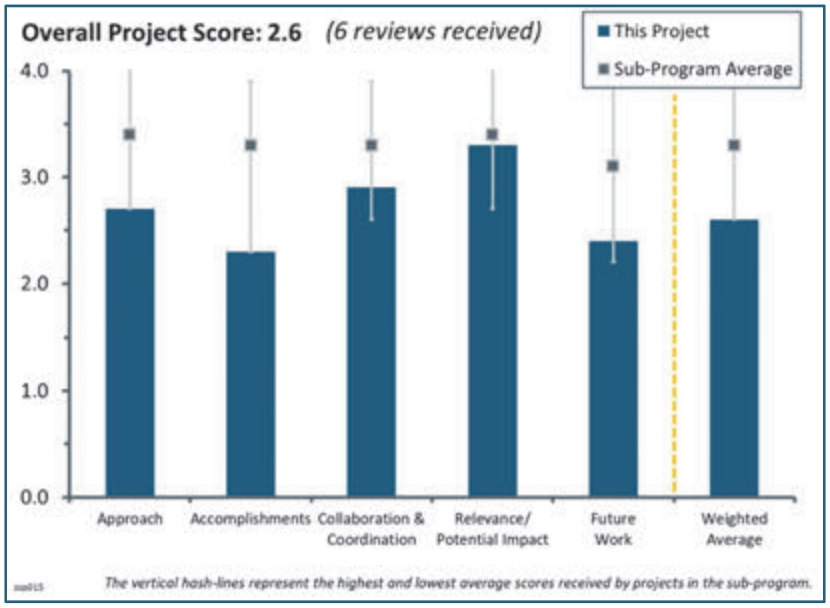
- The team should develop a list of types of defects and corresponding defect size that is determined to have a negative impact on performance. This list would then become a list of requirements for the diagnostic system to detect.
- The team should carry out more work with industry that builds stacks and study finished MEAs manufactured by others.

Project #MN-015: Continuous Fiber Composite Electrofusion Coupler

Brett Kimball; Automated Dynamics

Brief Summary of Project:

The objective of this project is to advance the state of the art for hydrogen transmission and distribution by improving the joining method that is used for piping. A composite-based coupler will be designed and tested, with the goal of achieving transmission pressure of 100 bar with a flow leak rate of less than 0.5% and a 50-year life expectancy for the part. To achieve this project's goals, work will focus on addressing three independent challenges in joining pipes: (1) tensile load through the coupler, (2) burst pressure, and (3) sealing of hydrogen in the pipe.



Question 1: Approach to performing the work

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

- The original approach of pursuing an all-non-metal coupler was innovative. This approach, however, has been abandoned because of an inability to meet long-term test requirements, specifically the fatigue test. A go/no-go decision in 2017 was not passed because the testing requirements were not met. To the company's credit, the project team appears to have worked with the Fuel Cell Technologies Office (FCTO) in detail to identify an alternative pathway and has received FCTO approval to pursue this pathway, even though the go/no-go was not met. The new approach includes metal components (though reportedly not in contact with hydrogen) but still has the benefits/impacts of not using O-rings and of enabling higher pressures.
- The hypothesis and original plan were strong and would have a significant effect on the industry. As is part of research, the project had to be re-scoped based on the results of the go/no-go milestones. The team members developed an alternative plan that seems reasonable and received a "go" decision from the U.S. Department of Energy (DOE). In the final year of the project, the re-scoped design will be evaluated and tested to the parameters approved by DOE.
- Automated Dynamics is well focused and practical for designing, building, and testing the new pipeline couplers.
- The original approach did not meet its go/no-go milestone. The new approach seems reasonable, but it has not yet been proven.
- The initial proposal focused on a novel coupling device for joining two lengths of polymer tubing that could transport hydrogen in a "pipeline." The contractor company was sold to a Swedish firm, and the firm changed the project so that it uses an already marketed coupler used today for natural gas pipelines. It seemed there was no purpose in continuing this activity.
- The approach is reasonable, but it seems to have a small scope of prototypes. While this is not inventing a new lightbulb, it appears that only a small number of options are being pursued for the budget.

Question 2: Accomplishments and progress

This project was rated **2.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- At the 2017 go/no-go decision point, the project had to be re-scoped owing to failure of the fatigue tests. A reasonable alternative was developed and approved by DOE. The team is currently developing the revised coupler.
- Progress has been delayed because of the inability of the original non-metal design to meet testing requirements, specifically the fatigue test. Accomplishments in the review period appear to be mainly related to a new design, as described in the Approach comments. From the very high- level information given in the slides, it is hard to understand how detailed or difficult the new design is, but this seems to be a small amount of progress overall for the year. It is good to hear that the new design is expected to be less expensive than the original design and that it will be able to leverage existing components and still have the benefits of not using O-rings and having higher pressure capabilities.
- The accomplishments are good. One would expect more options to have been covered for the budget.
- The presentation did not show any results from the original gadget. There was some concern about getting a longer-lasting seal, assuming that the natural gas tubing string could be successfully used for a hydrogen system. There was no convincing information given to assure reviewers of this.
- While the pipe can hold pressure, it is not passing the cycling test. The team has made some progress, but it is not clear what fundamental characterization has been performed to understand the failure. The team has laid out a reasonable plan for fiscal year 2018 to finish out the project.
- It appears the project did not make the December 2017 go/no-go criteria.

Question 3: Collaboration and coordination

This project was rated **2.9** for its collaboration and coordination with other institutions.

- The team is assembled of both industry and laboratory partners, which is a good mix for this type of research.
- It seemed that the new Swedish owner had expertise in pipe joining, and since that subject is of most concern, this change may be a positive one. There was no indication that the team had carried out any significant search for alternative couplings. There also was a suggested lifetime for the entire tubing string of 10 years, which is not a very interesting trend if one has to write off the capital expenditures on a 10-year basis. This adds to the cost for moving hydrogen around. There was no mention that a natural gas tubing string has such a short lifetime.
- Expertise from the other partners was well described and relevant to the project. Savannah River National Laboratory's involvement appeared to be limited to understanding the ASME requirements and testing. It was not clear whether any partner on the team has failure analysis expertise to understand the mechanisms for failure.
- Collaborators provide market/commercialization, guidance/expertise, and materials/testing expertise. It is not clear, overall, what the market could be for Automated Dynamics' work. Perhaps this could be provided from the FCTO cost modeling, or another collaboration might be appropriate.
- Automated Dynamics does have national laboratory and industry collaborators, but it is not clear who is doing what on the project.
- Automated Dynamics' collaborations may benefit from including work with folks in the gas industry.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This is a significant question that needs to be answered, as the potential of implementing plastic pipes for the transport of hydrogen is a cost-effective alternative that may achieve market penetration. A stable, non-metallic coupler will be required for widespread application.
- This project is very important to reducing the capital cost of installing hydrogen pipelines. Early market hotspots are expected to need such a solution in a near timeframe.
- Hydrogen transportation is a key issue/enabler for infrastructure.
- Good couplers on high-pressure pipelines are a requirement. However, it remains unclear whether couplers are a major technical roadblock to automotive hydrogen fuel commercialization.
- When discussing a hydrogen economy, distribution issues are obviously brought up. There are only two options. You can make hydrogen, using something like electricity at the point of use, or you can make it elsewhere and distribute the hydrogen to where it is needed. Transportation will obviously play a role. Therefore, distribution systems for hydrogen gas need to be understood. There is nothing more important than the tubing or piping. It is disappointing that the hype of last year has gone away. The carefully designed, electrically heated sealant was eliminated. Rather, a threaded compression fitting has moved into a "first choice" position. It seems like the project has concluded.
- It is not clear what the potential market is for the work. It is currently unclear how much hydrogen pipeline is expected to be installed and what the potential financial benefit of this technology might be. Nothing was stated in the presentation about how this technology may impact FCTO's plans with regards to H2@Scale or the buildout of a hydrogen pipeline. Perhaps this information was included in initial Annual Merit Review presentations, but it would be useful to provide at least high-level reminders with any status updates, given new FCTO targets or developments. The information provided on the relevance slide did not really address relevance to FCTO objectives or needs.

Question 5: Proposed future work

This project was rated **2.4** for its proposed future work.

- The proposed future work is to test the revised design. This was approved by DOE and seems to be reasonable and acceptable.
- Multiple prototype fatigue tests may be prudent to get a sense of reproducibility and variability.
- Proposed new coupler designs need to be tested.
- Required future work is pretty clear, given the status of the project, assuming that the new design can pass the fatigue test. Other activities mentioned, such as commercialization and cost evaluation, should obviously be undertaken after a successful go/no-go decision based on the new design passing the fatigue test.
- There was no future work discussed, which left the impression that the new company owner, a Swedish firm, expressed no interest in continuing the work, so future work was not all that apparent. Even so, the questions remain about whether the coupling device, a threaded plastic device, works with the smallest molecule, hydrogen, and whether the leakage rate will be acceptable. The question-and-answer session indicated that the tubing, which may be able to contain hydrogen, is available in 1 km spools. Therefore, a 50 km tubing string has 100 joints that could possibly leak, one from the incoming pipe and one from the delivery pipe on each coupling. It seems like getting an acceptable leakage rate will be a challenge.
- The proposed work basically involves trying to fatigue test again and iterating until the design passes. The team should outline what parameters could be changed to make the design more robust and, if needed, the reasonable number of iterations before deciding whether the solution will work.

Project strengths:

- The principal investigator addresses a stated FCTO barrier for pipelines and brings together a team that can address design and manufacturing, commercialization, and materials and testing. The output of this project (i.e., a coupling solution without O-rings that is capable of higher-pressure operation), if successful—even with the design change—appears still to be of value to DOE. The team had the ability to address the failed fatigue tests with a new design.
- The team was agile in revising the design after the go/no-go decision. The new design still shows promise and will help the industry if successful.
- Automated Dynamics produced well-focused and targeted work that designs, builds, and tests prototypes.
- The project team has tried to regroup after a failed test and took initiative to perform a redesign on the component between funding periods.
- The team has experience with composite piping.
- Automated Dynamics is working with a competent company, although no description was given about the quality of the new owner.

Project weaknesses:

- The failed fatigue test was an unwanted result, but a significant amount of research involves failure. If the new design does not work, it may hinder the widespread use of plastic tubing for hydrogen transport.
- The relevance and cost–benefit of the project are not clearly stated, which is especially relevant to H2@Scale. The original design did not work. This, in and of itself, is not a weakness, but the new design must be shown to be able to pass the fatigue test for additional efforts to be supported.
- The overall relevance/impact of the project is unclear.
- It is not yet clear that the team has a concrete plan to pass the test if the first iteration does not work.
- It is unclear whether the funding is congruent with the presented effort.
- There are no obvious successes. The questions about sealing hydrogen tubing strings remain unanswered.

Recommendations for additions/deletions to project scope:

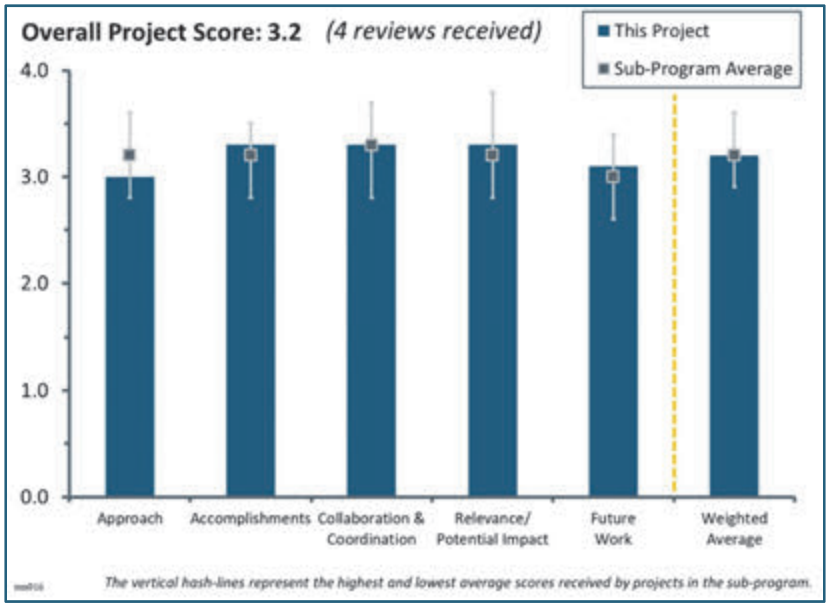
- The revised task plan seems reasonable for the amount of time and funding left on the project.
- The commercialization effort should be supported only if the new design passes the fatigue test. If this success is achieved, it seems that a cost evaluation will be very useful (as indicated in the Future Work), which should be done in tandem with or informed by any relevant FCTO/H2@Scale/H_2 Delivery analysis, cost modeling, etc.
- Automated Dynamics should increase the number of design options or produce variants on prototypes ahead of testing cycles. These options could include the testing of multiple durometer O-rings, varying the length of fused materials, and others. In such a way, reliability trends can be obtained in a shorter timeframe. A single-point prototype is not as informative as a suite of prototypes.
- It seems that this project has concluded. The initial novel coupler was not moving forward, and the problem remains. Perhaps the issue might be resolved by some work that determines the quality of coupling that can be achieved by the alternative hardware. However, it remains to be seen whether that will be good enough, i.e., whether the suggested quick fix will really work or what the diffusivity of hydrogen will be through the tubing. Certainly, other people must be using polymeric tubing for hydrogen piping.
- Automated Dynamics did not meet its go/no-go decision point in December 2017.

Project #MN-016: In-Line Quality Control of Polymer Electrolyte Membrane Materials

Paul Yelvington; Mainstream

Brief Summary of Project:

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



Question 1: Approach to performing the work

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

- The Mantis Eye approach to defect detection is excellent. The approach to validating the technology and the partner institutions is also excellent.
- The investigated approach is appropriate for addressing the main barriers and reaching the technical targets.
- This only missing component of this project is the involvement of membrane/membrane electrode assembly (MEA) manufacturers.
- Mainstream Engineering Corporation (Mainstream) has built an inspection station and systematically evaluated its capability. That said, there have been no demonstrations executed with potential commercial customers, and there is no evidence presented that suggests that commercial customers were consulted during the design of the inspection station.

Question 2: Accomplishments and progress

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

- Mainstream has demonstrated excellent progress in the development of the detection technology and in real-time image processing. At this point, the technology may fill a gap identified by membrane/MEA manufacturers and help meet DOE's goals, but improved resolution would make it a definite benefit.
- The project is moving along.
- Progress is good regarding the defect detection and the thickness determination, in particular with increasing web-line speed. Results on the impact of defect size on durability would have been appreciated.
- The inspection station has been built and qualified. This could become an important quality control (QC) tool for membrane manufacturers, but without input from membrane manufacturers, it is difficult to assess how valuable this QC tool will ultimately be.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- There is excellent and obvious collaboration with the National Renewable Energy Laboratory (NREL) and Georgia Institute of Technology (Georgia Tech). These two organizations provided the samples and coating lines for the implementation and testing of the Mainstream detection technology.
- The collaboration between Mainstream, NREL, and Georgia Tech appears well coordinated.
- It appears that all partners are participating.
- There appears to be good interaction with NREL and Georgia Tech in this project, but there was no engagement with membrane manufacturers during the design and validation phases.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is relevant to the goals of the Fuel Cell Technologies Office. Inline defect detection is critical to roll-to-roll processing to ensure a concurrently lower scrap rate, no over-quality, and thus a lower membrane cost.
- There is a high degree of alignment with Program goals, assuming this form of QC addresses manufacturer needs.
- The intent of the project—to build and qualify an inline QC tool for membrane manufacturing—is extremely relevant to low-cost PEM fuel cell manufacturing. The relevance score would be much higher with an increase of earlier involvement by potential end users to ensure that the product being developed will be commercially accepted.
- NREL conducted beginning-of-life (BOL) fuel cell performance tests on cells with varying size defects and determined that 40-micron defects cause problems with cell failure, while 10-micron defects do not. This led to the conclusion that the current hardware detection limit of 25 microns is adequate. However, while defects smaller than 40 microns may not be an issue with BOL performance, such defects may lead to premature cell failure during operation. Even defects smaller than 10 microns, which Mainstream indicates are possible with the current hardware and the use of multiple cameras, can be expected to cause premature cell failure due to gas crossover and the resulting product heat. An analysis and/or discussion of the spatial resolution limitations of the technique is necessary, as is an analysis of the cost of the system as a function of resolution, to determine the full potential and impact of this technology.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The future proposed work appears appropriate for achieving the project's targets. The demonstration of the prototype system for industry consumers is very important. The quantified results of the defect size on the durability should be presented as a cost analysis.
- It is critical that the commercial demonstrations are executed as stated in Mainstream's plans.
- Improving the defect resolution to 10 microns in the remaining two months of the project is a good start toward demonstrating the full utility of the technique. However, an analysis of the spatial resolution limitations of the technique and an analysis of the cost of the system as a function of resolution are needed to determine the full potential and impact of this technology.
- It is difficult to tell what decision points have been implemented.

Project strengths:

- The main overall project strength is the ability of the team to provide real-time detection and spatially resolved digital marking of the location of defects within the entire membrane width. The collaborations with NREL and Georgia Tech to test and validate the technology are also strengths.
- One of the project's strengths is the successful design and construction of an inspection station to identify membrane defects. The qualification of the inspection station by finding multiple types of defects is another strength.
- The Mainstream engineering team's association with the NREL team is of high value; the association will speed up the development and the validation of this kind of technology.
- The project is targeted at reducing defects and, therefore, reducing failures and associated costs of fuel cells.

Project weaknesses:

- Collaboration with a membrane manufacturer would strengthen the project. The project team focuses only on membranes for fuel cells. Perhaps the team could also look at other applications, such as PEM electrolyzers.
- There is a lack of input from potential customers during the design of the inspection station. No commercial demonstrations have been executed yet (although two are planned).
- The lack of pull from the market raises concerns about the actual need of this technology.
- The main project weakness is the demonstrated current detection limit of 25 microns.

Recommendations for additions/deletions to project scope:

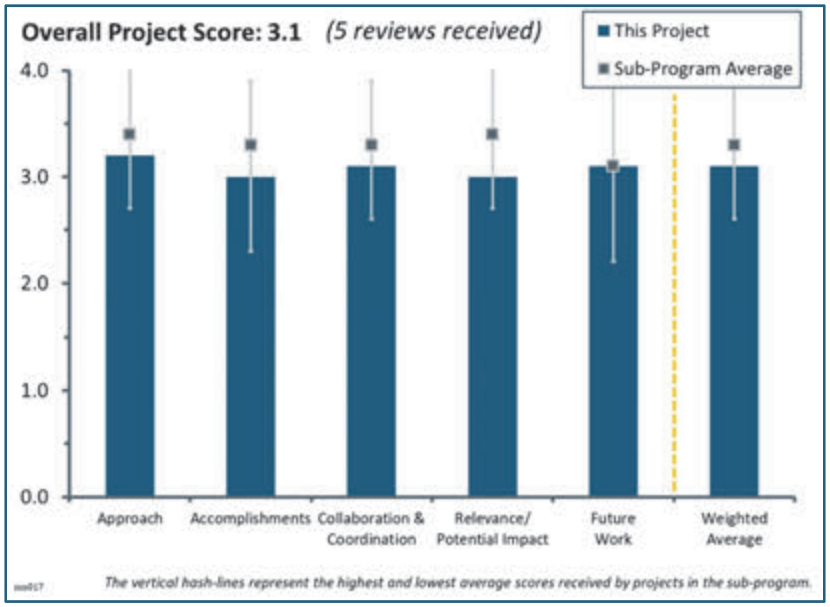
- It is recommended that the project team add an analysis of the spatial resolution limitations of the technique, as well as an analysis of the cost of the system as a function of resolution. These analyses are necessary to determine the full potential and impact of this technology.
- The project team should investigate the application of this technology to PEM electrolyzers. Also recommended is an investigation of the effect of defect size, not only on performance but also on durability.

Project #MN-017: Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations

Margaret Mann; National Renewable Energy Laboratory

Brief Summary of Project:

This project contributes to manufacturing cost analyses for major hydrogen refueling station (HRS) systems. National Renewable Energy Laboratory (NREL) will work with the Fuel Cell Technologies Office to establish HRS manufacturing cost models and a manufacturing cost framework to study costs of HRS systems, including the compressor, storage tanks, chiller and heat exchanger, and dispenser. Investigators will assist in highlighting potential cost reductions in the manufacturing phase for future research and development projects in this field.



Question 1: Approach to performing the work

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

- NREL methodology is solid, with good economic engineering. The project sought out good partners and looked at most of the important issues.
- NREL does a good job of analyzing the electrolyzer HRS.
- This is a concise, tight approach to performing the bottom-up manufacturing cost analysis.
- The proposed approach is correct.
- NREL completed a comprehensive assessment of manufacturing costs of polymer electrolyte membrane (PEM) fuel cell electrolyzer systems, which enabled realistic comparisons with commercial alkaline electrolyzer systems. The approaches for completing this assessment were sound, although it would have been helpful if the cost analyses could have been quantified on the basis of hydrogen cost and not system cost. Also, cost-reduction opportunities for PEM fuel cell electrolyzer systems were identified but not quantified. An ultimate recommendation on the potential of either approach to meet the U.S. Department of Energy's cost targets was not provided.

Question 2: Accomplishments and progress

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

- NREL has made significant progress from the previous year. The team has put together analyses on both PEM and alkaline electrolyzers, and it has outlined the detailed supply chain needed for the industry.
- The detailed study of HRS supply chains is well done and highly useful. Although the current market volume is modest, it is growing, and it has now become large enough to mature into a global business. Although this suggestion is outside of the charter, it would be interesting to have explored International Organization for Standards (ISO) standards to determine whether existing design and manufacturing

standards are regional or global. Although this is also outside the charter, it would have been interesting to explore early technical failures and early accidents. (It is easier to fix stuff before you build it.)

- This assessment is important for DOE to determine whether future investment in PEM electrolyzers is warranted. The analysis was thorough, and a good deal of information was obtained and compiled into a very thorough assessment. NREL stopped short of providing a quantitative conclusion regarding the commercial viability of either alkaline or PEM electrolyzer systems for HRSs.
- NREL completed a detailed analysis of electrolyzer system costs for the generation of hydrogen at a refueling station, but the costs associated with the rest of the dispensing systems, the hydrogen storage systems, and the real estate analysis were missing. Furthermore, it should be in the scope of work to conclude how many HRSs would be needed to re-fuel a significant portion of the passenger vehicle fleet.
- The reviewer provided the following comments:
    - The presentation focuses this year mostly on the onsite hydrogen production. It is not clear whether onsite hydrogen production is considered production linked to HRS systems only or any onsite production.
    - The HRS activity was reduced to an update of the global HRS trade flows. Unfortunately, there were some mistakes in those efforts. It is quite surprising to see that European HRS systems are mostly important HRS systems, whereas there are plenty of European HRS suppliers who are delivering HRS systems in the framework of European projects. Using the same color for importing and unknown suppliers leads to confusion and must be avoided. The two must be distinguishable. Moreover, the numbers for France are incorrect. At end of 2017, there were 19 active HRS systems, and more than 10 are planned. For the number of HRS systems planned in Europe by 2025, the project team should have referred to the Alternative Fuel Infrastructure Directive published by the European Commission last year. These numbers represent a commitment to the minimum number of publicly accessible HRS systems that should be deployed by 2025.
    - The table for comparison of the alkaline and PEM electrolyzers lacks precision. The system price is given in dollars per kilowatt, but the power range is unclear. The operating pressure should be given because it has an impact on system efficiency, and the expected operating hours should also be included when providing system durability information.
    - The tables presenting the key performance indicators (KPIs) of the PEM and alkaline electrolyzers should use the same KPIs. For instance, the hydrogen production rate, operating pressure, and temperature are missing for PEM electrolyzers. There is a mistake between Pt-Ir and platinum-group-metal-loading values. For PEM electrolyzers, the given values seem very optimistic (1.619 V @1.8 A/cm² if 80°C at 1 bar is assumed), in particular when considering a Nafion 117 membrane.
    - The rationale for 385 kg_{H2}/day for a 1 MW PEM electrolyzer should be given.
    - On slide 15, the system cost presented is around $500/kW, whereas in slide 6, the system cost in the table was $1,570/kW. It is unclear which number should be considered.
    - The AC/DC rectifiers are presented as very expensive, but when connected to renewable energies, a DC/DC converter might be sufficient. It would be interested to know how this could affect the overall system costs.
    - Slides 38 and 40 present the global electrolyzer producers. Important global players are missing. It is really surprising not to see Nel Hydrogen, the biggest alkaline electrolyzer manufacturer and also the new buyer of Proton OnSite. McPhy is also missing. Regarding PEM electrolyzers, the United Kingdom's ITM Power is missing.
- On slide 39, presenting the polarization of commercial PEM electrolyzers is not enough. Gas permeation should also be given, in particular when targeting an increase of the operating pressure (30 bar) to increase overall efficiency. Therefore, a figure presenting $\%H_2/0_2$ versus the current density should also be presented.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- NREL has several strong collaborative partners, including domestic and foreign-based ones, along with private-sector partners and laboratories. Collaborators include E4tech from the United Kingdom,

Forschungszentrum Julich (FZJ) from Germany, and three industry partners: AEG Power Solutions, Magna-Power, and Grundfos. The PI calls them collaborators, whereas slide 21 just states that these organizations provided cost data for the electrolyzers.
- Having collaborators from three other national laboratories makes sense because parallel studies are under way and because computer approaches exist to manage data. The project is almost complete. There was no description of "who did what," so most likely NREL built a multi-laboratory team, and the results flowed from that.
- The level of collaboration was commensurate with the objectives and needs for this analysis.
- Industry partners would be useful for the collaboration. In fact, many of the electrolyzer system original equipment manufacturers would understand the project team's system costs, even at the 1 MW scale under study.
- Collaboration and coordination efforts seem correct, but more connections with industry or international bodies would have been needed, in particular for the HRS mapping.

Question 4: Relevance/potential impact

This project was rated **3.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Current times dictate that hydrogen will prove useful as an energy carrier and energy-storage medium. Electrolyzers are old technologies. Typically, they have been built in low volumes and purchased by organizations that had no cost constraints, like the U.S. Navy. We now anticipate large markets for hydrogen-generation hardware, and the economic gain is changing. Hydrogen refueling is a new art, and that industry is just beginning. Initial costs for refueling stations are high, and costs need to come down. This project gives a snapshot of where we are in 2018, and it itemizes the parts requirements, making it easier to direct efforts to bring costs down.
- This work is highly relevant. The results could be used by both policymakers and manufacturers that are trying to be cost-competitive. These results could help shape future cost targets for both component and system costs. The results could support the future work of H2@Scale.
- The project should have studied the refueling station costs more, as well as studying those costs relative to the entire passenger vehicle fleet. No cost targets were identified, so it is difficult to gauge the relevance/ impact. For example, dividing the cost of all the current gasoline stations by the number of gasoline cars provides a number for the refueling station cost per vehicle. A similar number could be calculated for the HRS scenario. DOE could establish a target for such a metric, and the project could determine how far the technology is from the target.
- This project aims to provide an assessment that will inform DOE of the viability of PEM and alkaline electrolyzers for HRSs and to identify areas for investment to improve viability. It would have been helpful to see more definitive conclusions, which would provide more value to DOE in building its future project portfolio.
- The data provided will be useful for better understanding the United States' strengths and weaknesses in HRS and onsite electrolyzer manufacturing. However, to be really efficient, pointed imprecisions and mistakes should be corrected.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The project ended in June 2018.
- It is not clear that this project is continuing, but the stated future work areas are appropriate. Also, if the project continues, it would be interesting to include an assessment of high-temperature (solid oxide) electrolysis systems and how they compare to PEM and alkaline systems.
- There is proposed future work to complete the task—which is almost complete—and to continue exploring "emerging" technologies; this is all good work that needs to be done. What seems to be missing is the "innovation" piece and some understanding about how the really large investments in fuel cell technologies

can support both innovation and cost reductions in electrolyzer technologies. Issues such as hydrogen safety are entirely parallel, and much of the materials science for fuel cells will be valid for electrolyzers. Therefore, there is a solid technical base, and electrolyzer technologists do not have to reinvent. That will save capital and time.

- NREL should complete manufacturing cost analyses of onsite hydrogen production and PEM and alkaline electrolyzers. The project team should also study the cost effects of emerging manufacturing technologies. The team should also look at economies of scale for hydrogen production systems and the impact on both capital costs and production costs. The team should also study the change in capital expenditures of hydrogen production. The team should benchmark its results against new hydrogen installations.
- The proposed work is appropriate, but pointed imprecisions and mistakes in the global surveys should be corrected. Moreover, the impact of the electrolyzer operating pressure, the stack lifetime versus performance, should be better taken into account regarding the whole onsite hydrogen production HRS system.

Project strengths:

- The main strengths were to map the HRS flows globally and then to investigate the United States' strengths and weaknesses to favor the domestic industry.
- This is an important project to study the various refueling station costs.
- The project team used a sound approach for its cost analyses at the component and system levels.
- The team collected considerable data and organized the data in sensible ways.
- Thorough research was conducted that can support policymakers and industry.

Project weaknesses:

- The cost numbers are for stand-alone hardware rather than for systems. This is akin to estimating the cost of a jet engine rather than the whole aircraft. Electrolyzers usually make byproduct oxygen, a valuable substance. A large refinery like the Exxon complex in New Jersey, which includes one of the nation's largest electrical generation stations, is based on waste heat, and doing the numbers that are essential requires a system analysis.
    - Electrolyzers are somewhat inefficient, and there is a good heat flux that needs to be considered. So there are capital and operating expenditures. As with any energy facility, the real economic analysis is simple: the company borrows money, and the bankers want recovery: principal plus interest. That adds up to so much each month. If you get more income than that number, that is good; if not, that is bad. An analysis that focuses only on the "costs," i.e., what a manufacturing company can extract, does not address the real issue. It is good to know the bad news. Electrolyzers do have costs. It is also necessary to understand that nations tend to barter (for example, Russia is providing petroleum to China in exchange for high-speed trains), and in those cases, actual costs are never known accurately. Perhaps a deeper dive is necessary.
- The project team has shown some imprecisions in the survey analysis of HRS flows and electrolyzer manufacturers. This may affect the outcomes and recommendations from the project.
- More comparison studies should have been conducted with respect to gasoline stations.
- The project lacks definitive conclusions.

Recommendations for additions/deletions to project scope:

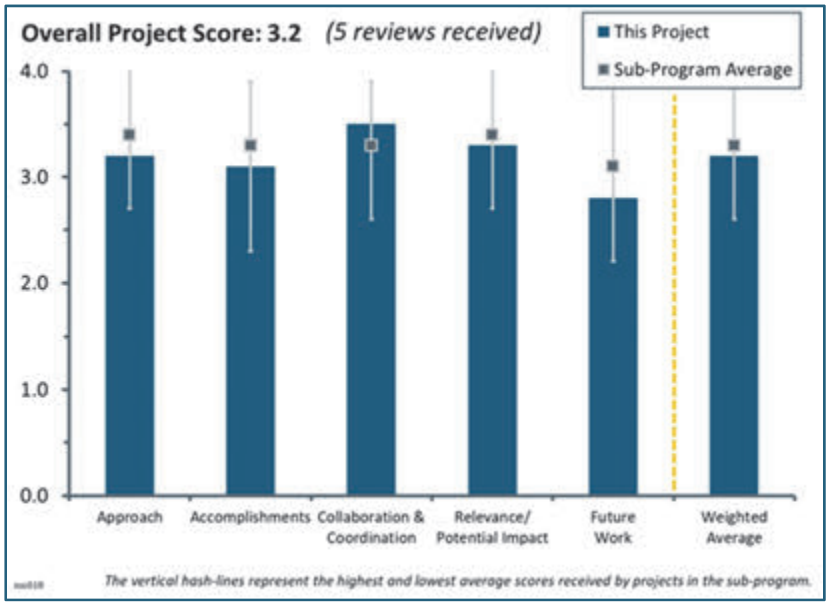
- The scope seems appropriate for the amount of funding and will provide valuable information to the research community and industry.
- It would have been interesting to look at some of the federal hardware, for example, the "oxygen generators" deployed on U.S. submarines. There are also hydrogen generators, which are used for cooling bearings in generators. This hardware, to some extent at least, is "commercial."
    - Siemens is selling an interesting fuel cell submarine, designed to submerge and remain underwater for long periods. Certainly, there is an oxygen generator in that hardware, as well. These military devices may cost even more than is suggested. However, they have unique specifications. Submarines are prone to be depth-charged, resulting in very high G forces, so the

hardware needs to be unusually robust. Certainly, a hydrogen leak into a submarine would be an event to avoid, so these are probably "excessive" safety features.
    - There are some things to be learned, and they need to be part of the NREL intelligence. It is not yet clear how much safety considerations influence cost and whether the existing standards are good enough for "general public use"—in other words, what protective protocols are necessary to ensure protection against a person with evil intent.
- It is not clear what the impacts are—if there are impacts—of onsite hydrogen production electrolyzers on an HRS with the rest of the electrolyzer production. Regarding the cost analysis, the main differences mentioned between countries are explained by labor and energy costs. The assumption of comparable materials costs is not as obvious and should also be considered more precisely. For instance, the costs of membranes in the United States, Germany, and China may differ significantly.
- The project has ended.

Project #MN-018: Roll-to-Roll Advanced Materials Manufacturing Lab Consortium

Claus Daniel; Oak Ridge National Laboratory

Brief Summary of Project:



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

Question 1: Approach to performing the work

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

- This project is aimed at developing R2R manufacturing techniques to reduce the cost of fuel cell stacks at high volumes by understanding and optimizing the process and material parameters. The project team's approach is promising, with a focus on MEA fabrication and testing, as well as the characterization of gas diffusion electrodes (GDEs) and inks to explore the process parameters. The team accomplishes this by leveraging various unique capabilities and expertise across multiple national laboratories.
- The proposed approach is correct, with the presence of complementary competencies (i.e., manufacturing, testing, characterization, and modeling). Focusing on MEA production, and in particular GDEs, is indeed crucial to reach DOE performance and cost targets. It is appreciated that the targets have been quantified.
- This project includes a well-put-together approach of the consortium and the research, involving both industry and laboratories. Setting up the cooperative research and development agreements (CRADAs) to get industry support is an effective way to move the research along.
- The team quickly identified a lowest-cost manufacturing approach. However, the team also focused much effort on the fuel cell testing of finished MEAs from manufacturing efforts.
- It is true that R2R manufacturing has considerable applications in fuel cell manufacturing, but even so, as in all manufacturing, one first has to know the raw materials and structures to be made with the manufacturing procedure. The project is based on improving (including lowering the cost of) technology that is already in use. The procedure is thoughtful but not that unique. The goals are clearly defined. A competent, durable team has been assembled. There is careful analysis. The emphasis on "[enabling] the United States to capture a substantial portion of R2R opportunity" may not be that realistic. Perhaps it should have read "a significant portion," realizing that 10% of a large number is a large number.

Question 2: Accomplishments and progress

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

- The results presented are of high quality and have been well explained. The team has confidence in the high potential of using R2R to produce catalyst-coated backings (CCBs), which have several advantages over catalyst-coated membranes (CCMs). The main parameters of the ink preparation have been taken into account and their respective influences noted. Finally, the performance obtained is comparable to the standard spraying process. There is a good balance between technological achievements and the comprehension of the physical mechanisms. This is important because, depending on the future MEA properties that industry will seek, the process parameters, the materials used, and the composition of the ink will have to be adapted.
- There are efforts to shift manufacturing in the United States by enhancing supply chain capabilities.
- The team has made good progress on several aspects of the project related to the goals, in particular, the mass activity achieved with the R2R electrodes (with an ionomer overlayer), 3D imaging with ionomer and pore distributions in the GDEs, and characterization of inks (as in viscosity and ultra-small-angle X-ray , USAXS). These investigations should be extended to explore the influence of the ionomer overlayer, as well. These results are definitely interesting, and the accomplishments stand out as a comprehensive investigation on the characterization of materials used in or produced by R2R manufacturing. For what the team has tried to accomplish, the results are promising, although a bit more characterization-focused. While the relevance of the results to the project is explained for certain tasks, the overall relevance to the objectives could be stated more clearly. Similarly, the modeling efforts, or their contribution/connection to the other findings in the project and process optimization, are lacking. Moreover, the team's accomplishments are well explained and coordinated, given the number of partners.
- The technology is still in flux, and details are critical. There is much opportunity for new ideas. The principal investigator (PI) discussed the pros and cons of the R2R versus CCM selection. Various manufacturing options are explored. The accomplishments define specific procedures, such as the "ink studies" formulation, mixing, and rheology, for example. This is all good information, but a wide range of combinations exist. Progress is certainly evident, but even so, the task is difficult. There are many variables, and assuming that one particular route is the optimum one will prove difficult. The essential task of MEA characterization is done by the National Renewable Energy Laboratory. Certainly, much of the good, hard work has been accomplished. How much of this will lead to a successful manufacturing engineering protocol remains to be seen. In short, there is good progress. The project seems to be on track.
- The team should analyze different manufacturing approaches and their impacts on overall costs, for example, the effects of solvent casting versus water-only casting in the catalyst ink. The PI mentioned advantages of casting ink directly on the gas diffusion layer (GDL). However, the advantage of casting ink on liner is faster line speeds; GDL line speeds will be limited.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- The project's collaboration is excellent; the project has multiple laboratories and industry partners, and it is set up in such a way that it has the ability to grow the partner membership.
- The project seems well organized and has collaborated with many partners. The contributions from each partner are clearly stated, but the coordination between different partners (i.e., national laboratories) could be improved or better explained. A flow diagram showing the information/sample flow would be very useful.
- All laboratory-based collaboration was excellent; however, while collaboration with industry partners was identified, no results were presented.
- Project coordination appears efficient regarding the results obtained during this first year. Each academic partner has a well-defined role. Collaboration with projects from the Fuel Cell Consortium for Performance and Durability (FC-PAD) and the Electrocatalysis Consortium (ElectroCat) would be welcome. Collaboration with industrial companies producing MEAs for polymer electrolyte membrane fuel cells

(PEMFCs) should take place next year, as the composition and structure of the CCBs for fuel cells and CCMs for electrolysis are not the same. The role of Eastman Business in the project is not clear at all.
- The staffing is drawn from four national laboratories and two small companies. The laboratories have acquired quality facilities and good people. The separation of tasks seems complete and appears credible but arbitrary. Industry leaders are not part of this. This is the usual concern where who the customer is and who gets to use this technology is unknown. Also ambiguous is what "part" is being "manufactured." Whether the supplier supplies the membrane, the ink, or the complete MEA is also not known. The 5,000+ fuel cell cars in California have working fuel cells, which all have large quantities of manufactured MEAs; it is unclear how this project interacts with that already-in-place supply chain.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The main objectives of the project are to reduce the cost of automotive fuel cell stacks at high volume (500,000 units/year) by improving and optimizing R2R manufacturing techniques. These objectives are directly relevant to the key cost/volume targets set by DOE; the project goals align very well with the DOE objectives. If successful, this project will make important contributions to addressing issues of cost for fuel cells.
- Focusing on the manufacturing of the active layer is really relevant to achieving DOE's performance and cost targets. As presented in the cost analysis of Brian James and, in particular, the sensitivity analysis, power density and catalyst charging are the most critical parameters. In addition to the ongoing studies of the active layers, this team is investigating their manufacturability using the most usual production means. To ensure a high impact, the team may further investigate the current compositions of active layers for fuel cells and electrolyzers, and also investigate the new active layers developed in laboratories.
- This project has high potential impact; improving the R2R manufacturing process could significantly reduce the cost of production in the fuel cell/hydrogen generation industry. This could lead to significant gains in U.S. manufacturing.
- The MEA is clearly at the heart of the technology. The rest of the fuel cell system is designed to establish reaction environments that result in appropriate conditions for excellent MEA performance. There could be nothing more relevant. Even so, there is a manufacturing technology in place, and this activity seems to ignore that fact. Siemens is installing PEMFCs in the submarines they are selling in global markets. If existing players are experiencing problems with MEA manufacturing, that fact was not presented. This project may well be adding value, but there was nothing described that might suggest that was or was not happening.
- It is unclear what the relevance or impact of DOE funding on this Technology Readiness Level 8 work really is. This project should be industry-funded.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- In addition to the proposed work, it would be interesting to investigate the impact of viscosity on the coating speed and the impact of water content and coating speed on the electrode structure after drying. Some complementary (nano) characterizations of the electrode structure (with the Oak Ridge National Laboratory, for instance) would be interesting to view (i.e., the obtained structures and morphologies, depending on the process parameters) and to compare with the state-of-the-art (SOA) MEAs.
    - This investigation would also be useful to validate the foreseen modeling activities.
    - In addition, only single current–voltage (I-V) curves have been presented. Some durability tests should also be investigated and completed with (nano) characterizations in cooperation with FC-PAD. The team may also investigate new active layers developed in laboratories.
- There is future work with additional inks and coating. Modeling work would also be required.

- The details of future work are not described. The way forward is not all that clear. The project's future work is hard to evaluate.
- The proposed future work tasks are vague and not descriptive. It is not clear what will be accomplished and how it aligns with the overall project goals.
- Future work should focus on collaboration with industry partners.

Project strengths:

- The coordination of the project, the defined role of each partner, and the competencies of the people involved are real strengths. In particular, the fact that some of them are also working on deposition of electrodes for batteries can facilitate the development phase for fuel cell electrodes.
- The individual laboratories' focusing on each laboratory's specialty is a significant strength. The ability to grow this project through CRADAs is an effective and beneficial way to have a return on investment of the DOE's cost share.
- The project leverages expertise across the laboratories to bridge manufacturing and advanced characterization. The team is able to carry out a wide range of tests and characterization studies.
- There is a good focus on manufacturing methods that are low-cost, as well as good progress on linking manufacturing parameters to fuel cell performance.
- This project has great people. The laboratories and manufacturing sites are well equipped. The modeling abilities are good. This is a winning team doing very good stuff.

Project weaknesses:

- It seems like the very good results presented here are on the same pathways, using the same techniques, and using equally qualified staff as others who are doing fuel cell research and development. It is good to have a team with a "manufacturing focus," even though one could argue that that emphasis has really been at the center of the DOE's focus for decades. An example is the continued emphasis on "lowering the platinum loading," a leading subject beginning in 1980 and continuing to current times, which has also been about cutting costs. However, as to the goals, the people, the facilities, and the results, there is no question; there is not a weakness to be seen.
- The main weakness of this project is the lack of visibility for industrial interests and transfers. The only one mentioned this year was considering an electrolyzer using only CCMs, whereas the focus has been put on CCBs.
- The future work plans lack details as to what will be accomplished and how the plans will help the overall project's goals on cost reduction. Some of the contributions from the laboratories (e.g., simulations) are not clear.
- It is uncertain what the real focus of this project is, or what the targets or goals are.

Recommendations for additions/deletions to project scope:

- It seems like the time has come to get to standards. One useful route might be for some combination of laboratories to come up with a plan (perhaps done in-house, perhaps farmed out to a contractor) to create, manufacture, and distribute "certified" (down to the source of the platinum) reproducible test specimens. The MEAs are sort of standard. This would lead to some meaningful tools. For example, someone working on new concepts could say that "our product is 1.17x that compared to the DOE standard." There also should be new rules that require all DOE contractors to report standard error. In other words, each published measurement is the result of three or five individual and totally parallel experiments, and then those results show error bars. This presentation is a good example of what is needed. There is a polarization curve, and then a second, obviously better. It looks good. But it is uncertain that that can be done twice with the same result. It is not clear that the "existing" result is correct (so the new data is really better) or simply better than a bad result. It is time to address this data issue. Of course, in the end, suppliers will necessarily sell products with certified performance specifications. Such a plan would give clear, definitive specifications to those who want to enter the parts market. That sort of discipline can save years of frustration and error for a willing, smart company.

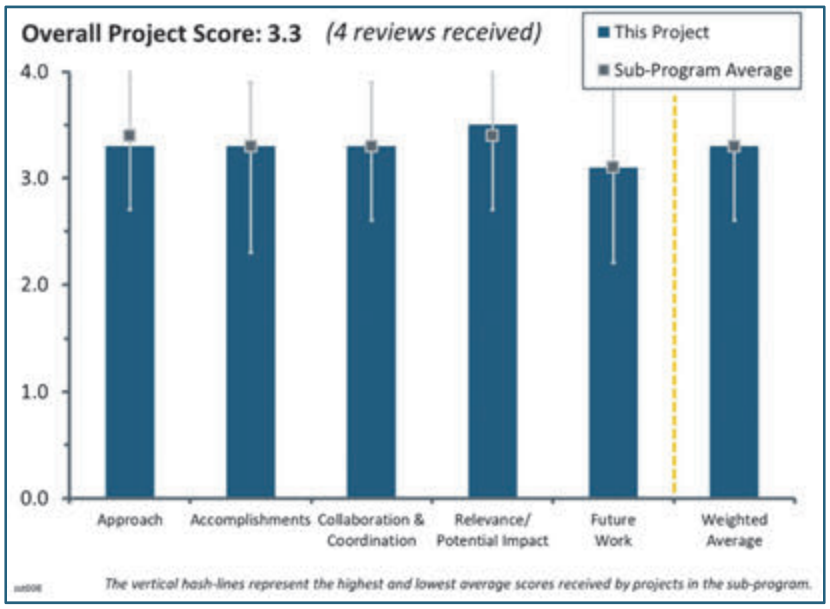
- It would be interesting to conduct complementary (nano) characterizations of the electrode structure (in collaboration with FC-PAD) to view the obtained structures and morphologies depending on the process parameters and compare the data with SOA MEAs. The project may also investigate new active layers developed in laboratories.
- It is uncertain whether studies of fuel cell performance belong within the scope of this project. This team should include the impact of different manufacturing methods on the cost of the final product, including material yield impacts.
- The project scope could include a brief explanation of the long-term strategy and goals, especially on how the accomplishments and findings will eventually help achieve the cost targets.

Project #MT-008: Hydrogen Energy Systems as a Grid Management Tool

Mitch Ewan; Hawaii Natural Energy Institute

Brief Summary of Project:

The objectives of this project are to (1) support development of a regulatory structure for permitting and installation of hydrogen systems in Hawaii and (2) validate the performance, durability, and cost benefits of grid-integrated hydrogen systems. The validation entails three tasks: (1) dynamic operation of electrolyzers to mitigate the impacts of intermittent renewable energy, (2) demonstration of the potential for multiple revenue streams from ancillary services and hydrogen production, and (3) introduction of hydrogen fuel for shuttle buses operated by the County of Hawaii Mass Transit Agency and Hawaii Volcanoes National Park.



Question 1: Approach to performing the work

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

- The approach has generated a large number of data and opportunities for additional work that should be addressed in future work plans. These future work plans should include advanced work on codes and standards, vehicle testing, infrastructure development, and the testing of utility products such as voltage control and frequency regulation.
- The team overcame past barriers that delayed the project and is poised to make excellent progress now and in the future. The grid ancillary services concept is very important to the integration framework of this project. The team's focus is very appropriate and inclusive—e.g., technical feasibility, validation of economics, and pioneering a regulatory structure.
- This is a good approach to evaluating the benefits of using electrolyzers to balance the grid load.
- The overall approach to the work is sound—modeling followed by testing. However, not many details were presented concerning how the work ahead is being planned, and it is therefore not possible to comment on the details of the approach that will be followed for the work ahead. The presentation did not reveal any of the key performance indicators (KPIs) that the project is targeting. In the absence of KPIs, it will be difficult to evaluate project progress. This should be remediated, and the project team should set clear technical and economic indicators.

Question 2: Accomplishments and progress

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

- Although there were some delays following the extensive modeling done in the earliest part of the project, the project is now ready to start operation. This represents a significant advancement toward achieving the project goals of validating performance, durability, and cost benefits of grid-integrated systems. During the last year, plant site preparations have been finalized, and the following seem to be in place: the hydrogen

electrolyzer, the hydrogen dispenser infrastructure, three buses re-converted to run on hydrogen, and three hydrogen transport trailers to carry 105 kilograms of hydrogen at 450 bars. A preliminary technoeconomic analysis of the project is still missing. This undermines the credibility of the project approach for potential replication activities in other locations and does not attract additional investors the project needs.
- The project has effectively shown that a hybrid battery/electrolyzer system can provide grid stability, while at the same time providing hydrogen for transportation applications on the island.
- Overall, this project meets the goals of DOE of how to best advance hydrogen infrastructure and market transformation.
- The project team has made excellent progress in this performance period, albeit part of it was trying to catch up from unanticipated delays incurred last year.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- All the relevant key entities in the State of Hawaii are involved, in addition to the federal partners, national laboratories, and industry partners.
- The list of sixteen organizations cooperating on this project is impressive.
- Collaboration and coordination with other institutions appear to be of high value. Additional collaboration with utilities is recommended.
- The project has excellent collaboration and coordination with others, as reflected in the project's sufficient funding to complete the installations and to obtain the required permits. Still, last year's project review noted the team lacked engagement with utilities. This still seems to be the case. As the project is now ready to start running additional exchanges with market actors to foster an expansion of grid services, the replication of the project elsewhere should be planned.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The successful completion and demonstration of this system will have implications for grid management across the country, as well as provide low-cost hydrogen for other projects.
- The project involves multiple hydrogen markets and applications that can deliver added value. This is a truly necessary ingredient for new energy systems.
- This project has high value as a template for future work and technology transformation at other locations.
- As stated in former reviews, the relevance and potential impact of this project is very significant. The project offers a sound example of the role that hydrogen technologies can have with grid balancing in an energy system with a high share of variable renewables, as well as a means to decarbonize the transport system. The project continues being of high relevance to the H2@Scale initiative. As operational data become available, the team should increase project visibility. In this regard, the project should disseminate the results to the scientific community and communicate the benefits of the project to the wider public. This can raise awareness and foster public acceptance of this type of project.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work of engaging with utilities for grid products is appropriate and would be of high value for technology transformation.
- The presenter provided an excellent summary of the proposed future activities. It was good that the slide included support for public outreach.
- Completing and testing systems is important, as is the public education aspect of this project once the volcano settles down and tourists return.

- The project is missing a clear plan for future activities. Instead, the team provided a set of individuals and activities during the presentation. It is not clear how far the project intends to go and how it will help to foster replication. Additionally, it is not clear how project success will be measured—this should be addressed.

Project strengths:

- The project has an excellent mix of local, federal, and state government collaboration and validation platforms (fuel cell buses, electrolyzer, potentially airport ground handling equipment, etc.). There is good emphasis on lessons learned and technology transfer. Utilities (e.g., Hawaii Electric Light Company) are interested. Enterprise Rent-a-Car and Kona Airport management are interested in collaborating through deploying fuel cell vehicles. Measures to address the corrosive environment (e.g., salt in seawater) and collaboration with Toyota Fuel Cells group were potential activities mentioned by the presenter.
- The project offers a sound example of the role that hydrogen technologies can have in grid balancing in an energy system with a high share of variable renewables as well as a means to decarbonize the transport system. The project fits very well with the objectives of H2@Scale, and there is great potential for replication. The project leader is dedicated and committed. This reinforces project continuity, although additional funding will be needed.
- The project demonstrated a good combination of grid stabilization and supplying hydrogen for shuttle buses. The project also provides a good opportunity to educate tourists in Hawaii.
- The data has been managed properly; however, as additional information and results are produced, additional provisions for management and dissemination of data will be needed.

Project weaknesses:

- The project could be more organized and focused on goals and pragmatic execution. Some project goals, including frequency regulation, appear to have been addressed with battery technology and without input from utility stakeholders. This objective is of high value and should be assessed for hydrogen fuel cell technology with utility involvement.
- There is a lack of engagement with the wider public and potential investors, as well as with utilities. This is key to demonstration of the market potential for multiple revenue streams, from ancillary service to grid balancing. Also, a technoeconomist analysis is still missing. It is unclear what the project KPIs will be; hence it is difficult to determine whether the project is achieving its objectives.
- The technoeconomic analysis capability is nearly completed; however, it will take time to get data that the capability can use.
- There is no specific data on the electrolyzer's ability to meet transient loads and stabilize grid frequency. The team includes only the statement that the electrolyzer was "close" to providing stability.

Recommendations for additions/deletions to project scope:

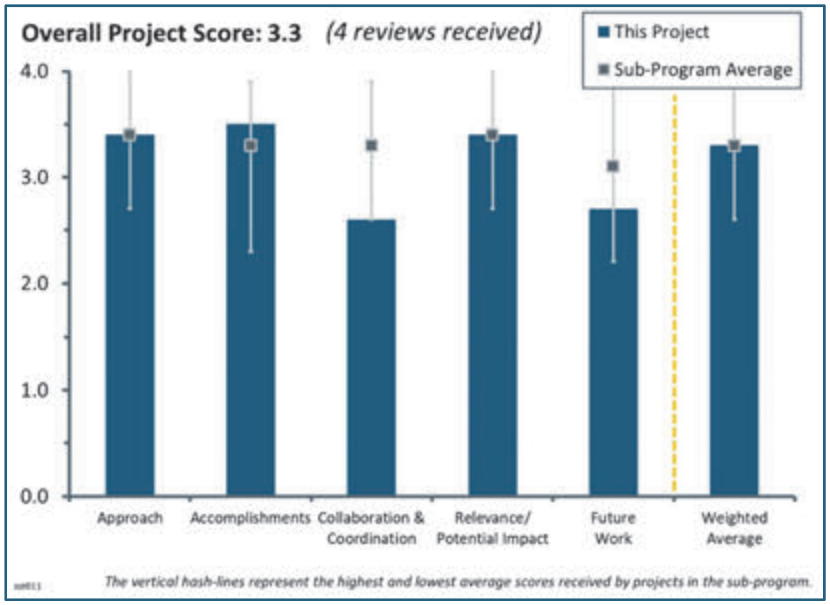
- The project's scope is appropriate. The team should establish both technical and economic project KPIs, develop a clear project plan for the work ahead, and plan for activities to foster replication. If relevant to the regional context, the team should investigate the role of hydrogen injection in the gas grid.
- The project team should continue work to assess grid products, including frequency regulation, voltage control, and energy storage, coupled with intermittent renewable generation with all costs and values. This work should be undertaken in concert with utility stakeholders.
- The project team should provide specific data on electrolyzer response time and any possible remedies to make it fast enough for frequency stabilization.

Project #MT-011: Fuel-Cell-Powered Airport Ground Support Equipment Deployment

Larry Pitts; Plug Power

Brief Summary of Project:

The objectives of this project are to develop fuel-cell-powered ground support equipment that (1) is cost-competitive and more energy-efficient, (2) is lower in carbon emissions, (3) reduces consumption of diesel, (4) decreases energy expenditures, and (5) validates the value proposition. This project will deploy 15 fuel-cell-powered units for two years at Memphis–Shelby County Airport. The fuel-cell-powered cargo tractors will be located in Memphis, Tennessee, where FedEx Express has a fleet of 1,383 cargo tractors to manage 270 flights per day.



Question 1: Approach to performing the work

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

- The overall project objectives were straightforward and obvious, so there was not much interpretation needed in developing a plan. When technical issues were encountered, the project team took decisive action to rectify them.
- The approach helps with understanding the operator interaction with the fuel cell through the use of real hardware compared to other technologies.
- This project had a good approach that dealt directly with the customer in real-life situations.
- This project has a very good approach with a nice demonstration.
- It would have been helpful if the presentation format had been followed.

Question 2: Accomplishments and progress

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

- The application is a good one; it is difficult to make the technology work in airport environments with all of the diesel and jet fuel emissions in air.
- The replacement of the fuel cell for the entire fleet in a short time was an outstanding achievement.
- The project team had good results on correcting failure modes, etc.
- The demonstration was run with a complete set of tractors and gathered enough data to do meaningful statistical analysis. It would be helpful to see some additional economic data supporting the total cost of ownership (TCO) compared to diesel (and battery) tractors. For example, it seems like the hydrogen storage/dispensing system is greatly oversized/expensive for the likely usage of this fleet, so it would be good to see some data and analysis on how the size was chosen or whether it could be optimized.

Question 3: Collaboration and coordination

This project was rated **2.6** for its collaboration and coordination with other institutions.

- The project team obviously collaborated well by achieving the installation of liquid hydrogen infrastructure and fleet of fuel cell tugs. It is not clear whether there is any collaboration with the airport on comparing operation of fuel cell tugs with operation of diesel tugs.
- This project was pretty much the application and adaptation of an existing commercial product to a new application, so it seems that the collaboration was pretty much limited to Plug Power and FedEx.
- The project appears to involve not technical collaboration but rather collaboration with users (drivers) and the company using the vehicles (FedEx).
- Given the effort to replace the fuel cells for the entire fleet, it must be assumed that a high level of collaboration was achieved, but it is an almost impossible task to provide a score. For that reason, a score of satisfactory was assigned because the exchange was accomplished and must have taken considerable collaboration and coordination.
- There was no collaboration identified because the review format was not followed and no collaborators were named, making it very difficult to provide a score.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This is a very strategic project. The success of this project opens up new market segments in the materials-handling space that has been an outstanding success for the fuel cell industry. The project opens up the opportunity to install hydrogen infrastructure at airports, which in turn opens up transportation market opportunities such as airport shuttle buses and rental car fleets.
- Emissions from ground equipment at airports are a very significant and difficult problem. It is very important to investigate the possible role that fuel cells could make in this application. Fuel cell technology may be the only zero-emissions technology that could meet the demands of this application.
- Obviously, this project is very relevant to the goal of getting hydrogen fuel cell vehicles into the real world.
- It is relevant to show the application of the commercial materials-handling solution to this specific application. However, no new ground was really broken by the project technically. A new industry/operator was introduced to the technology, which is always a good thing.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- Dispersing the fleet of ground handling equipment to other airports provides the opportunity to introduce the technology to other potential users of ground service equipment (GSE) at very low technical and economic risk. The units have already been operated in an intense operational environment with a major player (FedEx) and therefore have the credibility that will make it easier for other airports and end users to make informed decisions.
- The vendor should work with the airport in comparing hydrogen fuel cell tugs with diesel tugs in terms of operating costs (fuel, operations and maintenance, etc.).
- It is not completely clear whether the 2018 end of this project was part of the original plan or if it is driven by FedEx's request that the hydrogen fueling site be relocated. The poster states, "Explore prospects for relocating the fleet to another location," so it does not necessarily seem that there is/was a clear plan in place.

Project strengths:

- The project team proved short-term satisfactory operation of GSE by a major company (FedEx) in an intense operational environment; met the technical objectives of the project; overcame a major technical problem with the original fuel cell that required the replacement of the whole fleet of fuel cells; and accomplished the Plug Power mission and did not quit, thus preserving the integrity and reputation of the DOE Hydrogen and Fuel Cells Program. If the project team had quit, it would have been a public relations disaster for the fuel cell industry. Plug Power has earned thanks.
- The demonstration of the unique zero-emission, rapid-fueling, long-range, consistent power output performance characteristics in this ground support equipment application is very important. The project started off with some failures, but the project team worked well through those to demonstrate well the technology in this important application.
- The project used real demonstration hardware to expand the applications in which fuel cell systems may enjoy the commercial success currently seen by forklift materials-handling systems.
- This project is an excellent, real-world project evaluation and comparison with existing technology.

Project weaknesses:

- There were a number of equipment-/performance-related problems initially, which may have made the FedEx operators reluctant to fully use the equipment. There was not a product validation plan/process described in the poster, so that may have been a missing element. Also, the project had a very short duration, and it is unclear whether it ended sooner than planned. As a result of these two things, the fidelity of the data as a tool for making investment/TCO decisions for the cargo tug application is unclear.
- The project team did not follow the Annual Merit Review report format, thus making it difficult to assign some scores. While this did not have an effect on the project outcome, it has hurt the overall ability to provide a comprehensive review score. This may not matter.
- The project needs to focus on operational cost comparison between hydrogen fuel cells and diesel tugs.

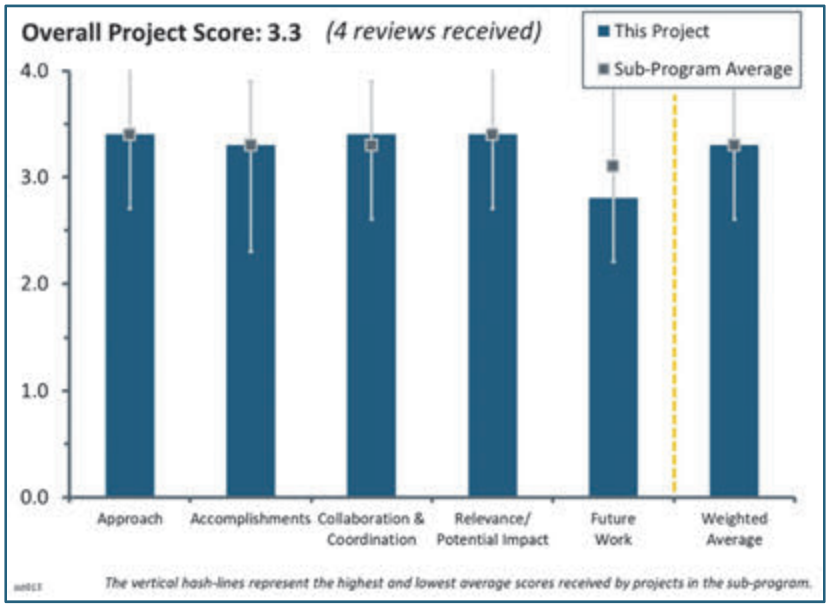
Recommendations for additions/deletions to project scope:

- The team should deploy GSE units to other airports to spread the success of this technology and open up the market.
- The project team should add a TCO analysis and comparison to incumbent technologies and add a validation plan to ensure that the equipment is reasonably reliable from the outset.
- The team should add a task for compart hydrogen and diesel fuel costs and operation and maintenance costs.

Project #MT-013: Maritime Fuel Cell Generator Project

Lennie Klebanoff; Sandia National Laboratories

Brief Summary of Project:



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

Question 1: Approach to performing the work

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

- The project approach is very sound, including upgrading the fuel cell, main inverter, and operator interface and analysis of the optimum fueling scenario for the port. It is important for an operator to know whether the system is functioning as designed. Reducing startup time and enabling operation in cold weather are also good.
- Building and testing full-scale hardware to demonstrate the validity of the system and giving prospective users something to see and touch are good approaches. The rapid cycle of feature/design improvements and retrofits based on learning from the first deployment is also a good approach. It is not clear how the approach for supplying hydrogen fuel was planned. It seems like the approach that was used (tube trailers) ended up being very expensive and did not demonstrate the cost-effectiveness of the system.
- The approach appears appropriate and aligned to provide meaningful feedback for the U.S. Department of Energy and the industry.
- The oral presentation covered a certain amount of bouncing around and included a thorough discussion of the relocation from Hawaii to Massachusetts but very little discussion on the relocation from Massachusetts. There may have been some excellent work in Massachusetts. The project team may have overcome or will overcome most barriers but appears utterly stymied by one barrier: location. The location problem may be especially concerning, as the project is scheduled to end this December; and the project has experience in Hawaii and a plan for and recent work in Massachusetts, but the project needs a home somewhere.

Question 2: Accomplishments and progress

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

- Project progress made included resolving technical issues identified in 2017, such as excessive downtime and the inverter's failure to meet operating requirements. In addition, enabling operation in colder weather is a very good accomplishment.
- The retrofit and testing of the unit based on learnings from the Hawaii deployment were successful. In terms of DOE goals, the project clearly demonstrates the ability to power refrigerated containers with a clean, quiet power source. However, it was unclear what the original plan for the second deployment was because, unfortunately, the arrangement with Massport could not be completed.
- Despite much excellent work and recognizing that the team made "outstanding progress toward project objectives," as documented by the extensive work performed in the written and oral presentations, the down-check comes because "there are weaknesses (a very specific weakness, location) that need to be addressed to improve the rate of progress...to overcoming barriers."
- This project contains good accomplishments and progress. Noteworthy is the work done by Hydrogenics to learn from the deployment activities in Hawaii and make improvements.

Question 3: Collaboration and coordination

This project was rated **3.0** for its collaboration and coordination with other institutions.

- There is outstanding, close, and appropriate collaboration among the partners. Whatever the reason for Massport's and Sandia National Laboratories' (SNL's) not reaching an agreement, that failure does not affect the recognized close collaboration otherwise present.
- The project contains great collaborations. Despite some setbacks, the project team is identifying great opportunities for new partnerships.
- Collaboration and coordination among the existing partners is very good, but the uncertainty associated with finding a port partner is still a factor.
- The collaboration between the project partners was good. However, the relationships with the organizations at the deployment sites have not gone well, so the unit has been "down" for six months while the effort is underway to find a deployment site. It is unfortunate that this could not have been done in parallel with the upgrade/test timing.

Question 4: Relevance/potential impact

This project was rated **3.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- It is important to show that fuel cells and hydrogen can compete in stationary applications to maintain momentum for the Hydrogen and Fuel Cells Program (the Program). This project, if successful, will contribute to this outcome. If the economics are not optimal, the benefits of gaining experience and engaging technology providers, regulators, and a port authority are still valuable.
- Despite the failure to secure an agreement with Massport and the lack of a location for a project with six months before its end date, the project nonetheless aligns very well with the Program as well as specific research and development goals. If the ability to complete the project or even the ability to have a location were part of the definition for relevance and/or impact, the grade for this section would be quite a bit different.
- The project has good relevance and impact and should continue to be funded/supported by DOE.
- It is very valuable to have a real, full-scale hardware demonstration. However, this particular project continues to have problems because the plan for deployment and responding to problems was not robust enough, so there is a concern that the reputation of fuel cells in this application suffered as a result.

Question 5: Proposed future work

This project was rated **2.1** for its proposed future work.

- The proposed future activities appear appropriate and beneficial.
- At this stage, owing to the particular circumstances for the project, a number of uncertainties may have an impact on future work. Therefore, the slide on future work tends to be less specific than the other slides. It would be good to document "lessons learned" for the benefit of the Program and its partners and contractors. The presenter said that the project is making progress in exploring the possibility of other host sites.
- The plan for future work is to try to find another deployment site. Hopefully, this will be successful, but it does not seem certain based on the problems with Massport. It is unclear whether the project team analyzed and understood the differences between the Hawaii deployment (what enabled it) and Massport. It looks like some additional work was done to improve the fueling plan at Massport, but it was still very expensive. It is unclear whether other alternatives were considered.
- The grade assigned (2.0) is a compromise between various considerations. On the plus side, the project team has built on past progress and is working to overcome barriers. However, the project team did not provide an indication that they can overcome the immediate weaknesses facing the team and complete the project by December. Further, the team was all but silent on the likelihood of overcoming the barriers. A better discussion of the immediate challenges ahead might have improved the grade.

Project strengths:

- The project has good direction, project leadership, and partners. The project is wisely building on previous learning to avoid future setbacks and delays. The work identifying new partners is well-thought-out and appears beneficial.
- The demonstration hardware was built and deployed, and lessons learned from the deployment were quickly incorporated into design changes/upgrades, which were implemented and tested.
- This project has very good collaboration and cost sharing among partners, industry, and other federal agencies.
- The greatest strength of this project is that the project focuses on real-world logistical challenges.

Project weaknesses:

- The second deployment did not happen, and now there is a delay trying to find another opportunity. The issue of high fuel/operating costs was not really resolved, and it is not clear what alternatives were examined or what analysis of possible pathways was done.
- The double relocation, first from Hawaii and then from Massport, wastes time and resources that could be used for other aspects of the project.
- It would be good to develop a plan to secure lower-cost hydrogen supplies over a number of years.
- Keeping the momentum and project moving forward could be a challenge if funding issues arise.

Recommendations for additions/deletions to project scope:

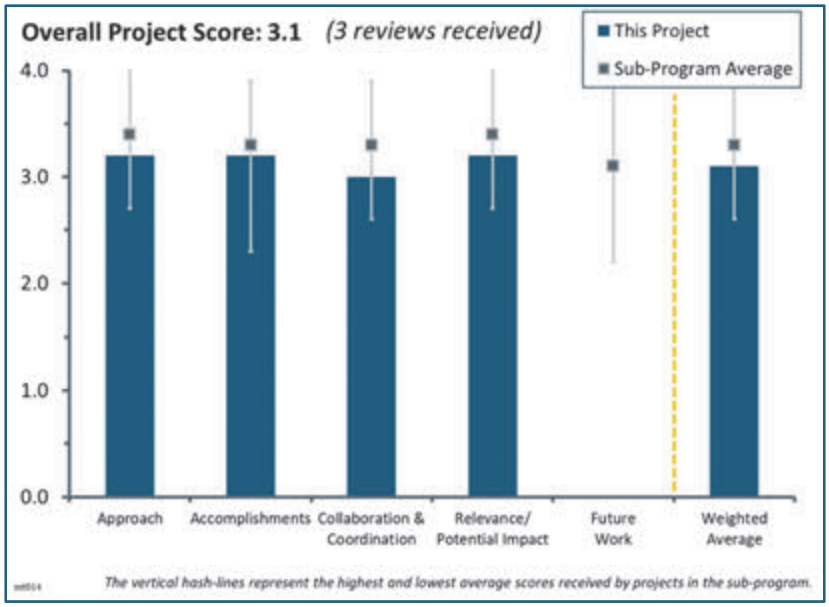
- An analysis of operating cost is needed to be competitive with incumbent technology, and then an analysis of multiple pathways for providing hydrogen should be looked at to determine whether it is possible to become cost-competitive. It is unclear what delivered cost/kilogram for the hydrogen is required for the economics to work.
- Having to move from Hawaii might have been a good point to end the project. Most people would have understood that forces beyond SNL's control forced the abrupt end. SNL should take advantage of the Massport fallout to end the project and complete the report. This scenario is not ideal and may even be distasteful, but ending the project now would avoid future occurrences of the problems that caused the two previous relocations and avoid what could be a very sloppy end.

Project #MT-014: Demonstration of Fuel Cell Auxiliary Power Unit to Power Truck Refrigeration Units in Refrigerated Trucks

Kriston Brooks; Pacific Northwest National Laboratory

Brief Summary of Project:

The purpose of this project is to demonstrate the viability of fuel-cell-based transport refrigeration units (TRUs) for refrigerated Class 8 trucks using demonstrations and business case development. Two fuel cell systems will be developed and deployed in commercial operations. Investigators will assess system performance and analyze market viability.



Question 1: Approach to performing the work

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

- This project was thoroughly planned and provided two possible solutions and trade-off opportunities.
- The project would have benefited from a more rigorous assessment of user adoption criteria and how the criteria would be assessed against the proposed designs. The approach description talked about the "voice of the customer," but this appeared to be a single-criterion assessment of net present value (NPV). A more comprehensive approach could have considered other parameters, such as monetized impact on load-carrying capacity, and could have also looked at the cost to achieve zero emissions versus NPV comparison to diesel. The NPV results between the two teams could not be compared because of a lack of common assumptions (e.g., one team assumed a greenhouse gas [GHG] credit value, and one did not). Common technical and economic specifications would have improved the value and ability of the project to interpret the findings of two separate demonstration teams.
- The demonstration itself was good, but the justification and analyses that were accomplished with it were not too compelling. The team should have focused upon the very significant and important environmental benefits that the technology could produce, with regard to GHG emissions and especially to criteria pollutant emissions and air quality; these are the main reasons to pursue such a fuel-cell-powered auxiliary power unit (APU).

Question 2: Accomplishments and progress

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

- The project was well executed and provided an in-depth analysis of the technical and economic aspects of this potential fuel cell application. It is necessary to have a more challenging market environment that makes the economics work, such as military forward operating bases, where diesel can cost over $200 per gallon delivered and where delivering fuel can cost the lives of our servicemembers in a combat environment. It is also necessary to reduce the capital cost of the equipment and investigate design changes.
- It is good to demonstrate that this technology works to support TRUs. There should be an emphasis on the environmental benefits, which are especially challenging to achieve in ports, where these types of loads and generators are concentrated.

- The work of the two project teams was terminated prior to the intended field demonstration. For this reason, in-service cost, reliability, and customer experience objectives could not be addressed. The design and business case tasks met the stated requirements.

Question 3: Collaboration and coordination

This project was rated **3.0** for its collaboration and coordination with other institutions.

- Several companies with competing technologies and business cases were involved, which supported a thorough evaluation of the technical solutions.
- The project team put together a strong core team of fuel cell manufacturers who were active in warehouse and goods-movement applications and were the two leading providers of APUs. The team also secured one demonstration host (the other dropped out). The project might have proceeded to full demonstration if gate criteria had been clearly defined up front. (Presumably, this was not done, but it was not clear, for example, what assumptions on hydrogen and diesel prices drove the no-go decisions.) Participation of an air district might have provided additional pull to get the project through to the demonstration phase.
- There does not appear to be any significant technical collaboration on the advancement of the technology itself but rather reasonable collaboration with the end user.

Question 4: Relevance/potential impact

This project was rated **3.2** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project provides a technical and economic baseline departure point for future efforts and new solutions. The market is not quite ready, but the concept is conceivable enough that changes in the situation could make it economically viable going forward.
- The project team addressed an important niche application with the potential to support early market entry for fuel cells. Valuation of emissions benefits and possibly forecasting of improved cost and weight in next-generation solutions might have created a stronger case to move forward to demonstration.
- The project could have been much more impactful if it had focused on the technology's environmental benefits instead of the economic benefits. The team should be working with local air quality management districts in affected areas (e.g., Houston, New York/New Jersey, Los Angeles/Long Beach) to incentivize and support, if not mandate, the use of this technology.

Question 5: Proposed future work

This project was not given a rating for its proposed future work.

- The project has been completed.

Project strengths:

- The project's strengths include a good technical approach and execution, as well as a good analysis of the business case and viability of the technical solutions. There is good exposure by industry of the potential of a hydrogen solution that could come into play if anti-idling policies also come into play. The team provided a good baseline upon which to base new technical solutions.
- The project addressed a potentially important application that ties to emissions reductions in goods movement. The team did well in securing strong fuel cell and APU partners.
- The demonstration of this technology for use in APU applications is important. The project appeared to succeed in doing this for the first time.

Project weaknesses:

- There are no weaknesses under the control of the project.
- The lack of emphasis on environmental benefits was the most significant weakness. The economic analyses were not too compelling, and the poster presentation itself was poor. The principal investigator was available at the poster but was difficult to engage in that setting because of the focus on one questioner at a time.
- Some areas that could have been improved include the gate criteria, which were not clearly defined, and the unpresented technoeconomic assumptions (such as discount rate); it appears that the teams did not use common assumptions.

Recommendations for additions/deletions to project scope:

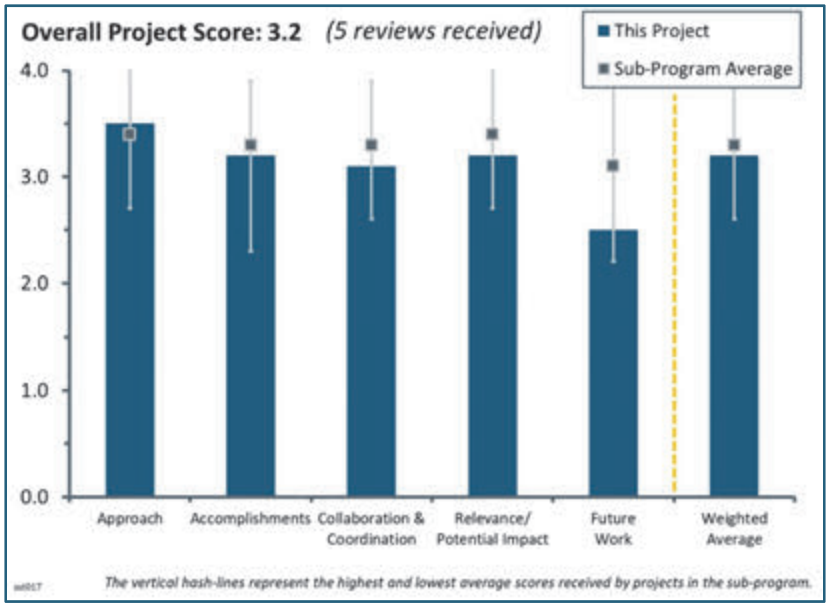
- The project is complete, so recommendations are not applicable.

Project #MT-017: FedEx Express Hydrogen Fuel Cell Extended-Range Battery Electric Vehicles

Phillip Galbach; FedEx Express

Brief Summary of Project:

This project will demonstrate hydrogen and fuel cell technologies in real-world environments. Fuel cells are being integrated into 20 battery electric pickup and delivery vehicles. Those trucks will operate 10-hour shifts 260 days annually, amounting to at least 5,000 hours per truck for a total of 100,000 hours over 1.92 years. The project is expected to reduce diesel consumption by 100,000 gallons and prevent 270 metric tons of carbon dioxide.



Question 1: Approach to performing the work

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

- The project objectives are well identified on the technical, environmental, and economic levels. From a technical point of view, the project is already testing the first prototype to validate its design and gathering data on its performance. The fact that a clear control strategy has been put in place will allow for further optimization of the fuel cell system and validation of its design. From an environmental point of view, the benefits that can be achieved are also specified, even though the sources from which the hydrogen for the project will be produced are not explained. In terms of barriers, the principal investigator (PI) has clearly stated that, besides the validation of the prototype, one key obstacle is to overcome concerns safety. With a greater number of hydrogen vehicles, new safety issues that need to be considered will emerge.
- The overall approach toward achieving the project objectives is sound, as demonstrated by the development of the powertrain. The test of the first prototype, before deciding whether to deploy a larger fleet of vehicles, followed by integration, was a good approach. The project's go/no-go point is the right approach for these types of projects. The role of each of the partners in the project is clear.
- There is an excellent partnership with FedEx, with the company's dominance in the truck delivery business. Comparing fuel cell trucks with conventional trucks was also a good approach.
- The team is running a little over budget and has suffered nasty personnel turnover. The team has some real challenges. At this point, this team has a real chance of failing miserably, but if successful, the project could well have an impact on the delivery vehicle sector in much the same way the Defense Logistics Agency (DLA) (and later the U.S. Department of Energy) transformed the use of fuel cells in forklifts. The team's approach is commended.
- The lack of continuity of project personnel is a concern for ensuring project success.

Question 2: Accomplishments and progress

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

- The test and validation of the first vehicle and powertrain requirements have been finalized. Following this, the first prototype has been up and running since January 2018. A remote data collection system is in place

that sends data for analysis to the fuel cell provider, Plug Power. The month of February saw little data, as the vehicle was down most of the time. This is normal following early (and especially winter) operation, and it is welcome to see that few issues were observed in the posterior months. The PI did not present any data analysis, as it was not ready.

- At the end of Budget Period 1 (BP1), the project is on schedule despite several difficulties during the first few months. It appears that a set of performance goals for the vehicle was not established before the beginning of the validation phase. However, the data-gathering techniques put in place by the consortium (data transmitted via mobile connection to a central database) will certainly help to gain a deeper understanding of the performance that can be achieved by this hybrid powertrain and contribute to the achievement of the DOE's overall goals.
- The project team appears to have struggled with schedule milestones, but the project now seems to be on schedule. In BP1, the team was slightly over budget, but it is close enough that the team should be able to overcome this currently minor discrepancy.
- The project team is off to a good start but must deploy the full 19 fuel cell trucks to provide a true comparison with existing technology.
- The DOE project objectives provided on slide 3 indicate "20 parcel delivery trucks will operate on shift 260 days annually for approximately 10 hours per day." Given that one vehicle has yet to yield substantial field demonstration results, it appears unlikely that the project can complete its activities by the October 2020 project end date.

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- The interaction among partners seems appropriate, and the role of each within the project is well defined and in line with their expertise. Cooperation with other projects carrying similar activities in the same domain (range extender) was not mentioned. The cooperation with relevant agencies (i.e., the safety panel) is foreseen in the plan and appears appropriate.
- Collaboration and coordination among partners have been excellent, and a reflection of this is that the first prototype is already in operation. This demonstrates a good collaboration between the fuel cell supplier, Plug Power, and the system integrator and end user, FedEx.
- Partner organizations all seem to have well-defined roles and appear to each be meeting their individual responsibilities.
- There is good collaboration with commercial partners and with the National Renewable Energy Laboratory.
- The vehicle maintenance partner is not well defined.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is well in line with the market transformation objectives of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, as its goal is indeed to validate early business cases and validate technologies in real-world conditions. Furthermore, it has also been highlighted that the goal of the reduction of pollutants and greenhouse gas emissions is of common interest to the intended user of the new vehicle (FedEx) and the DOE Office of Energy Efficiency and Renewable Energy. The collection of data throughout the vehicle's use will provide useful insights and allow for progress toward these goals.
- FedEx seems to have a clear plan and strong commitment to fleet electrification. Should this project be successful (with cost and reliability at acceptable levels), the impact would be significant and could potentially be extended to other vehicle operators.
- This project could change the delivery vehicle sector in much the same way that the DLA investment in fuel cell forklifts changed that particular industry.

- If this project can encourage FedEx to convert its huge fleet into one that operates on fuel cells, it would be a major accomplishment for the hydrogen fuel cell establishment.
- The project looks to be beneficial, but given the problems with demonstration activities of the first unit, it is unclear that there will be substantial relevance/impact.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- This is a good plan. If FedEx decides to proceed, it will be a major accomplishment since the team must fund the next phase and then await DOE reimbursement; hence, a FedEx commitment to front money for this project would be a major achievement.
- The proposed future work is dependent on a go/no-go decision date that is planned for October. It seems likely that the team's October decision will be correct.
- The continuation of the project will be subject to FedEx's decision, as part of the go/no-go point. This will depend mainly on (1) demonstrating acceptable levels of reliability for the first vehicle prototype, (2) securing adequate levels of maintenance for the larger fleet of 20 vehicles to be deployed, and (3) putting together a convincing business case to FedEx management to finance up front the deployment of the 20-vehicle fleet. The project consortium is well aware of this. As presented, the prototype vehicle will be tested until September 2018. Following this, data will be analyzed, and the go/no-go decision will take place at the end of October 2018. This timing is very challenging, and it is recommended that the project extend the testing and data collection exercise to one year—and therefore postpone the go/no-go decision until the first quarter (Q1) of 2019.
- The logic of the work for the remaining period, in theory, is clear: if the first prototype reaches satisfactory results, the consortium will continue with building the other prototypes and start gathering a large number of data that will allow the team to have a better idea of the performance of this type of powertrain (fuel cell and hydrogen range extender) for the intended use. At the same time, the PI clearly stated that many factors will have to be taken into consideration for the go/no-go decision, some of which might prove difficult to overcome. The team's ability to ensure standard safety compliance for the next phase (linked to the management of several hydrogen vehicles), in particular, was flagged as a serious challenge. As a consequence, scarce data were provided for the actual implementation of the project during BP2, as there seemed to be some skepticism about the project team's ability to continue.
- The project does not appear to have enough time remaining to accomplish the goal for demonstrating operation of 20 units. In addition, there are potential safety issues that are yet to be addressed, which could require redesign and greater costs.

Project strengths:

- The involvement of FedEx offers an interesting exploitation potential. If the fleet of 20 vehicles proves to meet the company's needs, the project team would have the capability of rapidly upscaling this hydrogen-based solution. The team's method of gathering data on the operational performance of the vehicle in a centralized database is also very good.
- FedEx appears to be a good partner that could enable beneficial results/learnings if the project objectives are met.
- The strength of this project is in the leverage opportunity the project can create for delivery vehicles. If DOE would like to replicate the success enjoyed with fuel cell forklifts, additional resources might be necessary.
- This is clearly a market-oriented project driven by strong end-user demand. There is significant replication potential within FedEx and also potentially in other fleet operators.
- This project has an excellent real-world partner to evaluate fuel cell hybrid delivery trunks in real-world applications.

Project weaknesses:

- Personnel changes seem to have plagued this project, but it appears to be moving ahead in any case.
- This is not a weakness in itself, but it is unfortunate that the total cost of ownership analysis was not ready to be presented during the project presentation.
- There are many project weaknesses, including a massive turnover of personnel. Another problem appears to be the miserable performance reliability of the fuel cell systems. Time and budget management may be a challenge that will not be overcome. Finally, the many challenges facing the team may overwhelm the project leadership and the supporters so that the project falls apart when it does not need to.
- The project is utilizing a storage tank location/configuration that exposes piping and valves to anticipated impact zones. This did not appear to be a safe configuration.
- A weakness is the uncertainty concerning the continuation of the project.

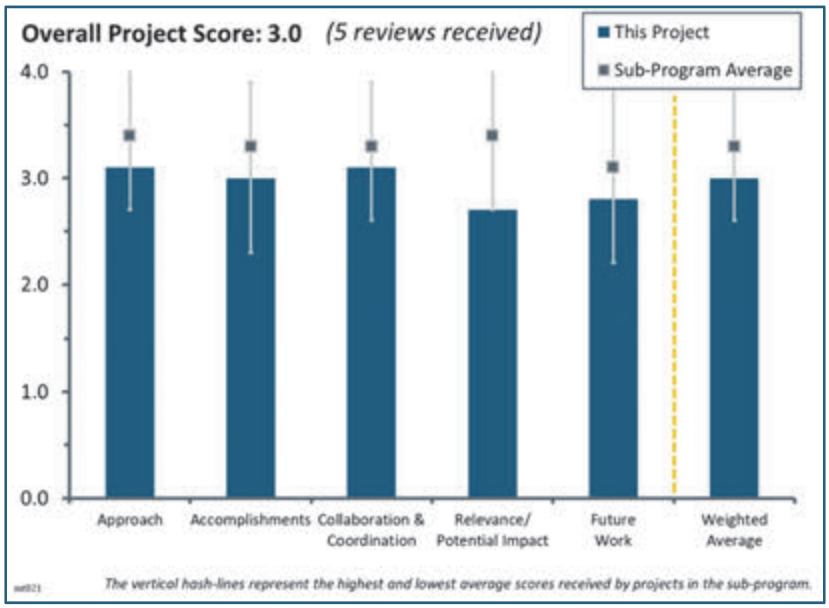
Recommendations for additions/deletions to project scope:

- As presented, the prototype vehicle will be tested until September 2018. Following this, data will be analyzed, and the go/no-go decision will take place at the end of October 2018. This timing is very challenging, and it is recommended that the project extend the testing and data collection exercise to one year—and therefore postpone the go/no-go decision until Q1 2019.
- Other safety issues identified during the submittal of the safety plan should be addressed for the design prior to the construction of additional vehicles.
- If true "zero emissions" is a goal as stated, then at some point the project might consider photovoltaic-generated hydrogen (perhaps in California) to run these trucks.
- DOE may want to consider a more active management role. The problems facing the team members may overwhelm their ability to complete the project.

Project #MT-021: Northeast Demonstration and Deployment of FCRx200

Abas Goodarzi; US Hybrid

Brief Summary of Project:



The project's objectives are to (1) design, develop, test, and demonstrate one fuel cell range-extended plug-in hybrid utility vehicle (FCRx200) at a commercial operator's site; (2) given the success of the initial prototype, receive approval to proceed with fleet development to deploy and operate a minimum of 20 FCRx200s for at least 5,000 hours or 30 months per vehicle, whichever occurs first, at the commercial operator's site; and (3) conduct an economic assessment, a payback analysis, a life-cycle cost analysis, an incremental capital cost per unit analysis, a fuel savings analysis, and a payback time analysis (concerning the use of hydrogen-fueled fuel cell range extenders in commercial fleets), as well as comments from the operator detailing the experience during operation. The economic assessment will be facilitated using data collected and submitted to the National Renewable Energy Laboratory on a quarterly basis. Upon project completion, the team will be able to make recommendations on the marketability of the FCRx200 vehicle.

Question 1: Approach to performing the work

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

- The presenter made the challenges and nuances of the project crystal clear; this presentation might have been one of the best of the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (Program) Annual Merit Review (AMR) presentations. Especially noteworthy was the detailed presentation of the team's approach, as well as the modeling and system analysis.
- The approach of the project, overall, is well designed. Following the development stage, the team will test and demonstrate one fuel cell range-extended plug-in hybrid utility vehicle; should the initial prototype be successful, it is expected to be deployed in a fleet of 20 vehicles. Following the 2017 AMR, it is welcome to see that an initial economical assessment has already been undertaken at this stage—originally, this was slated to be done only at the end of the project, which expert reviewers considered too late. The economical assessment presented by the principal investigator (PI) contains a number of underlying assumptions that were not presented in detail. It was therefore not possible to assess the robustness during the project presentation—also because it was not yet time to discuss these aspects. It would have been useful, for instance, to get further insight on the fuel cell system cost assumptions, as the current figures show $14,000 for a 10 kW system, which seems very low. However, to fully assess this, it would be necessary to understand the technology the fuel cells used, whether they were polymer electrolyte membrane fuel cells or solid oxide fuel cells. It was not possible to get the details on this.
- The objectives of the project are well described and well enshrined in the philosophy of a market transformation project. Much of the focus is on the optimal integration of a fuel cell system in a battery electric vehicle (BEV) with the scope of enlarging the application of the vehicle and making it more marketable. The main barriers considered by this project are of a technical and economic nature. From a technical point of view, the key achievement obtained to date is the design and engineering of the system to

fit into a pre-existing chassis. While it is well understood that the scope of a market transformation project is not to improve the performance of individual technical components, the aspect of system performance did not appear to be sufficiently considered. In other words, it is not clear how much attention was put into optimizing the system (in terms of range, durability, efficiency, etc.) during the design optimization phase to get the best performance possible. Cost and customer satisfaction are the key, if not only, parameters considered.
- The approach seems reasonable, although the exact objectives seem rather vague.
- The presentation did not adequately demonstrate why these activities are good for the Program or the broader fuel cell community.

Question 2: Accomplishments and progress

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

- The team's measurement of its technical achievements was noted often during the review. Among the project advancements, the team recognized when it was necessary to increase the fuel cell from 5 kW to 10 kW, completed freeze testing of the stack, and seem to have made sound design adjustments.
- The project concept is well aligned with DOE goals in terms of market transformation. If successful, this project will enable original equipment manufacturers (OEMs) to find a commercial application for the vehicle in which the fuel cell range extender system will be integrated. The project implementation is following its original path. Whether the project will achieve its goals, however, is hard to judge at this stage. In fact, most of the measurable performance indicators will be made available at the end of the project. Select technical data were presented; however, these were not compared to initial technical goals, making it difficult to understand whether the progress was in line with the plan.
- The work to date has been focused on the design and development of first prototype powertrain. This work is ongoing but close to being finalized. The information provided does not make it easy to understand the key performance indicators against which the fuel cell has been designed; therefore, it is not possible to fully understand whether the design specifications are in line with specific DOE targets. For instance, no information was given on the durability and lifetime of the fuel cell. The PI seems to be well aware that the end product should meet OEM requirements; nevertheless, it is necessary to trust that the PI will meet performance targets. For the go/no-go point, it will be necessary to ask for more details on the performance targets achieved, as well as those remaining on the project timeline. In this regard, a Gantt chart or a similar graphic illustrating key progress and milestones that have yet to be achieved, as well as depicting planned tasks, would help.
- While the project is making some progress, it is not clear that the results will be helpful for DOE goals.
- It is too early to tell how the project team is doing.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The PI declared that the team made efforts to reach out to similar projects (dealing with range extenders) but did not succeed in making contact; these efforts should continue in the next budget period. The coordination of the partners involved in this specific project is appropriate. The consortium is well conceived, and each partner has specific expertise that fits well with the overall purpose of the project.
- There are active roles for each of the collaborators. The team appears complete, and each collaborator is fully on board.
- The project seems to be well managed, and collaboration among consortium partners has been positive—especially between the powertrain provider and the OEM. Should the first prototype result be successful, the project team should try to engage with other potential end users to foster replication during the demonstration phase. It is suggested that a plan on how this can be achieved be developed before the demonstration phase starts. In this regard, the PI has mentioned that the team has contacted a large number of potential end users, but no further details were provided. It is unclear whether the powertrain supplier

fully owns the intellectual property rights of the powertrain to be integrated, and hence it is difficult to assess how relevant it would be to also target other OEMs at a later stage.
- The project appears to have a good team for the anticipated activities. However, it is not clear that all project partners (Nissan, for example) are engaged or committed to the project's success.
- This project does not seem to address the overall market projection for utility vans. It is unclear how many there are in the United States and whether successful demonstration of these vans could apply to other van markets.

Question 4: Relevance/potential impact

This project was rated **2.7** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Overall, the project is well aligned with the Program's goals and objectives; should it be successful, the project could contribute to opening up new markets for fuel cell applications in the automotive sector. However, how the project intends to build volumes beyond the 20-vehicle fleet remains unclear. To clarify, the perspective of the OEM should be represented for the next project review.
- If successful, the project will indeed help to advance the goals of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan, as it will allow the final user, involved in the project, to make use of a new hybrid powertrain. At the same time, from the materials provided, it was hard to understand two important elements: it was unclear which innovations the project would generate (it appears that design optimization will not be disclosed, as it is deemed commercially sensitive), and therefore, it is unclear who else, besides the partners involved in the project, will be able to benefit from this activity.
- The project team's work and success may have an outsized impact on both the automotive industry and the fuel cell industry. The bigger problem is that while this team is performing outstanding work, the beneficiaries of this work may be overseas companies and other nations, rather the United States and domestic companies. This is due in large part to the funding of the national laboratories, rather than the U.S. industry, coupled with the relative inactivity among domestic OEMs.
- It is unclear how this project, if successful, would affect the total van market.
- Given the presenter's focus (in enabling a bill of materials), it is unclear whether the project is aimed at meeting the FCTO goals and objectives.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The team proposes additional work in a wide variety of areas (i.e., fueling interface, vehicle cooling, structure analysis, driver interface and telematics, balance of plant, sensors and safety, performance validation, and demonstration) that are all crucial to success. These areas include problems of which any regular user of fuel cell electric vehicles is well aware, and the team knows that a resolution is necessary.
- The proposed future work seems like a reasonable plan to get these utility vans on the road and under testing.
- On a general level, it is clear what the remaining work is intended to be. However, no details on the remaining project activities were presented, especially on the "how." Next year, a Gantt chart should be presented showing completed progress but, more importantly, showing uncompleted tasks and milestones to be achieved. The most important immediate milestones are (1) the point in time when the first prototype vehicle is ready to start operation, followed by (2) the first-year results to be obtained before deciding whether the wider 20-vehicle fleet is to be deployed.
- The main blocks of the remaining work are laid down in a clear manner; however, scarce details were shared on the next steps. It is also not clear which elements will be considered for the go/no-go decision.
- The lack of a safety plan or hazards analysis suggests that the project is not well prepared for future work.

Project strengths:

- The project has a pragmatic approach and, if successful, will allow the final user to commercialize a pure BEV that, for the time being, has no commercial application. It will, therefore, help to make the case for the use of fuel cells and hydrogen technologies in transport. Furthermore, the strong focus on the customer needs of the project will also allow the team to show the financial sustainability of the hybrid solution proposed.
- This is a market-oriented project with apparently committed partners—both the powertrain supplier and the OEM. The project has clear potential to open up new markets, in particular, for the retrofitting of BEVs with fuel cells to extend the range.
- There are many project strengths. The presentation looks at many challenges and appears to have answers, or at least a plan to pursue for all. Throughout the presentation, the team lists many interesting observations and potential solutions.
- The project contains a good OEM and national laboratory development team.
- No specific project strengths were identified by this reviewer.

Project weaknesses:

- The innovation potential of the project is not entirely clear. Much effort will be put into designing the system and integrating it into an existing powertrain. It appears, however, that large parts of this effort will remain unknown outside the consortium involved in the project (due to commercial sensitivity). Much of the effort, then, seems to be oriented to the customer satisfaction of the final user involved in the project; therefore, the project is targeting a very specific vehicle for a specific use, defined by one final user. Therefore, it is not clear at this stage that the fuel cell and hydrogen industry as a whole will be able to benefit from any of the findings of this project.
- The project appears to be moving forward, despite having no commitment to safety planning or a safety plan and no hazards analysis (waiting until the design is complete is inappropriate and puts the project at risk both financially and in terms of ensuring safety). Additionally, since fuel tanks are to be located in the front of the vehicle, the project team should be transparent and thorough on the basis of the safety of tanks in credible crash scenarios.
- The project's technical KPIs remain unknown and should be provided to enable assessment of the accomplishment of specific DOE targets. It is unclear how the project intends to build volumes beyond the 20-vehicle fleet. To clarify, the perspective of the OEM should be represented at the next project review.
- The impact of this project is its weakness because, even if successful, it is not clear if this has a significant market share.

Recommendations for additions/deletions to project scope:

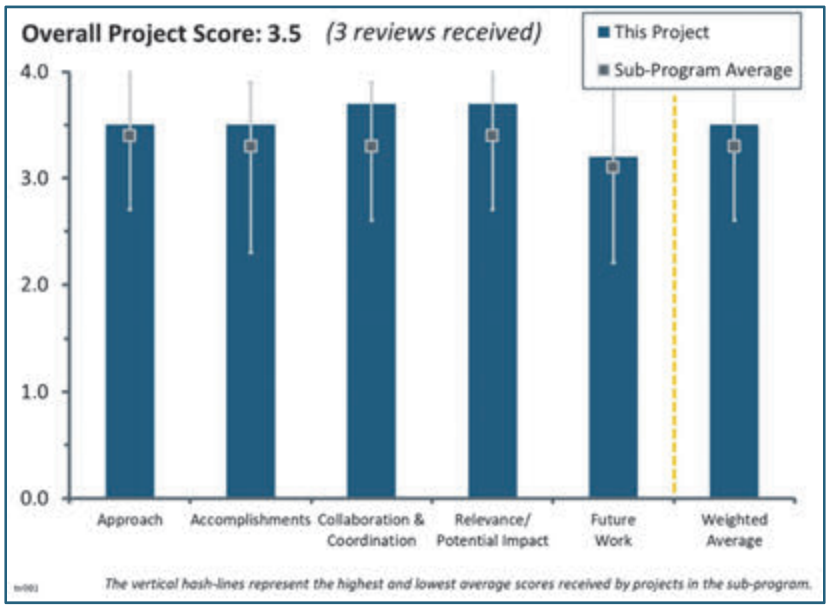
- No recommendations are offered; this was a very good presentation.
- A set of project KPIs seems to be missing—this will make it difficult to objectively asses the go/no-go point in the project. Technical details of the project remain unknown. A detailed project Gantt chart should be developed and presented. The perspective of the OEM should be better represented and conveyed in future presentations.
- It is recommended that the project put greater emphasis on technical achievements that go beyond the specific case assessed in the project (i.e., producing public deliverables exploitable by other players). It is also suggested that the project clarify the technical goals to be achieved and establish a clear dissemination and exploitation strategy.
- The overall value of continuing this project is questionable, given the lack of focus on DOE goals and objectives and a change in direction of the FCTO focus (early research and development).
- The protect team should analyze the fraction of the U.S. vehicle market that would be affected by the successful development of this fuel cell hybrid utility van.

Project #TV-001: Fuel Cell Electric Vehicle Evaluation

Jennifer Kurtz; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to validate hydrogen-powered fuel cell electric vehicles (FCEVs) in real-world settings and to identify the current status and evolution of the technology. The analysis objectively assesses progress toward targets and market needs defined by the U.S. Department of Energy and stakeholders, provides feedback to hydrogen research and development, and publishes results for key stakeholder use and investment decisions. Fiscal year 2017 objectives focus on analysis and reporting of FCEV durability, range, fuel economy, fueling behavior, and reliability.



Question 1: Approach to performing the work

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

- This project's approach to collection and reporting of data, which has been developed and refined since 2012, has been superb. The National Fuel Cell Technology Evaluation Center (NFCTEC) efficiently processes data submitted to it by vehicle manufacturers. Its approach has resulted in a very cost-effective mechanism to transform raw data into detailed data products (DDPs) and composite data products (CDPs). The Fuel Cell Technologies Office (FCTO) barrier addressed by the project is the first one listed under Technical Barriers in the Technology Validation (TV) section of the FCTO Hydrogen and Fuel Cells Program Multi-Year Research, Development, and Demonstration Plan. However, success of the project's approach, and its ability to deliver outstanding results, are linked with the quality and quantity of the data submitted to the National Renewable Energy Laboratory (NREL). With reduction in the number of manufacturers associated with the project, and the number of data sets provided, NREL is constrained. With reluctance, the reviewer concluded that the project approach requires more robust manufacturer inputs to fully address the barrier, which results in a current evaluation of "good."
- The project approach is technically sound. The project approach is based on FCEVs in use. The project began in in 2012, and the approach changed with the introduction of new FCEVs through the fourth quarter (Q4) of 2017 (54 new FCEVs total). The approach is flexible and responsive to the FCEV marketplace and reports on "lack of current controlled and on-road FCEV data." The approach supports solving the barrier: lack of data. The approach taken leads to FCEV technology validation that the participants use for their evaluations and apply to their business decisions. The approach is modern and current with the needs of the FCEV industry.
- Testing pre-commercial vehicles and sharing data publicly that would not be available otherwise are valuable for auto-manufacturers and the potential buyers. However, given the commercial availability of some FCEVs and the declining number of partners involved, it is positive that this project is tapering down.

Question 2: Accomplishments and progress

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

- The project accomplishments are shown through the participation of the automakers and the confidence on their part about the confidentiality of the data management. The NREL evaluation and reporting of the on-road FCEV performance and consumer fueling behavior are very variable—for example, the average fill size (less than two kilograms, which this project studies and reports as absolutely "new, important news"). The accomplishments contribute to DOE goals for the use of hydrogen refueling infrastructure, as they focus on the cars that use the infrastructure. The automakers, likewise, learn more about their FCEVs while "in use" (for a third set of neutral eyes). This project contributes greatly to the DOE goals of car/infrastructure deployment for hydrogen used in the transportation sector and, from a broader perspective, as a component of H2@Scale.
- The team has done a very good job collecting and publishing data, but little new information and learning have been obtained from the vehicles in the last year. Now that we know that the vehicles are safe and perform according to specifications, it would be better to focus more money on infrastructure.
- Slide 6 starkly displays that the number of original equipment manufacturers (OEMs) delivering data is only half the number it was a few years ago. It is also noted on that slide that not all analysis topics are published, owing to data limitations. Nevertheless, as documented on NREL's poster session display, the NFCTEC seems to be making the most of information at its disposal from three manufacturers. While publication of results for some analytical categories is more limited than before, NREL has taken the initiative to use data for new purposes (e.g., development of a predictive fueling demand model [slides 10–14]). NREL still publishes CDPs consistent with available OEM data and protection of confidentiality. As such, NREL continues to take advantage of previous work to produce cost-effective results.

Question 3: Collaboration and coordination

This project was rated **3.7** for its collaboration and coordination with other institutions.

- NFCTEC is highly regarded and continues to work on maintaining its relationships and credibility with a variety of stakeholders having an interest in the progress of fuel cells and hydrogen fueling. Three OEMs continue to provide data for the project and to work with NREL on the review and approval of its analytical products. It seems there are multiple reasons for the reduction of OEMs contributing to the project. The project was created in conjunction with an FCEV Learning Demonstration Program funded by DOE. With the conclusion of that initiative, some OEMs have evidently determined that the benefits of participation are not worth the cost and effort. Based on the involvement of and coordination with the current OEMs, the reviewer evaluated this criterion as "Excellent." However, if additional OEMs do not resume collaboration with the project, NREL's ability to produce desired CDPs is expected to be further compromised.
- This project has been going on for a very long time. Since then, many stakeholders have been invited to participate, including OEMs, industry, and other organizations. Third-party involvement has been appropriate.
- The poster presentation mentioned the information-sharing with the automaker community. Other collaboration must be considered or already accomplished, but the verbal presentation did not cover this.

Question 4: Relevance/potential impact

This project was rated **3.7** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project continues to be highly relevant as originally designed, refined, and implemented. Fuel cell technology and related hydrogen fueling technology are still being researched and developed. It is possible that reports on progress relative to technical targets continue to be valuable, including for OEMs desiring to assess the status of their products relative to those of competitors. Slide 20 indicates there is a significant

gap between current technology and DOE targets for key FCEV metrics. Particularly, given the relatively minor impact on FCTO's budget, this project's relevance may be as high as for any project in its portfolio. However, the potential benefits are dependent on decisions by others to participate.

- This project is relevant to a number of companies (i.e., automakers and hydrogen refueling station developers). The potential impact could include new designs of FCEV functions and/or new designs of hydrogen refueling stations. This project is also relevant to policymakers because they need to know how practical it is to use the FCEVs reliably, so the policy goals are realistic and represent well-researched questions and summaries. The project includes 54 vehicle types/models, and the related on-road use of all of these vehicles can provide a basis for technology assessment of the industry, projection of future vehicles, and the technical requirements for future hydrogen refueling stations (fueling protocols).
- During the pre-commercial years, this information was particularly relevant to developing safety protocols and refueling standards, standardizing storage pressure, etc. Now that some FCEVs have become commercially available, there is little need to continue to hire drivers to produce results. If data becomes difficult to obtain from that manufacturer, and this information is valuable, ad hoc studies such as TV-149 should be funded.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Most of the future work described on slide 17 is a continuation of familiar, ongoing work using inputs from OEM collaborators, which is reasonable and logical. It is questionable whether it is advisable or desirable to shift the focus of the project "...to reporting on the current market status of commercially available FCEVs, production figures, market analysis, and geographic distribution." Despite the project's positive history, continued relevance, and accomplishments, FCTO should consider phasing it out in the absence of a more substantial OEM commitment and contribution of data.
- The principal investigator mentioned hydrogen station design may be included in the future work plans. Such work, from the NREL perspective and expertise level, is needed to make sure future stations are optimized for performance (fueling protocols and two-way communications: nozzle to car).
- The project's change of focus is appreciated, from reporting on pre-commercial technologies to reporting on current market status of commercially available FCEVs and refueling stations, particularly given that countrywide information is not available elsewhere.

Project strengths:

- This project produces real-world use data of the FCEVs and hydrogen refueling stations from a neutral laboratory. This project is expertly managed, and the results remain consistent over the years (since 2012). This project supports historic data analysis and projections of FCEV performance. From a hydrogen refueling station perspective, this project provides information about station use (frequency, actual fueling, and successful application of the technical fueling protocols). From an industry perspective, this project provides what we all need to make certain the consumer needs are met, both from a vehicle perspective and a hydrogen refueling station perspective.
- The project, as originally designed, refined, and implemented, continues to be highly relevant. The project team at NREL's NFCTEC is exceptionally qualified. It has significant experience and expertise in receiving, handling, protecting, and analyzing data related to emerging fuel cell and hydrogen technologies. The team has credibility and solid professional relationships with relevant stakeholders established over a period of years. The project approach results in products such as DDPs and CDPs, which are valued by many having an interest in the state of fuel cell and hydrogen technologies. Significant results are achieved with a relatively small amount of FCTO's budget.
- This project has a long history of data collection, analysis, and information-sharing. The team is trusted by OEMs to produce valuable aggregated data. Another strength is the team's access to vehicle information.

Project weaknesses:

- The project hinges on voluntary participation from the automakers. The extent to which they participate determines the depth of the work. For those automakers that participate, this project provides an excellent product.
- NREL's ability to produce desired results is constrained by a reduction in the number of OEMs associated with the project and the number of datasets provided. If additional OEMs do not resume collaboration with the project, NREL's ability to produce desired CDPs is expected to be further compromised. In that event, the barrier—a lack of FCEV performance and durability data—will not be fully addressed.
- Since vehicles have become commercially available, there is little need to continue collecting data in the same format and for the same purposes.

Recommendations for additions/deletions to project scope:

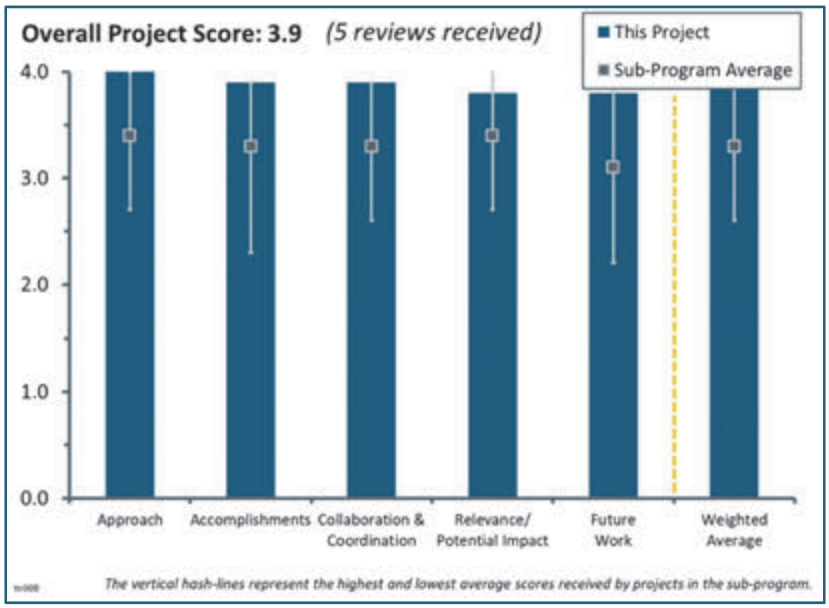
- In the past, this project has been evaluated as "outstanding" across the board by this reviewer. However, FCTO should phase the project out in the absence of a more substantial OEM commitment and contribution of data. If it has not done so, FCTO should assess the merits of a continued, reinvigorated FCEV Learning Demonstration Program. In the process, the Office should clearly identify the factors that resulted in OEM participation and determine whether the conditions causing industry to contribute data can be replicated. Regarding NREL's proposal to shift the project focus from reporting on pre-competitive technologies to reporting on current market status of commercially available FCEVs, the Alternative Fuels Data Center (AFDC) should be tasked with responsibility for providing information on current market status. AFDC is also managed by NREL and already produces numerous reports, publications, and other information on alternative fuels, including hydrogen, and the vehicles which use them.
- The team should add a firm from China. This project should be used to push the envelope of FCEVs released, both in terms of number of FCEVs and FCEV models. It would be interesting to know whether this data can be used to provide designs for hydrogen refueling station developers.
- Proposed future steps are adequate for this project to remain relevant. Focusing on the current status of commercially available FCEVs will be more interesting.

Project #TV-008: Fuel Cell Bus Evaluations

Leslie Eudy; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to validate fuel cell electric bus (FCEB) performance and cost compared to U.S. Department of Energy (DOE)/ U.S. Department of Transportation (DOT) targets and conventional technologies and to document progress and lessons learned on implementing fuel cell systems in transit operations. Annual FCEB status reports compare results reported from transit partners and assess progress and needs for successful implementation of FCEBs, addressing barriers to market acceptance.



Question 1: Approach to performing the work

This project was rated **4.0** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project's approach is to compare FCEBs with other alternative vehicles and fuels, validate the fuel cell bus technology, and provide data while the buses are in use. This is real-world service. Comparisons were made between bus lifetimes, the lifetime of the power plant, reliability, the amount of maintenance needed, and fuel economy. The approach of analyzing fuel economy is appreciated since this topic is rarely addressed for alternative fuels; rather, the approach is often to get the fueling station in, obtain vehicles, and pursue customer adoption. The researcher/analyst presented the technology validation data (organized via this project) to transit agencies; the National Renewable Energy Laboratory (NREL) then collected the fueling records from the transit agencies. Compressed natural gas was used as the baseline, and annual reports were given to the DOE/DOT. The approach presented is effective and proactive.
- The barriers that this project addresses are clearly identified. In the Technology Validation (TV) sub-program section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan, they are barrier A ("Lack of Fuel Cell Electric Vehicle and Fuel Cell Bus Performance and Durability Data") and barrier D ("Lack of Hydrogen Infrastructure Performance and Availability Data"). The approach to the work, summarized in slide 4, has been refined and successfully employed for a number of years. Data from transit agencies are collected, analyzed, and transformed into reports on the status and progress of FCEBs being operated at multiple locations within the United States. Information on FCEBs and the data included in the project's 2018 reports are provided on slides 4 and 5.
- The approach is excellent—clean data acquisition, analysis, and presentation. The technology set that makes up this project is about as all-encompassing as possible—that is, excellent. It is critical that the FCEBs be compared to both conventional and newer technologies based on traditional systems. This project now does that. Activities in the maintenance and fueling activities are being tracked, and with sufficient detail to understand where problems occur (balance of plant [BOP], fueling, or fuel cell stack). Overall, the approach is excellent.
- The NREL FCEB testing project continues to be an important avenue for objective data on FCEB performance. As long as FCEBs continue to show viability as a zero-emission bus option (which, as of today, they do), and development of new generations of FCEBs continues (which it is), then this project is the best way to ensure that reliable and objective data on the technology is available for decision makers.

- This project has a reliable and consistent approach.

Question 2: Accomplishments and progress

This project was rated **3.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project's extensive accomplishments are well documented in the principal investigator's outstanding presentation. Summary results of NREL's data-handling and analysis were provided in slides 7 through 14. Detailed reports on a variety of metrics continue to impress, even after multiple reviews of this project. The metrics included in the presentation consist of current and projected numbers of FCEBs, hours accumulated by the fuel cell system for each bus reported on, fuel economy progress and comparisons, hydrogen use and fueling information, bus and fuel cell reliability trends, maintenance costs, comparisons and trends, and issues affecting FCEB performance. The response to prior-year reviewer recommendations (documented in slide 15) is also outstanding.
- This project contributes to the DOE goals of using hydrogen as a transportation fuel as a component of the DOE initiative H2@Scale. The project is based on data and facts, and it validates the technology used by public agencies to provide transportation (six bus fleets) while reducing greenhouse gas emissions. Tracking fuel cell hours (while in real-world service) is important for the overall DOE goal of adoption and proliferation of FCEBs (and other alternative fuels). With the technology validation and application of this work effort, the 33 buses currently on the road provide data and information to support growing fleets (the plan is for 71 buses to be on the road by the end of 2019).
- This project now includes as many different relevant bus platforms as possible to provide a meaningful comparison and, more importantly, to show technology growth in performance and reliability. In addition to vehicle performance, maintenance, fueling, and other normal operations are being tracked. Overall, this project is really outstanding.
- This project is well designed and has been refined over the years, so it is extremely effective at meeting its goals and addressing DOE's goals. There is one small point: on slide 9 for Fuel Economy, it would be good to show the DOE target as on the other slides. Also, on the summary slide (slide 21), it looks like the range target has been met, although that is not indicated.
- This project has excellent accomplishments and progress. In future presentations, the project team should clarify what type of battery electric bus (BEB) is reported on, as currently, the comparison appears to include not only long-/full-range buses but also short-range BEBs versus long-/full-range FCEBs. For added value, the team should mention the technology maintenance readiness level (TMRL) work done. Moving forward, it is recommended the project team also indicate which buses are tested by the Altoona Bus Research and Testing Center—which is a neutral indicator of meeting federal bus requirements.

Question 3: Collaboration and coordination

This project was rated **3.9** for its collaboration and coordination with other institutions.

- NREL has many partners and collaborators who contribute to this project. Since this project was first initiated in 2003, this has worked effectively to cultivate productive relationships. Six transit fleets, located in California, Massachusetts, and Ohio, currently provide operational data, as do hydrogen fuel providers. Bus and fuel cell manufacturers share information on their products. Fleets, fuel providers, and manufacturers all review and provide feedback on documents and materials resulting from the project. As shown on slides 2 and 16, NREL's work is jointly funded by FCTO and the Federal Transit Administration (FTA). FTA's funding supports evaluations of both FCEBs and BEBs. NREL also coordinates and shares information with other organizations with an interest in FCEBs, including the California Air Resources Board and others mentioned on slide 16. The bottom line is that "impressive" accurately describes NREL's credibility and ongoing communications with numerous organizations.
- The collaboration and coordination activities include two major FCEB manufacturers (the only ones) and transit agencies. The presenter mentioned European and Asian FCEB projects but did not mention collaboration with those particular agencies. It is uncertain whether economies of scale can be reached unless bus companies around the world participate in dialogue (and perhaps they already are). The

presenter mentioned that NREL gives "free" third-party certification (for FCEBs) to the transit agencies; the potential here is great and is akin to feeding neutral, third-party input to fuel cell users and leading them to the continued adoption of fuel cells because those users understand the value of the adoption of FCEBs from an analytical point of view.
- The collaboration/coordination involved in this project is appropriate. It is expected that more collaborators and cooperators will be embraced as more vehicles are added to the sample set.
- There are no concerns here; this is a long-running initiative that has established very effective stakeholder engagement processes.
- The collaboration within this project is excellent; there are no comments for improvement.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This FCEB evaluation project makes an exceptionally valuable contribution to (1) documenting the progress of fuel cell buses toward achieving the FCTO bus targets and DOE Hydrogen and Fuel Cell Program objectives; (2) understanding how performance and cost of FCEBs stack up relative to performance and cost of conventional diesel, hybrid, and battery electric buses; and (3) identifying market barriers and technology development priorities. The bottom line is that NREL's results (including analyses, reports, and insights on technical issues) provide much information that is beneficial for those making decisions on investments in technology research and development, buses and related systems, and fueling infrastructure.
- The project evaluates fuel economy using agreed-upon performance indicators. Maintenance workers who work on non-FCEBs are consulted, which strengthens this project, thanks to the knowledge base being tapped, and provides exposure of the maintenance workers to new technologies. The presenter mentioned the steep learning curve for fuel cells. The NREL project will perhaps shorten the time needed to learn about and adopt fuel cells as well as document the items that are evaluated and assessed.
- This project is critically important to understanding the state-of-the-art of the technology, providing information on the status of the technology in the field, and providing critical information to help guide research resources to improve the technology. The impact of this work is huge, aiding a rapid, successful deployment of this technology and providing solid, defensible data to demonstrate to other transit agencies the success of this technology. The only reason this section was not scored as "Outstanding" is because, strictly speaking, this is not low-technology-readiness-level (low-TRL) work (<4). However, it is critically important to inform and help direct early-term research resources (TRL<4) for maximum impact.
- The project is still relevant and offers excellent value. It has been improved by adding in comparisons to BEBs and, more importantly, the coming addition of new buses with current-generation fuel cell bus technology. One ongoing concern about the project is the diminishing return on analyzing technology that is several years old (and in some cases, by companies that are no longer in business). Obviously, that is partly a result of needing long-term lifetimes and reliability data, but it would be good to start getting new performance data from new buses. A risk for the project is that the market is moving definitively toward BEBs as the preferred zero-emission technology, making FCEBs a dead-end technology that does not warrant further data collection. That is something to keep in mind as the work continues, although it seems unlikely that this would happen in the next few years.
- This project is most relevant with many transit agencies considering their involvement and adoption of electric buses.

Question 5: Proposed future work

This project was rated **3.8** for its proposed future work.

- The future for this project looks like more of the same, except with more buses through which to collect data and perform analyses. Slide 19 indicates an expectation of new sites, buses, and designs. With continued funding for the project, increases in transit agencies and buses are anticipated. In addition,

slide 18 indicates that NREL plans to introduce the analysis of fuel cell electric trucks this year. Building on its successful model, NREL's proposed future work is reasonable and should continue to provide outstanding value. As suggested on slide 17, NREL is expected to maintain a focus on establishing productive working relationships with additional transit agencies.

- Moving this analysis activity to class 5, 6, 7, and 8 trucks and other heavy applications is the correct growth direction.
- The presentation mentioned the need to evaluate new fuel cell electric vehicle models as they are introduced. Presently, 25 buses (total) are under evaluation. The reviewer did not pick up on the quantity of models under evaluation, but if there are two (one per manufacturer), a greater diversity in models should be evaluated in the future. The researcher/analyst presented a structured (and not very different from last year's) approach, and this could be applied to new models in the future.
- The proposed future plans look good. Getting new FCEBs into the analysis is critical to ensuring that this project continues to provide high value. It is also important to continue the comparisons against BEBs, along with the necessary context to help interpret the data. For example, on a chart like the one on slide 13, it could be a good idea to compare the results of FCEBs and BEBs of a similar age, since the current chart compares state-of-the-art BEBs against both older-generation and current-generation FCEBs, which may be misleading. The bullet points on slide 27 seem to align with this suggestion of comparing buses of a similar age and/or size.
- New interim targets should include a specific year instead of the timeless "ultimate" descriptor. The project team should consider a DOE-funded effort to make the TMRL concept available for trucks and coach buses, in addition to transit buses.

Project strengths:

- The strength of this project includes the comparison between FCEBs and BEBs. The parts supplier availability is also included. On the topic of technology validation, the presenter mentioned that the team "[tried] to get the word out." This dissemination about real-world operations is a strength of the project. Another strength is that this work results in the ability to evaluate fuel cell trucks. Finally, the presenter mentioned that the team planned to transfer this work/knowledge to the light-duty vehicle industry. This frame of mind is very much appreciated because data about the practical use of fuel cells is very much needed. The presenter also works on evaluating new fuel cell technology with "older" fuel cell technologies, both from a research and a validation point of view. In general, this presenter did a great job explaining the team's perspective of technology transfer (knowledge).
- The NREL project team is highly regarded and credible. The team has established great relationships with numerous organizations with a stake in advanced bus technologies. This project has a long-term record of accomplishment. It is cost-effective and provides outstanding returns for a relatively small amount of funding by FCTO. The project's benefit-to-cost ratio is likely as good as, or better than, that of any other project in FCTO's portfolio. The approach to data collection, analysis, and reporting results has been successful and is time-tested. Documentation of FCEB performance and FCEB progress relative to targets is outstanding. Reports of the results are provided to stakeholders through multiple publications and presentations at conferences and briefings.
- This is a well-organized study to collect, track, and analyze performance data of (now) FCEB and (soon) other classes of heavy-duty applications. The project does an outstanding job of this. The collection of data encompasses more than just the vehicle—it includes operational issues as well. The fidelity of the data collection allows for the separation of fuel cell operation and reliability from other systems that are not fuel-cell-dependent, like the BOP.
- The project has a well established and vetted data collection plan with consistency in data collection and reporting. The team also provided stakeholders (such as DOE, DOT, industry, and other policymakers) with objective information on the progress of FCEBs. The dissemination of results is very good. The project has been strengthened by adding comparisons to BEBs.
- This project's strengths lie in its essential neutral data collection and the assessment of bus operational data capabilities, especially since contracted transit agencies and private consultancy firms typically do not have the same neutrality.

Project weaknesses:

- No project weaknesses were identified.
- This project's weakness is DOE and other agency funding.
- While the project provides value in tracking long-term reliability and life of the fuel cell system and buses, that presents a weakness in that the technology being examined is increasingly obsolete—and in some cases, technology from companies that are no longer in business is being used. The new FCEBs coming to Alameda–Contra Costa Transit will help counter that.
- The project did not include the impact of ambient temperature on bus operations and fueling; this is planned for accomplishment in the future. Another weakness of the project is that some fleets have only one bus—this is a fact of the user community and not a weakness of the researcher/analyst.

Recommendations for additions/deletions to project scope:

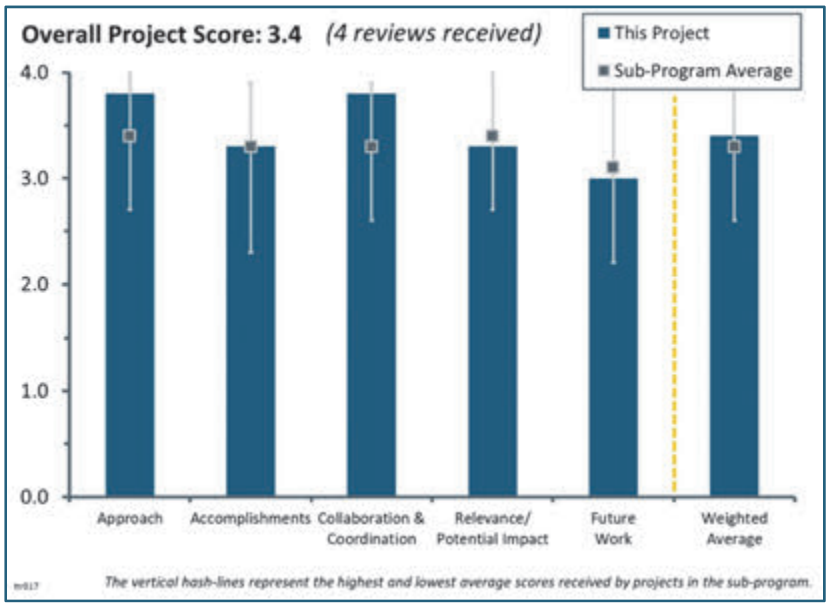
- It is recommended that the FCTO continue support for this project and the future work proposed by NREL. Taking on the analysis of fuel cell trucks would be a good addition to the project's scope. As confirmed by project results (slide 21), some FCEB technical and cost targets have not yet been achieved. During questioning after the project presentation, the reviewer inquired whether the additional work associated with more transit agencies and buses, and the introduction of trucks, could reasonably be accomplished with the "same low price" of $200,000 per year. Some funding increase could be justified.
- It is recommended that the project team consider bus makers from Europe and Asia in future renditions of this project. It is also recommended that the team consider fueling protocols for buses and other medium- and heavy-duty vehicles during the next steps of this project. If protocols that work for all these vehicles can be agreed upon, the use of the FCEBs may increase.
- This project should remain well funded as the industry moves into heavy-duty applications. It is recommended that this work be submitted to the Transportation Research Board's (TRB's) Standing Committee on Alternative Transportation Fuels and Technologies (ADC80) for the January 2019 meeting. The TRB committee has specifically asked for information in this space, and this work does an outstanding job and needs to be put into the TRB community.
- It could be useful to separate out newer FCEBs from the older-generation FCEBs in the analysis, mainly when comparing against BEBs, which are fairly new, and to make clear the different ranges and passenger capacity of the different FCEBs and BEBs.

Project #TV-017: Hydrogen Station Data Collection and Analysis

Sam Sprik; National Renewable Energy Laboratory

Brief Summary of Project:

This project evaluates hydrogen infrastructure performance, cost, utilization, maintenance, and safety. Data analysis supports validation of hydrogen infrastructure, identifies status and technological improvements, provides feedback to hydrogen research, and provides results of analyses for stakeholder use.



Question 1: Approach to performing the work

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

- The project requires significant amounts of coordination and collaboration with industry and state entities. At the same time, the project has a high degree of interaction with sensitive business information, which companies are often not willing to share. The project approach has found ways to work within these constraints and receive more data than would otherwise be available for public consumption, while finding ways to protect individual business interests. The approach allows for much-needed information to enter the public domain and be useful for policy and decision makers.
- This project is an evaluation of the level of success of market penetration for hydrogen refueling infrastructure, as well as fuel cell electric vehicles (FCEVs). The information provided is interesting and useful for both automobile manufacturers and the public. This is the only source for countrywide information.
- Data validation is a very important, and a direct approach—just asking/surveying the field—is appropriate.
- Overall, the approach is good, but it is not clear whether collection must continue for all data points (at the risk of collecting data for data collection's sake). Also, the U.S. Department of Energy should consider ending data collection from retail hydrogen stations, as there are more than 100 retail stations in operation in California, and the California Energy Commission pays the National Renewable Energy Laboratory (NREL) through a contract to collect data from all these stations. An alternative could be to give minimum funding if California agencies provide funding for data collection so that NREL can continue to report out at a national level.

Question 2: Accomplishments and progress

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

- Most of the information to track the progress of refueling infrastructures and FCEV penetration is available thanks to this project. It is especially good to see cost information along with performance data.
- Substantial useful data have been collected to understand trends and the reality of the hydrogen workspace. Data on numbers, geographic distribution, and station type are useful. Data on hourly dispensing rates confirm that FCEVs track internal combustion engine vehicles quite closely. The hydrogen price data show a surprisingly large span. It would be interesting to see the price broken down further to determine whether there are trends by geography, station type, or station utilization. As in the past year, maintenance data

identify the compressor as the most cost-impactful element. Causes of failure should continue to be evaluated.

- It is impressive to see the project continue to develop new methods of analyzing data and finding new ways to provide insights on the developing utilization of the hydrogen fueling station network in California. Having said that, the lost opportunity analysis likely requires further refinement. It seems that, as formulated, the projected value really presents the cumulative lost opportunity as summed across all the stations. It does not (and perhaps cannot) provide any information on the counterbalance: the incremental gained opportunity that may have been experienced at one station because of the opportunity lost at another. The cumulative across the network then is likely smaller than presented so far. Still, it would be very interesting if this project could actually provide inside on the net (negative and positive) lost fueling opportunity. It would be interesting to know whether there is any sign in the fueling data, as collected, that customers had to forego using their vehicles for any period of time because of one or more stations' downtime. Such a metric could be very useful to track as an indicator of overall network health. It would also be interesting to see this broken down regionally and on sub-network levels, as the total station network continues to grow.
- The project has provided good added value to the default Alternative Fuels Data Center hydrogen map for retail stations (and has an option to see additional non-retail stations). The number of FCEVs for the first quarter of 2018 is incorrect; NREL should default, like the rest of the industry, to using the California number of FCEVs as posted monthly on the California Fuel Cell Partnership (CaFCP) website, instead of using reports from the California Air Resources Board (CARB), which are released once a year. The issue is that a number of retail stations used in data assessment do not match the time stamp of the total number of FCEVs (the number of stations used by NREL is based on announcements from the California Governor's Office of Business and Economic Development/CaFCP, which are much more accurate with actual numbers). The continued collection of operational FCEVs and fueling stations comes with the risk of collecting too much data that is not essential to understanding technology progress. It would be better for the project team to define "connector/destination" station so as not to confuse viewers of data reported. The hydrogen price should be reported as "passenger car retail price"—this number is used also for heavy-duty (HD) applications, although that hydrogen price is applies only to those projects using passenger car retail hydrogen stations, not HD stations. In terms of missed opportunity fueling, it is unclear whether the point is to publicly point out that if a station is not available, FCEV users go elsewhere to fuel, and there are missed revenues, or if other conclusions should be drawn. It appears that industry is clearly aware this results in missed revenue and FCEV user inconvenience.

Question 3: Collaboration and coordination

This project was rated **3.8** for its collaboration and coordination with other institutions.

- The unique clean-room characteristics of this project's data collection and reporting are likely a key to increasing the amount of collaboration and coordination with industry stakeholders.
- Every station provider is involved, as are organizations that provide support and funding institutions. Furthermore, researchers are open to feedback from industry.
- It appears there is collaboration and coordination with many other institutions, including contracts with the California Energy Commission and CARB.
- The selection of collaborators seems appropriate. Obviously, the station providers have to be consulted. Actively incorporating interactions with listed organizations is also a good idea.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This work is critically important to station network development efforts that are currently ongoing on the ground today. Policy and decision makers, as well as their supporting staffs, are using this data to help track progress and chart the path forward for hydrogen fueling network development.

- As station owners are becoming savvier at installing stations, there are fewer surprises or new learning. However, it is still important to track utilization, safety, station availability, reliability of the components, number of cars in service, and refueling patterns for future generations of station owners and to improve current stations.
- This project is highly relevant to understanding the trends and problems of actual stations.
- The progress assessed serves as a benchmark for public (not industry) awareness about the status of technology. The more widespread the market commercialization of technology becomes, the less relevance NREL's data collection has.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work is to continue collecting the same data as in the past. This is appropriate.
- The general direction of the future work plan is good, and continuing efforts must be preserved for this project. It was exciting to see some new ideas (such as the opportunity lost analysis presented) for data analysis developed in the past year, and it would have been very good to see more concepts like this proposed in the future work section. It is hoped that expansion of the analysis concepts continues in the future.
- In the future, it would be interesting to see how the reliability of the components and the number/type of safety incidents evolve over time. It is difficult to tell whether reliability is improving or whether the number of safety incidents is changing.
- The project team is cautioned not to collect data for "data collection's sake"—this is interesting, but it is not necessary to spend federal funding on this.

Project strengths:

- The project's strength is its unique ability to provide valuable information about the developing hydrogen fueling network; this information is not normally available in the public domain. The project's ability to balance the information sensitivity needs of individual companies with public data consumption needs is a key part of this.
- NREL is the appropriate agency to collect and aggregate the data. The team has good experience and understanding of hydrogen station issues. The data results are presented in a clear and understandable format.
- The data is free, as disclosing information is required by law. This project consists of many years of data and expertise, and the project team has good data analyses capabilities.
- This project provides insight into the progress made with FCEVs and hydrogen infrastructure.

Project weaknesses:

- The compressor energy usage should be defined, if included (considering the low kilowatt-hours per kilogram dispensed). Certain data should be distinguished. The project team needs to clarify whether the compressor was a booster compressor (if so, the team must identify what compressor energy was used in the central compressor plant where the tube trailer was filled). The team needs to address whether compression moved from low pressure (20–80 psi) to high pressure (+90 MPa). The team also needs to simplify the number of data items collected because of the lack of root cause information explaining the story behind the data collected.
- Data is sparse on everything except tube-trailer-delivered-hydrogen stations. This is because there are very few stations that do anything else.
- It is not likely that new future innovations will be generated from the data since station owners have plenty of experience at this point.

Recommendations for additions/deletions to project scope:

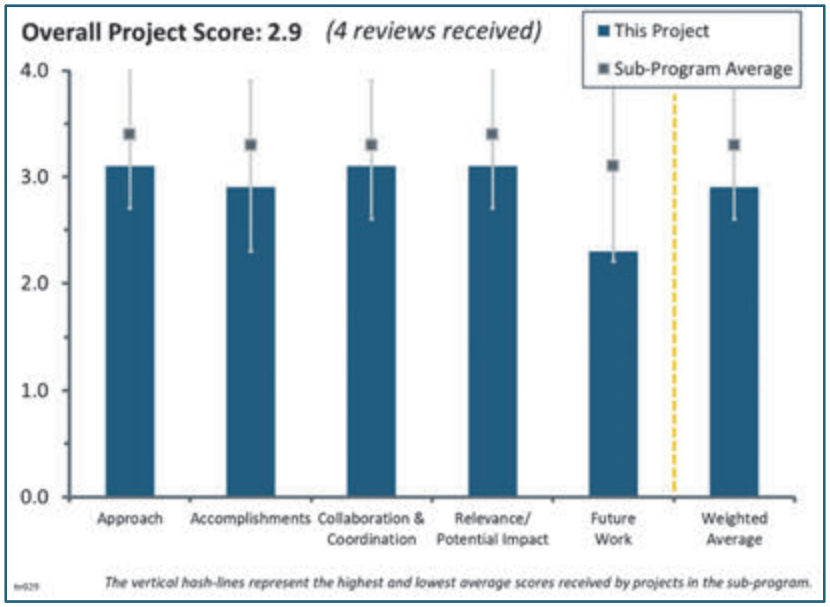
- The project team should look into the differences between various types of hydrogen stations and whether trends/differences can be correlated. The electricity price (cents per kilowatt-hour) shown in the backup slides is very high—this should be further explored/explained.
- The project is encouraged to continue development and expansion of creative new data analysis concepts to continue providing new insights into the evolving operation of hydrogen fueling station networks.
- In the future, it would be good to see how component reliability and safety evolve over time. It is difficult to tell whether reliability is improving or the number of safety incidents is changing.
- There were a limited number of data points collected.

Project #TV-029: Performance and Durability Testing of Volumetrically Efficient Cryogenic Vessels and High-Pressure Liquid Hydrogen Pump

Salvador Aceves; Lawrence Livermore National Laboratory

Brief Summary of Project:

This project explores the potential for reaching high volumetric (50 g H_2/L target) and gravimetric (9% H_2 weight fraction target) storage performance within a small (63.5 L internal volume), high-aspect-ratio (34 cm outer diameter and 100 cm length) cryogenic pressure vessel with long durability (1,500 thermomechanical cycles) refueled by a liquid hydrogen (LH2) pump to be tested for degradation after delivery of 24 tons of LH2. Cryogenic pressurized hydrogen storage and delivery provides safety, cost, and weight advantages over alternative approaches to long-range (500+ km) zero-emissions transportation.



Question 1: Approach to performing the work

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

- The team has a good approach to proving the safety and performance of the cryogenic vessels that will extend the fuel cell electric vehicle (FCEV) range.
- The approach combines testing the pressure vessel and the pump into the same series of tests, so it is economical in terms of the number of tests required. Although boil-off was mentioned in one of the slides, there was no specific discussion of the boil-off performance and potential for loss of fuel from the hydrogen storage system due to boil-off. It would be good to understand those items as practical concerns when using this technology.
- Technical barriers addressed by this project are among those documented in the Technology Validation sub-program section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan (MYRDDP). The project has also dealt with barriers identified in the Hydrogen Storage sub-program section (for example, barriers A, D, E, J, and N) and the Hydrogen Production and Delivery sub-program section (barriers C and H) of the MYRDDP. This underscores the interest and joint funding by three Hydrogen and Fuel Cells Program [former] sub-programs. If the sole evaluation criterion were the number of liquid hydrogen barriers associated with the project, it could be viewed as "Outstanding." The reviewer's knowledge of cryogenic vessels and liquid hydrogen technologies is limited. The project's approach seems reasonable. However, the number of tests, equipment tested, and test results seem minimal in the context of the project's cost and the four-year-plus time period.
- This project suffers from an unclear approach toward the topics it seeks to address. The project's proposed tasks are intended to address infrastructure and hydrogen storage, yet they miss several opportunities to investigate all applications of the technology from a singular focus toward onboard vehicle storage. The project does not address the impact on other methods of using cryogen-compressed (cryo-compressed) technology in other aspects of the infrastructure.

Question 2: Accomplishments and progress

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

- Test facility construction and commissioning and pump model development and validation are key project accomplishments. Both of these accomplishments will have significant value for future testing and design work and will hopefully be available to companies trying to design and bring to market systems that are related to LH2 fueling and storage.
- The team has made excellent progress, and the project is complete.
- The information on accomplishments could have been enhanced by (1) providing more specific data (e.g., on durability metrics) resulting from cycle testing the BMW cryogenic vessel prototype, (2) citing quantified results linked to selected barriers that are deterrents to the commercialization of LH2 pumps and storage vessels, and (3) indicating what accomplishments have been achieved during the final year of the project, i.e., since the last Hydrogen and Fuel Cells Program Annual Merit Review (AMR). As noted in the "Approach" section, accomplishments are limited, given the project time period and cost. During a poster session discussion with the principal investigator, Dr. Aceves, it was stated that data collection days at the hydrogen test facility during the past year were "about the same" as 19—the number of days cited at last year's AMR.
- The value returned for this project is poor in comparison to the overall cost. The project's accomplishments provide information but lack analysis and useful information to facilitate the next phase of development or technology transfer.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The project partners—Spencer Composites Corporation, the Linde Group, BMW, and Lawrence Livermore National Laboratory (LLNL)—have been collaborating for an extended period, on both this and other projects. Together, the partners have developed, contributed to, and utilized an integrated and capable hydrogen test facility at LLNL.
- The team has a good balance of partners with the necessary technical capabilities.
- While the project worked well with the collaborators, there was a good deal of defensiveness in the answers to the reviewer questions from the previous year; it seems like there is an "us versus them" mentality, as opposed to "let us solve this since we are all in it together." That said, the larger issue of a holistic exploration of LH2 fueling/vehicle storage is beyond the scope of this project.
- The project does not cite any collaborators beyond those who already have a deep understanding of the technology. Collaboration with skeptics of the technology and a more diverse group of stakeholders would facilitate more impactful and relevant accomplishments.

Question 4: Relevance/potential impact

This project was rated **3.1** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project aligns well with DOE goals to increase FCEV range. This solution is focused on light-duty vehicles but would still be an excellent fit for medium- and heavy-duty vehicles. LH2 could be a significant benefit for larger vehicles that need longer ranges for commercial viability.
- The potential benefits of LH2 fueling/vehicle storage as described by the investigators here are significant. There needs to be an umbrella project, of which this would be a sub-project, that covers all of the elements needed to enable the use of LH2 to directly fuel vehicles. Recognizing that the issues of the vehicle fueling interface and boil-off control are beyond the scope of this project, it would be helpful to briefly summarize the approaches; otherwise, this project could be considered isolated, instead as part of a practical infrastructure-dispensing vehicle system.

- There seem to be disparate conclusions by individuals who do have the requisite expertise. The LLNL team makes a case for relevance—in reality, however, the relevance of this project, or ones like it in the future, is linked to LH2's potential economic viability, safety consideration, and commercialization prospects.
- This project has tremendous potential impact and is very relevant to the development of infrastructure, yet this impact and relevance are not realized.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- The proposed future work should focus on the promulgation of the results and technology transfer to improve the impact of the project. The technical topics cited are good, but they are not as important as better promotion of the impact and analysis that demonstrates all of the potential uses of the technology evaluation.
- While remaining challenges and barriers are cited, no future work is proposed. The project's scheduled completion is June 2018.
- The project has ended, and no future work is planned.
- The project is complete.

Project strengths:

- The project has benefitted from intellectual and cost-share contributions by industry partners. A LH2 test facility has been built and is available at LLNL.
- The project team has developed excellent test facilities and modeling capabilities. The team has provided useful durability data on two key elements of a LH2 fuel system.
- The technology demonstrated is progressive and very relevant to the commercialization of FCEV infrastructure.
- This project consists of excellent team capabilities and collaboration. The validation of LH2 tanks for vehicles could help increase the range to make them more commercially acceptable.

Project weaknesses:

- The project needs to better explain the practicality of the system being tested, in terms of its interfaces to infrastructure and vehicle systems. For example, it is not clear what happens to the fuel available in the vehicle if it is parked for an extended period of time, or whether boil-off/latency renders the whole idea impractical. Also, the question remains whether the fueling nozzle/receptacle system for cryo-pressure fueling is practical for consumer use.
- The tank takes up considerable space that limits the ability to carry cargo. This technology would be well suited for larger vehicles that could benefit from the added range, with minimal impact to the cargo area (e.g., SUVs, vans, trucks—including light-, medium-, and heavy-duty vehicles).
- The project concept and approach seem to have merit in addressing important barriers to the adoption of LH2 technologies. However, project implementation has had minimal benefit, in terms of actually removing barriers.
- The project is weak on analysis and on the promotion of technology potentials.

Recommendations for additions/deletions to project scope:

- There are no recommendations for additions or deletions related specifically to the project, which is concluding. The DOE should assess whether the LLNL hydrogen test facility has value for other LH2 development and testing activities. Slide 11 cites and responds to a prior reviewer comment, specifically: "The issue of LH2 feasibility should be addressed by DOE before any further investment in similar testing and validation. LH2 may have potential advantages, as suggested by the project team. However, an objective, hard-nosed, comprehensive assessment of the current state of technology, and technology prospects, should be done prior to making another significant investment in validation of selected

components." If it is not already doing so, FCTO should consider such an independent assessment. Perhaps this could be assigned to the Hydrogen and Fuel Cell Technical Advisory Committee.

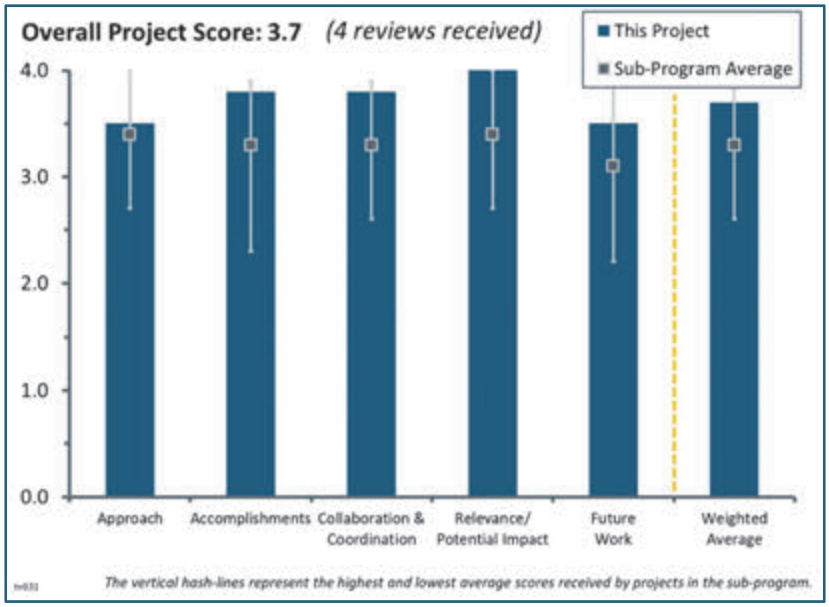
- This project has ended; however, it would be valuable to have a follow-up project to address the remaining barriers listed in the presentation:
    - Demonstration of pump performance versus fill pressure
    - Demonstration of solutions for long-term vacuum stability
    - Demonstration of rapid and inexpensive manufacture of cryogenic vessels
- It would be helpful to know more about the LH2 delivered to the station to the vehicle usage sequence to better understand how cryo-pressure storage might be part of a practical commercial station and vehicle application.

Project #TV-031: Dynamic Modeling and Validation of Electrolyzers in Real-Time Grid Simulation

Rob Hovsapian; Idaho National Laboratory

Brief Summary of Project:

This project is demonstrating the fast-reacting performance of electrolyzers and characterizing the potential and highest economic value of their installation to enable participation in energy markets and demand response programs. A novel approach of distributed real-time simulation is used, with electrolyzer hardware at the National Renewable Energy Laboratory (NREL), in conjunction with power system simulations at Idaho National Laboratory (INL).



Question 1: Approach to performing the work

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

- The presenter provided a comprehensive review of information and gave confidence that a full review of existing electrolyzer information, including hardware in the loop, was conducted. It is very important to have real-world utility input. The hardware with digital blueprint, covering connections across multiple locations, allows for a good use of resources and a better understanding of incoming resource allocation and grid impacts/benefits. A key element is allowing the front-end controller to prioritize communication from multiple systems and signals that can be translated to electrolyzer language for best operation.
- The authors have already presented localized analyses (as on the "economic benefits to states," slide 17) of hydrogen production costs for the "typical" electrolyzer operation case (no demand response and no grid services) across the entire nation. This is highly valuable information. At the same time, the project is looking to leverage highly specific and high-resolution data, analytical methods, and experimental validation for localized cost analysis of production; this includes demand response and grid services in certain case studies. While the same resolution cannot be expected for the state benefit analysis to include grid services and demand response in all locales, it seems that a sufficiently expanded set of case studies should provide insights into developing a set of heuristics that could give a rough approximation of hydrogen costs across all the nation, when these services are included. There is currently no similar effort outlined in the approach, but it would make a useful addition.
- There is a good use of simulated profiles based on actual utility data and recognition of the need for interface and controls to effectively communicate between the electrolyzer and the source. There is a good description of the need for different timescale responses on the controller.
- The development of grid simulation hardware is an excellent approach and allows for a much broader range of test conditions and scenario tests than can easily be done in a field test.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The vendor's neutral approach will allow for application by multiple organizations and shows major progress toward the goal of widespread adoption. This is a great accomplishment, versus focusing on just a single proprietary partner. There is outstanding progress on this project, with three out of four milestones complete, including two tasks (G1 and G2). The effort appears on track to finish all promised work. The team will need some additional run time and real-time testing, but all tasks should be done before the end of the project in 2018. Proving the equipment and communication protocols will require 200 hours of testing and 500 hours of testing events, given the complicated hardware and control schemes. Economic assessments show the project meeting zero-carbon hydrogen production options at $4/kg. The demand response is more than fast enough to meet signals from utilities, proving confidence and applicability of the technology.
- The progress to date is very good. The breadth of evaluation across the United States is particularly impressive, as this provides industry with critical information into strategic planning on how, when, and where we can anticipate the early adoption of this technology, as well as the likely impact and value to the grid operators.
- The data that are coming out of this project should help build solid business cases and analysis, based on reliable and trustworthy data sources for policy and decision makers. This work is the first of its kind and is going a long way to meet critical information needs.
- Controller design is an important accomplishment; it would be nice to actually see electrolyzer data or profile data to help with understanding how much the signal varies and how the electrolyzer responds.

Question 3: Collaboration and coordination

This project was rated **3.8** for its collaboration and coordination with other institutions.

- The project includes inputs from utilities (Pacific Gas & Electric, plus three others), multiple laboratory inputs from INL and NREL, and inputs from both Florida State University and California State University, which help in workforce development. California Air Resources Board input and a deep understanding of results both show extraordinary cooperation. Just the hardware build and system programming, along with the electrolyzer and equipment design build, show outstanding coordination and leadership in bringing together multiple organization cultures to meet goals on time and within budget.
- The engagement with the utility sector is an almost-unique aspect of this work. The real-grid-data-sharing is a critical piece of what makes this project likely to have a high impact, as decision makers will likely see significant added value in the validation with real-world grid operation dynamics.
- The description of collaboration with utilities, with specific descriptions of interactions, is good. Getting actual utility data for the models provides much more credibility to the results and the technical approach.
- A broader evaluation of the testing by the power utility industry representatives is recommended. It would be interesting to see if the utility industry agrees on the characteristics of the testing/simulations with respect to slow and fast response. These tests need to be representative of typical best/worst case scenarios and validated by the utilities. In the end, the value that this brings to the grid needs to be quantified. The direct impact on reducing hydrogen costs by taking advantage of demand response is only part of the value to the utility. The question that remains is how to put a value on the effect that the electrolyzer has on the power grid, with respect to frequency and voltage regulation, as well as the grid impact of having large-scale demand response capabilities.

Question 4: Relevance/potential impact

This project was rated **4.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is extremely relevant to California and any other states that are going to move from 30% variable renewable energy generation to 50%. Grid management is one of the major challenges to deep decarbonization. The open nature of the hardware will ensure widespread adoption beyond the United States to other countries with deep decarbonization plans and efforts. This will also allow lower-cost hydrogen production and accelerate zero-emission vehicle updates.
- The sustainable future of low-cost hydrogen is contingent upon understanding not only how grid-generated hydrogen adds value as a fuel or a feedstock but also how it adds value to the grid through storage and grid resilience. The outcomes of this and similar studies can help implement hydrogen as a mechanism to allow for further penetration of renewables, making all grid activities (including battery electric vehicles) more renewable. As such, it is important that we develop tools to determine the additional value to the grid that such services provide; it is strongly recommended that the team consider methods to quantify all of the value this can bring to the utility.
- This type of information is highly relevant to H2@Scale. Concrete demonstration that the electrolyzer hardware can actually serve this application is important, as it lends credibility for moving forward with the installation of large electrolyzers.
- This project is filling a critical information gap.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The project team's future work is relevant. The team will finalize project milestones by testing higher renewable energy penetrations and will work with Arizona state utilities, where there may be the largest single-point transportation fuel demand in the near future. Further exploration with other electrolyzer manufacturers will be key for proving the value of the open-source approach, as well as adoption outside of the laboratory-funded test demonstration project.
- Future plans are reasonable, and next steps are needed to provide a well-rounded picture across different geographic regions.
- The next phases of testing and validation are anticipated. The test plans look sufficient.
- There was mention during the presentation that the front-end controller allows coordinated aggregation of responses from multiple units to respond to utility grid demand signals. The concept appeared to be that several units could act in a coordinated fashion if the demand signal was greater than the individual units' capabilities. However, there did not seem to be any discussion of results or plan for future work with this concept. This seems like a very interesting aspect that should be included in the future work plan. Additionally, there should be other opportunities identified for electrolyzer operation in the project's scheme other than just renewable generation response. The potential for reaction in grids with low renewable energy generation, the reaction in emergency response, and the reaction on different grid scales (perhaps down to microgrids) could be useful in helping build additional cases for decision makers.

Project strengths:

- The strengths of the project are the potential impact with decision and policy makers and the information gap that this work is filling. These concepts are currently active in several discussions and planning meetings, deliberation gatherings, workshops, etc. The availability of this information is positive, especially the technical potential for electrolyzers and the business case analysis, which are crucial parts of the conversation.
- Major strengths are the coordination of key stakeholders and the addressing of a pressing problem of large-scale renewable energy and grid management. The open-source hardware and pursuit of multiple

electrolyzer vendors are outstanding. Workforce development through participation with state universities such as California and Florida also give value that is often overlooked.
- There is a good tie to energy demand maps and utility profiles. Controller development is a highly valuable achievement to enable these simulations. Challenges were well addressed.
- The development of the test hardware is a critical step in this development, and the progress to validate this has been quite good. The project brings high-value data and analysis to industry.

Project weaknesses:

- There were minimal weaknesses identified.
- One of the project's weaknesses was the validation of testing protocols; the project would be strengthened by having an independent evaluation of the test protocols by a broader cross-section of utility operators. Establishing a method to determine the value of voltage/frequency regulation to the utility is an important need. A comparison on a cost/performance basis of electrolysis versus other technologies to regulate the grid would be an important outcome. It is not apparent that electrolysis is the best solution to utility regulation and demand response. Quantifying and comparing with other technologies would be an important outcome.
- The only weakness of the project is that detailed analyses should have been completed for more locations. However, this seems more of a fundamental limitation of time and resources available than a weakness in the project's execution.
- It would be helpful to include more actual (unallocated) data.

Recommendations for additions/deletions to project scope:

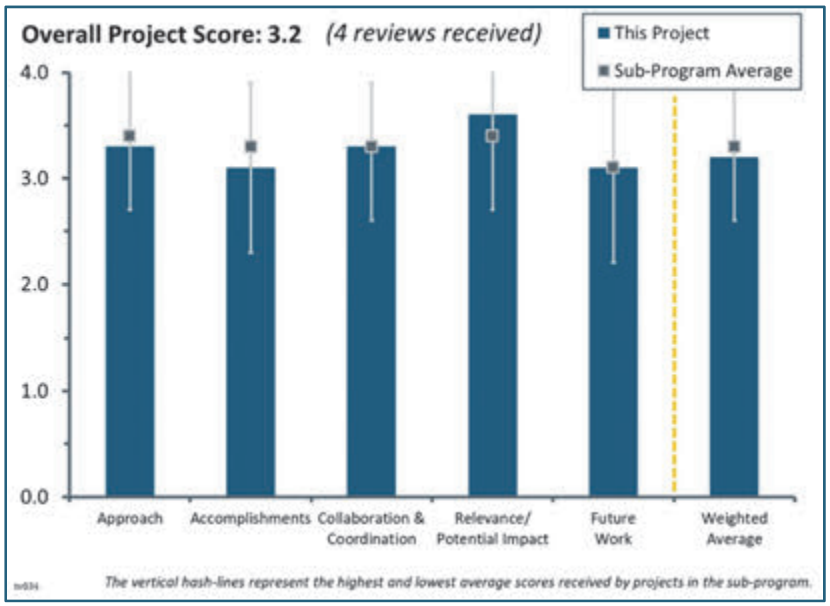
- If possible, it is recommended that the project add a comparative analysis of the technical and economic potential of electrolyzers to achieve the combined grid and transportation benefits investigated in this work, as compared to other technologies (battery storage, vehicle-to-grid and vehicle–grid integration, ultracapacitators, flywheels, etc.) seeking to achieve the same goals in various usage cases (including addressing high renewable energy penetration on the grid).
- It is recommended that the project increase the scope to work with the Arizona utility and other electrolyzer manufacturers and vendors to implement control communications hardware to the interface between the utility and the hydrogen production equipment.

Project #TV-034: Fuel Cell Hybrid Electric Delivery Van

Jason Hanlin; Center for Transportation and the Environment

Brief Summary of Project:

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



Question 1: Approach to performing the work

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

- The overall approach is excellent and consists of retrofitting a delivery van for fuel cell electric vehicle operation, shakedown testing, and demonstrating successful operation before moving on to producing an increased number for field demonstration, while making incremental improvements/changes in existing electric vehicle technology for the conversion.
- Both the approach and the planned work are sound. Developing a kit that can be used for new trucks and the conversion of existing trucks will help to commercialize the technology within this application (or similar applications). Two years is a sufficient amount of time to validate performance.
- This project has been very slow to progress, but the team does seem to have effectively addressed the issues that were causing delays, and there is a plan for moving forward onto the next phase. Fortunately (or unfortunately), the market for electric trucks has not progressed very quickly, so the project can still provide value. The ability to test the fuel cell van on routes with a range of other technologies is a major strength of the project. The need to develop a market study is questionable, however, as that is something that can be done by market analysts. The real value here is in developing and testing a vehicle and making the results available.
- The project has a reasonable approach. Owing to current delays with integration, the December 2018 milestone for the go/no-go decision point appears optimistic, as the integrator still needs to figure out the issues of the first prototype vehicle. It is recommended that the project team put more burden on the vehicle integrator to prioritize the development, testing, and operational support of newly developed components (direct-current–direct-current [DC-to-DC] convertor, etc.). This is to ensure that these components work and, if issues arise, that resolution receives internal priority.

Question 2: Accomplishments and progress

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

- Although the project has had early issues that caused the schedule to slip, the team has made significant progress over the last year. The prototype truck will be on the road and in service in the next few months.
- The project aligns well with DOE goals. Progress has been slow, but the project appears to be finally poised to begin demonstrations; therefore, progress has occurred on that front.
- There is good progress; however, it would be good to see that the rate of development and testing is accelerated/prioritized wherever possible for the next period. The truck is on-road as of the DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review, per the reference made during the presentation and the shared video (per the presenter making this available to those interested).
- Progress on this project has been slow—mostly because of delays in long-delivery items and in the custom DC-to-DC converter build-out. It is not clear why the build-out decision was made. It seems as though that could be an Achilles heel; it has caused delays and is a point of challenge in that it has not been field-tested for this application.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- The project has excellent partners that include solid original equipment manufacturers and a demonstration partner that can put the truck into service to validate performance.
- The collaborators/coordinators are good and appropriate for this project.
- It seems as though the project management of the partners improved over the past year.
- It is not clear whether United Parcel Service (UPS) was present and directly involved with other areas of integration, outside of the high-voltage and low-voltage wiring review. UPS staff could have acquired significant understanding of the vehicle system and have had even better insight and ability to support test the first vehicle.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The successful completion of this project is excellently aligned with the relevance and impact of developing and demonstrating a fuel cell powertrain in this application. The precise balance between the energy stored in the batteries and in the hydrogen is an optimization issue that is dependent on the cost, performance requirements, and duty cycle of this application. There are other projects addressing the optimization issue as part of this overall Program. It is suggested that the team look into optimizing the power systems after successful demonstration of the technology.
- This is a highly relevant and potentially impactful project because of the increased understanding of the operational range limitations of battery electric options in last-mile delivery vehicle space for medium-duty vehicles.
- The project aligns well with DOE goals and will help accelerate market growth for fuel cell technology in medium- and heavy-duty applications.
- The project still aligns well with DOE goals in supporting the development of fuel cell commercial vehicles.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- It is good to see that there is adequate funding to support six vehicles. Even if the original goal of sixteen may not be reached, six vehicles should still be adequate to provide useful data. The key is to keep the project moving. Further delays could make the technology developed under Phase I begin to look fairly obsolete by the time Phase II rolls around.
- The proposed future plans are good. However, given the delays in Phase I, it is suggested (in keeping with a previous reviewer comment), assuming a successful build, that the length of the demonstration of Phase I hardware be shortened and the number of vehicles in Phase II be reduced by a factor of two. The training of drivers and first responders is important, but when completed, this vehicle will (or should) operate in parity with conventional vehicles—purchasers of the Toyota Mirai do not get training.
- The future work is well planned to accomplish project goals. A six-month demonstration should be sufficient to evaluate the pilot truck, but there is concern this will not start soon enough to meet the go/no-go decision point of 2018.
- It is unclear whether the Linde Gases station in West Sacramento is ready to receive and facilitate the fueling of the first vehicle or if a number of steps still need to happen on the operational side (outside of training and fueling agreements). It would be good to hear that the project includes the effort of Unique Electric Solutions (UES) to accelerate the testing of the unproven DC-to-DC converter and verify the capability of this component. The DC-to-DC converter appears to be the wildcard component for the functionality of this vehicle. Fueling training time appears overly conservative, as Toyota Mirai drivers do not receive much, if any, fueling training.

Project strengths:

- The project is well-thought-out and should result in a positive outcome. When successful, it will be a powerful demonstration of this technology to the end users/operators of the parcel delivery industry. The commitment of some of the partners (for example, the Center for Transportation and the Environment) in ensuring that financial resources are available for completion is notable.
- This project has a good team with the right balance of capabilities to execute the project, proving that fuel cell technology in this application can be carried into other medium- and heavy-duty truck applications. The economic assessment planned will be a valuable input to the industry.
- The project concept is still valid, as there is a real need to find zero-emission technologies that can meet the demands of a typical delivery van. It appears that the van will be tested on different types of delivery routes, which is also a strength. Although the need to develop a DC-to-DC converter for this van was the cause of major delays, this may end up as a net positive if the converter works well.
- This project's strength lies in fuel cells as range extenders in medium-duty last-mile delivery vehicle service. Both the collaboration with UPS and the use of actual route data were also strengths.

Project weaknesses:

- The uncertainty of full funding for the second phase of the project is unfortunate. Even with the smaller number of trucks, the project is expected to provide valuable input to the industry.
- Most of the problems with this project appear to be mostly out of the project management's control. With that said, it would have been assumed that mitigation measures would have been put in place to mitigate these issues. For example, labor and administration costs during delays should have been anticipated and a contingency put in play.
- The project's weaknesses lie in the delays in getting to the demonstration phase, the limitations of infrastructure availability, and the funding shortfalls. It will be important to stay on schedule over the next year. It may be that the six-vehicle demonstration is sufficient and the full sixteen vehicles are not needed, but this work does demonstrate the risks of funding a project in which the partner providing matching funds can withdraw its commitment so readily.
- The DC-to-DC converter has so far been untested. Funding for the next project phase is undetermined.

Recommendations for additions/deletions to project scope:

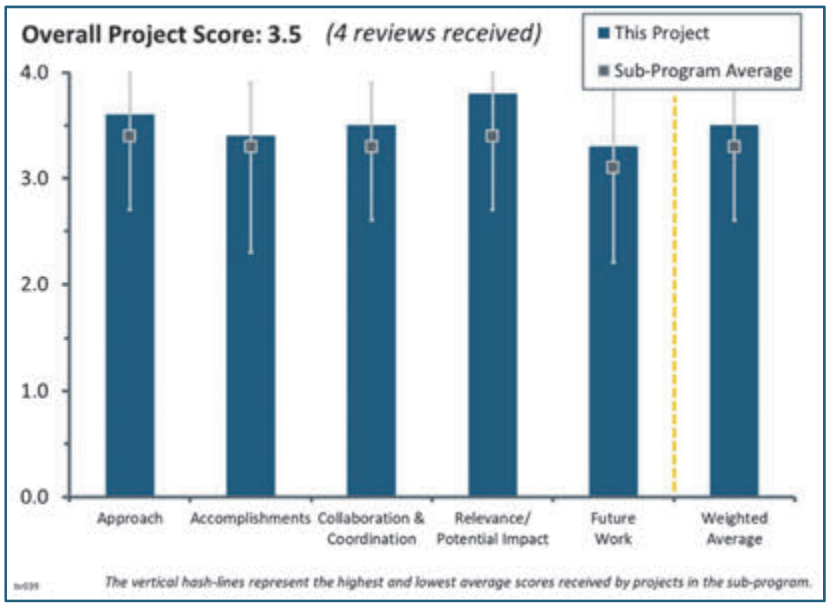
- There are no recommendations for Phase I, but the Phase II plan could potentially leave out the market study and focus only on the demonstration, data collection, and data analysis.
- Assuming successful vehicle completion, it is recommended that the length of the shakedown/ demonstration for Phase I be shortened and the number of vehicles in Phase II be reduced by a factor of two. Also, it is recommended that this team consult with Argonne National Laboratory to optimize the energy storage and powertrain split between batteries and hydrogen to produce an optimized balance consistent with performance requirements, driver expectations, etc.
- The project team should address whether it is feasible to switch to 700 bar hydrogen tanks for added range. This would also lead to more fueling opportunities with current stations in California. The team should encourage the integrator to commercialize the new/custom DC-to-DC converter. This could help alleviate issues with parts availability and potentially lower future cost.
- It is recommended that the project team accelerate testing and that UES prioritize solving issues with the custom DC-to-DC converter.

Project #TV-039: Innovative Advanced Hydrogen Mobile Fueler

Sara Odom; Electricore

Brief Summary of Project:

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



Question 1: Approach to performing the work

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

- Mobile fuelers are a great way to kick-start the buildout of a fueling infrastructure. There have been a number of mobile fuelers developed in the past. This concept uses proven existing hydrogen fueling station concepts and hardware and fits on a flatbed 45-foot trailer. This station has already been designed to satisfy the SAE International (SAE) J2601 fill protocol, and SAE 2719/International Organization for Standardization (ISO) 14687 fuel quality specifications with a point-of-sale system. This concept/approach to the development of a mobile hydrogen fueler is excellent. The approach is well-thought-out and clearly developed by a team that has experience in these types of projects.
- The approach includes how the refueler will support the lack of hydrogen refueling backup in the northeastern United States. The approach stands to solve the technical issues of hydrogen storage on board a trailer. The approach is based on codes and standards. The specifications were approved by the U.S. Department of Energy (DOE), the components selected, and long-lead-time components ordered, and the final design documents were also approved by DOE. The Hydrogen Safety Panel reviewed this project, and initial hazard analyses were completed.
- This is an excellent plan to address the barrier of hydrogen access for light-duty fuel cell electric vehicles (FCEVs).
- The project approach looks reasonable. For future presentations, the principal investigator (PI) should mention capability to plug in the fueler to 480 V, three-phase to run the compressor, instead of relying on a diesel generator to provide power.

Question 2: Accomplishments and progress

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

- This project addresses energy consumption of the mobile refueler, which is an overarching DOE goal. The DOE goal of hydrogen infrastructure buildout is addressed, for when completed, the project (trailer/ refueler) can be used to educate hydrogen producers, testers, and users about codes and standards for mobile refueling. This project contributes to the DOE H2@Scale approach: transportation component (the

plan is to be able to fill 20–40 cars daily). Regulatory requirements for transporting hydrogen on U.S. roads, at least in the Northeast, will be discussed and resolved with this project (addressing regulatory barriers and the goal of addressing any unreasonable barriers).
- Largely, the project is on schedule, making excellent progress and not withstanding a small delay because of the liquid nitrogen (LN2) cooling system design effort. However, it is probable the overall system and operation will be better. This should not be a major issue, and the project will finish as scheduled.
- The team has made excellent progress toward meeting project objectives. The project has had no significant delays to the schedule.
- In addition to energy consumption reduction, use of LN2 also helps with economics. It will be interesting to hear whether the U.S. Department of Transportation (DOT) approves a special permit, which will benefit the industry at large if approved. Slide 8 indicates the trailer is not delivered, which appears to conflict with slide 9 information that the trailer is 95% complete.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- The team has a good balance of technical expertise from original equipment manufacturers and consultants. It will be good to see the addition of a site partner for demonstration. Selecting the right location/partner will be important to ensuring success and gaining acceptance of this hydrogen fueling technology.
- The project has exactly the right number and type of collaborators to ensure a successful project execution.
- It appears collaboration and coordination are well covered. The PI could possibly consider collaboration with the California Department of Food and Agriculture Division of Measurement Standards for preliminary discussion about metering and meter calibration on a mobile fueler.
- The planned collaboration includes NREL (data collection), automotive companies (Toyota was mentioned), the Hydrogen Safety Panel (Safety Plan review), DOT (permitting), and a tank company (Hexagon Lincoln was in the report but not the verbal presentation). The team needs to conduct more outreach. Perhaps the team could contact hydrogen refueling station developers, metering agencies, and automakers. It is unclear whether there can be a common approach for quality testing and evaluation of metering in the states where hydrogen infrastructure is being rolled out.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Developing mobile fuelers is an excellent way to help kick-start the deployment of a hydrogen fueling infrastructure. They can be used to augment stationary hydrogen fueling stations and provide redundancy when needed. Indeed, mobile fuelers make up a major part of other countries' strategies for early deployment of a hydrogen fueling infrastructure. The relevance of this project/concept for strategic hydrogen fueling infrastructure deployment is extremely high. Indeed, this project will be establishing new permits (DOT exemption for high-pressure hydrogen transport) and construction of high-pressure (95 MPa) hydrogen transport cylinders that can be used in the future by other similar activities. This is excellent.
- This project is relevant as a backup and emergency fueler for the hydrogen refueling infrastructure in the northeastern United States. The need for backup relates to potential station downtime when the cars are introduced in the Northeast. The goal is to use the refueler to support stations beyond 2020. The team plans to release the refueler in 2019. The refueler can be a model for others to follow, as more refuelers will be needed in the United States with the proliferation of FCEVs.
- This is an excellent project with significant potential impact and relevance—particularly the DOT special permit and the ability to reduce the packaging/footprint size of a small hydrogen station.
- This project is well aligned with DOE goals and objectives. Providing access to hydrogen fuel is extremely important to gaining public acceptance and increasing awareness.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project is under way to meet the 2019 deployment. The project managers report cost overruns, so more attention is needed for cost accounting in future work. The future work reportedly includes coordination, testing, and evaluation with a Nationally Recognized Testing Laboratory in "preparation for listing," which entails completing the design, equipment procurement, and refueler operation. It seems like there are cost overruns. The permit for the transport of 100 MPa is needed. The question becomes how much more it would be to pay for this project, based on the results thus far.
- Perhaps a 95 MPa storage location under the compressor box could also be applied at stationary/permanent retail stations to reduce the footprint. This appears to be a design concept that is already implemented at compressed natural gas (CNG) stations to reduce the footprint needs (this may be something with which Bauer Compressors can help). The PI did not mention grounding, and it is unclear whether this will be a typical grounding rod, as installed by a general contractor/electrical contractor. It may be good to address this as part of logistics to site the AHMF; it is a requirement for existing 35 MPa mobile fuelers. It is unclear how the AHMF can be used to facilitate 70 MPa medium- and heavy-duty FCEV demonstration projects.
- The proposed future work plan will keep this project on schedule, yielding exactly what this project started out to do: build an advanced, fully functional mobile fueler. The project is compliant with the appropriate filling protocol (SAE J2601) and fuel quality (SAE 2719/ISO 14687). This system will undergo the same performance testing and qualification already established (i.e., the CSA Group's hydrogen dispenser testing apparatus and/or the NREL/California Air Resources Board's Hydrogen Station Equipment Performance [HyStEP] testing device).
- The future work is well-thought-out. It would be good to see a longer demonstration period.

Project strengths:

- The deliverable (i.e., mobile fueler) is based on existing stationary hydrogen fueling systems; mounting this on a flatbed trailer is excellent. The execution plan is excellent and should yield an excellent system on time. The team is very committed and dedicated to the success of this project. For example, the industrial partner on the team absorbed an increase in costing resulting from issues with the LN2 cooling system. The cost absorption kept the project moving forward in a timely manner without an increase in cost to DOE.
- This is a good team that is well capable of carrying out the project. This is a good solution to the barrier of fuel access in the early stage of the market. This project could enable potential users to "try before they buy." The project results would help potential users get comfortable with the technology while they plan for a fixed station.
- This is the first small station size 70 MPa mobile fueler that meets the SAE J2601 H70-T40 fueling protocol. A DOT special permit for 95 MPa efforts is also a strength. In addition, footprint reduction efforts provide fueling in a variety of locations with swift installation after permitting is completed.
- There is a need for refueling. The project is standards-based, and there is an interest in practical considerations (weight). The goal of data sharing is also a strength.

Project weaknesses:

- It would be helpful for the PI to clarify for reviewers (as well as potential site hosts) how refueling of buffer storage occurs. In California, operation with a diesel generator may be challenging in 2020 (even for low emissions). Therefore, there is a need to emphasize capability for plug-in of a system. It is unclear how operating expenses are expected to compare to those of permanent retail stations.
- It would be good to see longer a demonstration period. It is unclear whether the system can be scaled up to supply fuel to larger vehicles. The team should consider using this for medium- and/or heavy-duty vehicles.
- Cost controls are needed, cost overrun is reported (verbally during the presentation), and there is no clear path for permitting,

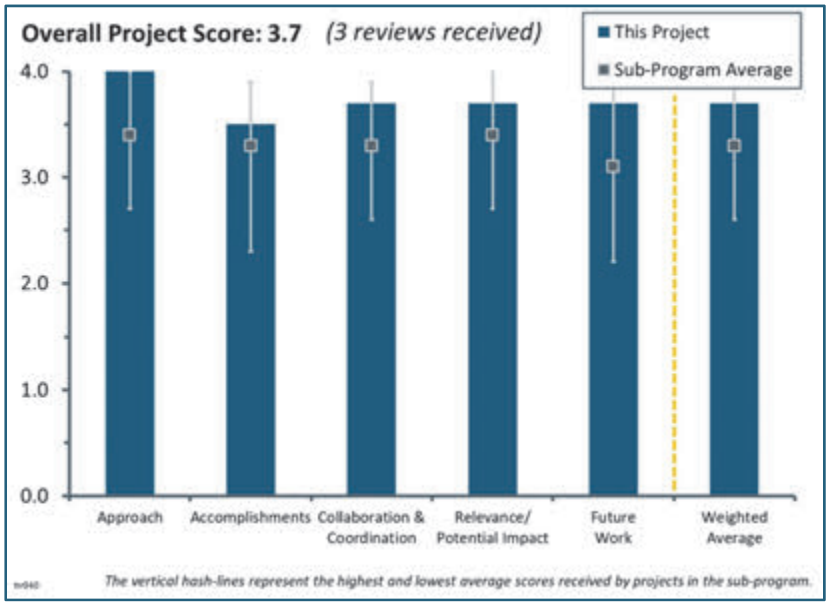
Recommendations for additions/deletions to project scope:

- A roadmap to integrate with existing stations in the northeastern United States should be added. Permitting contacts are needed. Plans for maintenance were not verbally presented but most likely exist. Plans to keep the refueler at a site operated by one of the project partners were presented, but it is uncertain what the accessibility for others would be if the trailer were kept at this location. It is unclear what the fuel distribution plan is for the location mentioned.
- The team should consider transferability of "under compressor box 95 MPa storage" on the AHMF to permanent retail station designs that may help reduce the footprint (already practice for select CNG station providers).
- It would be good to have a longer demonstration period. The team could publish the experience from demonstration partners; this could include how well the station met the user expectations.

Project #TV-040: High-Temperature Electrolysis Test Stand

Richard Boardman; Idaho National Laboratory

Brief Summary of Project:



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

Question 1: Approach to performing the work

This project was rated **4.0** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach of developing a 25 kW test stand followed by a 250 kW unit is logical and reasonable.
- This project is focused on providing data to fill in information gaps in the implementation and demonstration of high-temperature electrolyzers. It is also noteworthy that the project is sizing the testing equipment to balance costs (smaller systems) and physical/commercial relevance (larger systems). There is a bit of concern as to whether the synthetic fuels portion of the project might distract from the more fundamental electrolyzer operation characterization. However, for the moment, it does not seem to be a severe impediment. It is also very good that this project is leveraging advancements made in the similar low-temperature electrolysis project and making the most of the resources there by implementing the same front-end controller developed in that project.
- The rationale for two reactor scales was well presented. A critical scale is required to be able to measure the relevant effects without unnecessary expense. Controller design is typically a critical component of a project like this and has appropriate focus to provide the most relevant information.

Question 2: Accomplishments and progress

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

- The project appears to be progressing well, with a reasonable progression of scale in the equipment tested, and the first of those equipment-testing phases beginning soon. With a project horizon to 2020, this appears to be satisfactory progress. There was a mention that the project's continuation is determined annually through DOE consideration.

- The project appears to be on schedule for the 25 kW test unit. It is not clear about the plan for the 250 kW unit.
- The project is slightly behind but on a good track.

Question 3: Collaboration and coordination

This project was rated **3.7** for its collaboration and coordination with other institutions.

- The mix of collaborators seems thorough and appropriate. It was not entirely clear what the role of Exelon in the project was. This project appears to have many parallels with the similar low-temperature electrolysis project, in which partner Pacific Gas and Electric is helping with real-world grid operation data. It was not entirely clear whether Exelon was filling a similar role or only acting in an advisory role. Any amount of real-world data and operation information Exelon is able to support and provide should be enthusiastically pursued.
- Collaboration with each entity was described well. There was good interaction with other national laboratories, stack suppliers, and grid operators.
- It is not clear about the collaboration with suppliers/developers of HTEs.

Question 4: Relevance/potential impact

This project was rated **3.7** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is important in showing both technical feasibility for solid oxide electrolyzer cell technology, as well as improved technoeconomic data for market viability.
- It is critical to have reliable and versatile test units for HTE technology.
- While the project does meet overall DOE objectives and is a valuable project within its field, it is hard to see the higher-level initiative as mission-critical. With the recent history of the development of the energy industry, both domestically and internationally, it is difficult to see a future with a large nuclear power presence. This project may lead to some insights that could build better-informed cases for when and where the technology might fit in better than expected within most projections of the future energy market. However, at the moment, it is difficult to say with certainty that this will be mission-critical to the success of hydrogen as a fuel in the future.

Question 5: Proposed future work

This project was rated **3.7** for its proposed future work.

- Next steps for the project are clearly defined, and continued engagement with industrial advisors is planned.
- As with the overall approach for the project, the plans for future work are well ordered and logical.
- If "Support of the advancement of HTE stack technology...." is one of the objectives of this project, no plans and discussion of approaches were given in the presentation.

Project strengths:

- This project has good engagement with industry and fills a clear gap in the ability to test large prototypes for HTE.
- The strengths of the project are its likely relevance for the industry, the technology that is being demonstrated, and the way in which the project is intelligently leveraging complementary work completed in other projects.
- This project is logical and has a well-defined approach.

Project weaknesses:

- No major weaknesses are noted for this project.
- The project's weakness is the uncertainty in the ultimate relevance of the technology in the developing energy market, especially given the latest trends. This does not mean the work should end; it just does not seem mission-critical.
- The project's weakness is that its scope is unclear.

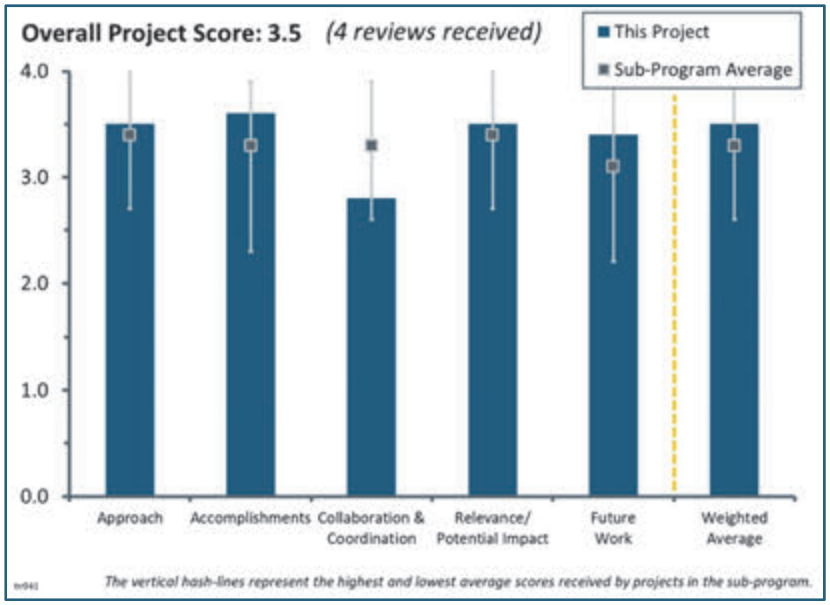
Recommendations for additions/deletions to project scope:

- Since the project has already installed the synthetic fuel production skid, no change is recommended at this time. However, at an earlier stage of the project, the project might have narrowed the scope by not including this additional aspect.
- The project should have a better definition for the effort "Support the advancement of HTE stack technology for robust performance…"

Project #TV-041: Modular Solid Oxide Electrolyzer Cell System for Efficient Hydrogen Production at High Current Density

Hossein Ghezel-Ayagh; FuelCell Energy

Brief Summary of Project:



This project seeks to demonstrate the potential of solid oxide electrolysis cell (SOEC) systems to produce hydrogen at a cost less than $2 per kilogram, exclusive of delivery, compression, storage, and dispensing. Project activities aim to (1) improve SOEC performance to achieve greater than 95% stack electrical efficiency based on lower heating value of hydrogen, resulting in a significant reduction in cost of electricity use for electrolysis; (2) enhance SOEC stack endurance by reducing its degradation rate; (3) develop an SOEC system configuration to achieve greater than 75% overall (thermal and electric) efficiency; and (4) improve subsystem robustness for system operation compatible with intermittent renewable energy sources and their load profiles.

Question 1: Approach to performing the work

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

- The approach of developing the single cell, stack, and then the overall system is very straightforward and appropriate.
- The approach is well designed and appropriate for this type of work.
- The approach is complete and very organized.
- The project seems to be more of a technology or product development project than a technology validation project. The technology development work is reasonably laid out. A technology validation project would have more on-line operating time, along with multiple stacks to conduct statistics. The slides stated that the approach was a "top-down" type of approach, but since the project starts with the cell and moves to the stack, it seems more like a bottom-up approach. Overall, the approach is appropriate for a technology development activity, not for a technology validation project. At minimum, the team should have had multiple stacks to do statistics.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project team has made excellent progress, considering the complexity of the work.
- The project is on track and is very well aligned. The team has made excellent progress.
- The cell and stack testing results are very positive, and the parametric studies are very interesting. The team did more testing than the milestones required and had some very interesting data. For the degradation mechanisms report on slide 10, it would have been interesting (1) to state where the Ni was going and (2) to

explain what the reaction layer forming in the anode was. Furthermore, the go/no-go data was not consistent with the cell and stack performance data. For example, on slides 9 and 10, the cells show degradation, and on slide 11, the stack shows degradation; yet when the project team reported the go/no-go, the cell showed no degradation. This test should be repeated to see whether the team can replicate the excellent performance. The stack should also be analyzed to see whether the team can determine why the result is so positive and how to replicate it. The robot assembly consists of very nice work and is a good accomplishment. It seems to be more part of a manufacturing development effort, rather than a technology validation effort. The system is designed to operate at 5 bar, which is a very good accomplishment. The assumption that 200°C waste heat will be available does not seem very realistic. For a chemical engineer, this waste heat could be used somewhere in the plant; a more reasonable assumption is 110°C–125°C waste heat.

- The team appears to have made very good progress in the past year. One helpful aspect for performance evaluation would be the establishment of a cell baseline performance, as a reference, on each of the data performance slides.

Question 3: Collaboration and coordination

This project was rated **2.8** for its collaboration and coordination with other institutions.

- Collaboration is an area of weakness in this project, which would be significantly strengthened if a third-party partner were involved in the technical evaluation, and especially in the technoeconomic analysis (TEA). The technology under development has the potential to change the market; therefore, it is important to have credible and independent verification of the performance and economics. With the addition of a third-party evaluation, this could be a top-tier project in the Hydrogen and Fuel Cells Program portfolio.
- The collaboration is not clear. It is unclear whether a wholly owned subsidiary counts as a collaborator, but that is up to DOE.
- There is not a lot of collaboration per se, as it is essentially one company, and the role of the National Energy Technology Laboratory (NETL) is indirect.
- The role of NETL in this project is unclear.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This technology has the potential to change the market in the hydrogen economy development. The project has the potential to meet DOE goals while also addressing power issues related to grid-generated hydrogen, providing a compelling alternative to natural-gas-to-hydrogen (via steam methane reforming), as used today.
- When successfully completed, the project should have significant impact on the advancement of high-temperature electrolysis technology.
- High-temperature electrolysis is definitely relevant to Fuel Cell Technologies Office goals.
- This work may certainly have some impact on the market (when scaled up), but it is a technology development project, not a technology validation project (as indicated by previous reviewers and agreed to by the project leads).

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The project seems to have addressed all barriers and is now working to address technical challenges.
- The proposed future work is relevant and appropriate.
- The prototype performance testing and the TEA of the overall system performance will be critical deliverables for the project and should be given the highest priority.

- The project team plans to test the stack over long periods. It would be nice multiple stacks could be tested so the team could calculate some statistics. The team members should see if they can replicate the very interesting results obtained from their current stacks.

Project strengths:

- This project has unique technology that leverages the natural-gas-to-hydrogen reforming method while producing power. This could be a significant game changer in the industry as we begin to reach the limits of renewable penetration in the grid and run into dollars-per-kilogram issues with electrolysis. Some regions of the country will have significant opportunities for this pathway.
- The project team is doing research on a very important area. The team has a good deal of experience, and the project itself is well funded and has demonstrated good durability.
- The project has a well designed and logical approach to addressing the technical barriers.
- This project is innovative and is moving along well.

Project weaknesses:

- The project does not have any partners other than a wholly owned subsidiary. Also, the researchers are not doing any statistics. This is especially important for the stack that was used for the go/no-go and showed interesting performance. The project team needs to figure out why the stack is performing as well as it is and replicate the performance.
- The project would be strengthened by independent evaluation of the TEA results. Many questions from reviewers on the technical validity of the results in the areas of energy integration and overall process efficiency could be addressed by the addition of a partner to complete/validate the results independently.
- Details on certain approaches (e.g., how to reduce performance degradation) are lacking.

Recommendations for additions/deletions to project scope:

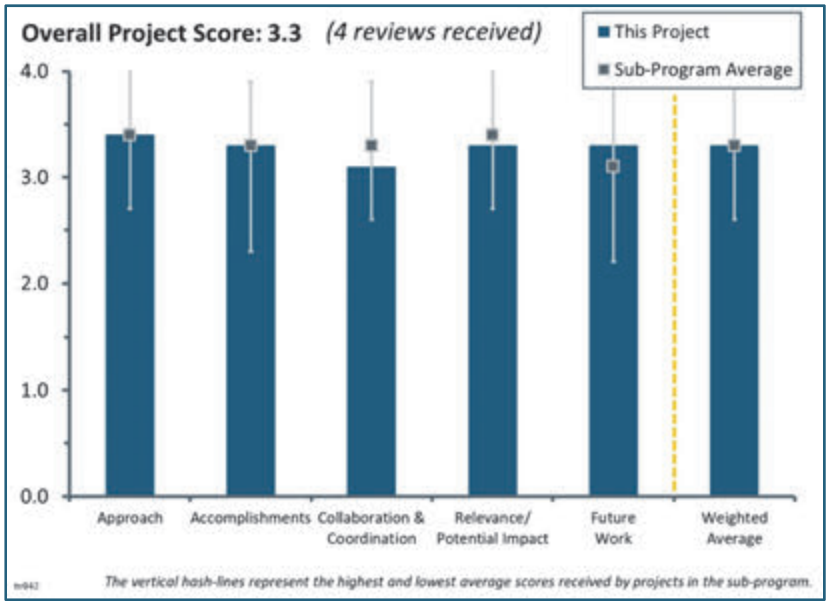
- The project team needs to do more technical evaluation (such as performance replication).
- It is recommended that the team define priorities and provide more details on future work.

Project #TV-042: Optimal Stationary Fuel Cell Integration and Control (Energy Dispatch Controller)

Genevieve Saur; National Renewable Energy Laboratory

Brief Summary of Project:

Current control strategies for building systems tend to be simplistic. The objective of this project is to create an open-source, novel energy dispatch controller to optimize the dispatch of different building components such as combined heat and power, storage, and renewable generation systems. Such a controller, which will incorporate improved forecasting capabilities and model predictive control strategies, would enable these building systems to participate in grid ancillary services markets. A planning tool for sizing building components utilizing simulated dispatch will also be developed.



Question 1: Approach to performing the work

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

- The project has a clear approach to working with multiple technologies, including fuel cells, to optimize cost and reduce energy use. The use of dynamic schedules is the right approach to find optimum building operation, reduce cost, and facilitate more renewable energy integration while saving money. The clear target of reducing fuel cell costs and operation shows the value of the work. The cross-functional approach is very valuable, given the integration of multiple disciplines across fuel cells, buildings, grid integration, and renewable energy production. The predictive control to help manage temperature setpoints with minimal intervention is critical to widespread uptake and not relying on steep learning curves from the occupants. The model structure is comprehensive and covers all the major energy consumption levers for reducing cost.
- The project approach is well aligned with the project goals.
- The approach is well designed and appropriate.

Question 2: Accomplishments and progress

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

- The effort to simplify the building and get to a reduced order model that is easier to integrate is an important first step to integrating and validating the model. Deep modeling of building dynamics and temperature of various subcomponents with different rates of heat transfer shows attention to detail and the challenge of optimizing multiple inputs. The co-simulation model used by industry should allow for easier implementation to the combined model and make it easier to explain how the model works, as industry already uses this model for managing energy use.
- The accomplishments of this project seem excellent; however, the communication of the actual accomplishments versus simply results makes evaluation challenging. This project seems to be

concentrating on the development of a model, which leaves the accomplishments lost in model details, rather than demonstration of the impact of the technology. The observer is left to infer too much from the results. It is also difficult to determine how the efforts to improve the model are accomplishments. It is not clear what issues were addressed or how the efforts improved the current state of the art.
- This project shows good progress, but it is unclear how the challenges of this complex issue will be addressed to meet the overall project and DOE goals.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The project shows outstanding collaboration among various laboratories, universities, and industry. The cross-functional and cross-discipline effort requires clear goals and directions to meet project milestones and to validate the model. The extensive panel of collaborators and project advisors shows a well-rounded group required to get to comprehensive testing and evaluation.
- There is excellent coordination with other national laboratories. Improved interaction and collaboration with industries are necessary.
- The collaboration partners are all focused in research. The lack of clarity in results, the lack of focus in research, and the overall poor communication of efforts in this project seems attributable to the lack of diversity in the project partners. Dissenting opinions and relevance to industry for adoption of results are critical to strong project impacts; otherwise, the project becomes an interesting exercise with no net impact.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is quite relevant to DOE goals for saving energy and supporting the commercialization of fuel cells. The project has three clear impacts: grid modernization, building control, and fuel cell deployments. The efforts of this project are very relevant and, when validated, have the potential to save significant energy, considering building energy use is one of the top sectors of energy use.
- When successfully completed, this project will have a significant impact on the ways building energy is managed.
- This project could have a significant impact on the barriers it seeks to address. However, the lack of clarity in the information, the lack of focus, and the lack of diversity in collaborators significantly restrict the realization of this impact.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The next steps will be critical to playing out the value of the project. All the parts will come together and will have to be validated and integrated into an actual case study and application. The reduced order model will have to be finalized to the depth needed, followed by integration with the co-simulation model where testing is completed.
- The proposed future work is consistent with the project plan.
- The proposed future work is focused solely on continued levels of detail for the current effort. The researchers should consider efforts that improve the impact and relevance of the work and seek partners to help guide the future work, rather than just following the science to the next level of detail.

Project strengths:

- Building efficiency and integration of fuel cells has been demonstrated globally as a tremendous potential benefit. The use of grid modernization as a vehicle to promote and promulgate fuel cell technology into

building efficiency improvements has significant potential. Thus, this work has the potential for significant impact.

- The project's number one strength is the integrated nature of multiple disciplines and the bringing together of different expertise to solve energy consumption. Building management, fuel cells, and renewable energy can all be optimized only when each area has a tool, as developed through this project, that allows seamless real-time communication, or predictive modeling.
- The project has a well-designed and appropriate approach.

Project weaknesses:

- The project's weakness is the challenge of relying on a third party to take source code and bring a viable commercial product to market that can actually be implemented outside of the laboratory resource framework and expertise.
- Despite the potential for significant impact, the project is not well positioned to provide that impact. It is not likely that this project will uncover a significantly unknown aspect of fuel cell integration or grid modernization benefit. The project is most beneficial in the demonstration of opportunities for these technologies. Thus, the project needs a stronger component of information promulgation and a better understanding of the barriers to technology implementation. It is unclear what the barriers are in the promulgation. It is also unclear what commercial partners need to understand from this research to realize the benefits. Lastly, it is unclear how this project can address those needs. A steering committee composed of commercial partners or workshops with commercial partners to determine the needs are both potential methods to realizing the project's potential.
- The project shows minimal interaction and collaboration with industry such as energy companies, building management companies, and architecture/building design firms.

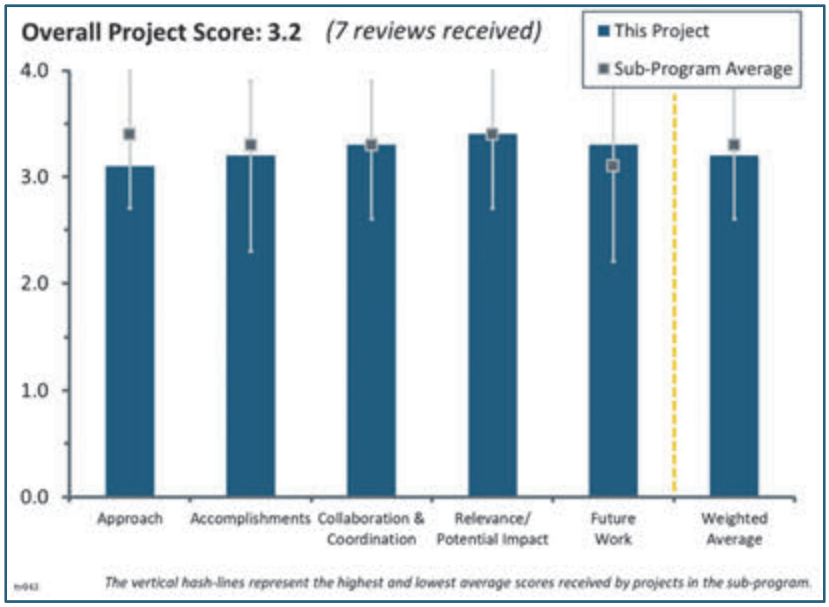
Recommendations for additions/deletions to project scope:

- The team should add scope to support implementation of source code in preliminary hardware to allow the start on the pathway to commercialization on top of low-cost open-source hardware.
- More interaction/collaboration with energy management companies and architecture/design firms is recommended.

Project #TV-043: Integrated Systems Modeling of the Interactions between Stationary Hydrogen, Vehicle, and Grid Resources

Samveg Saxena; Lawrence Berkeley National Laboratory

Brief Summary of Project:



Hydrogen technologies offer the unique ability to simultaneously support the electricity and transportation sectors, but the value proposition for such systems remains unclear. This project is developing an integrated modeling capability to establish the available capacity, value, and impacts of interconnecting hydrogen infrastructure and fuel cell electric vehicles to the electric grid. The potential to support the grid and the potential to balance resources from flexible hydrogen systems, such as dispatchable production of hydrogen by electrolysis, are quantified. The project is also developing methods to optimize the system configuration and operating strategy for grid-integrated hydrogen systems.

Question 1: Approach to performing the work

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

- The approach is good in couple of key ways: (1) it relies on existing (and presumably validated) models for many of the inputs, rather than attempting to recreate them, and (2) it is comprehensive in dealing with electrical inputs and vehicles needed.
- While this is nominally a Technology Validation (TV) project, in actuality it is a Systems Analysis (SA) project. Not surprisingly, the "barriers addressed" (slide 2) are not specifically included among the technical barriers cited in the TV section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan (MYRDDP). This project does address selected barriers cited in the SA section of the MYRDDP. The hydrogen–vehicle–grid-integration model (H2VGI Model) utilizes and builds on a foundation provided by prior work on other models. The approach, as summarized in slides 5 through 8, seems comprehensive and impressive. While the cost is significant, and there is concern about overlap with other analysis and modeling efforts, as an SA project, the approach likely warrants an "Excellent," or even an "Outstanding." However, it is minimally responsive to TV objectives. Therefore, the compromise is an evaluation of the approach as "Good."
- This is a great approach to the effort of looking at integrated transportation and grid hydrogen production. There may be some challenges with bringing together so many models, with complicated assumptions, to reach transparent and "realistic" results.
- The team has made good use of real-world data (driving diaries and National Renewable Energy Laboratory [NREL] composite data products on refueling behavior) to input into the model. It would be good to see more information on what the "H_2 fueling station as a flexible load" profile looks like. It would be helpful to start with the U.S. Department of Energy target price for hydrogen and see whether the scenarios can be narrowed down to a few that look like they hold the most promise in achieving that target.
- The project is looking into the technical potential to flatten the duck curve using surplus electricity to make hydrogen and, in the H2G scenario (a reversible electrolyzer), to make hydrogen or supply electricity back

to the grid. This study goal is worthwhile. However, the approach does not seem to integrate cost into the picture. The duck curve seems to be exclusively for central electrolysis, yet the next slide indicates that distributed electrolysis is half the price. It is not clear whether the project also included distributed electrolysis in the duck curve analysis—and if not, why not.
- The approach of this project is appropriate and reasonable.
- The main issue (and reason for the grade assigned) is that much of the purpose of the project is to examine issues that industry can address, yet the two partners are national laboratories rather than industry. The project team will develop a model with little indication that the model data will be vetted well by suppliers and other industry.

Question 2: Accomplishments and progress

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

- Dr. Wei's presentation (slides 9 through 14) conveys a message that modeling results from the project have excellent potential to be beneficial for both government and industry stakeholders. Practical applications, and important questions, are helping to guide some complex and sophisticated modeling work. Without further study, this reviewer is not qualified to comment on the model's design, methodology, assumptions, inputs, etc.; however, the capabilities of the investigators and analysts at the national laboratories involved provide confidence in the results, including those highlighted and summarized in the presentation. Performance indicators for a project of this type are inherently not clear and measurable. Slide 8 perhaps comes closest to a statement against which to measure project accomplishments. Based on that statement of activities and questions, there has been excellent progress in achieving project objectives.
- The project has made good progress toward goals by showing preliminary cost numbers, even if the numbers were not entirely expected, with distributed generation's being lower-cost than centralized production. Sub-model development and integration has been completed within the expected time. Preliminary case study results have been peer-reviewed.
- The work being published in the *Journal of Power Sources* is very informative, and the publication will be the first time that utilities have concrete information with which to begin thinking about hydrogen as integrated with the grid.
- The accomplishments and progress of this work are very relevant, and the assumptions are clear.
- In slide 8, the main takeaway seems to be the limited benefit of electrolyzers for peak shaving (rather than the stated takeaway of the analysis being conducted for the first time). It is not clear whether the presenter was saying that the impact of electrolysis is significant or only modest/minor. The impact seems limited. The presenter's comparison of central vs. distributed was interesting and noteworthy. It supports analysis done many years ago (but presumably with undated assumptions). However, the assumptions are not clearly shown. While a comprehensive display of all assumptions is impractical, additional information should still be included (at least in the backup pages). On another note, the feedback gained from stakeholder outreach is excellent.
- The construction of the model, the use of real-world inputs so far, and the use of the webinars to gather stakeholder information are significant accomplishments. It would be good to see more sensitivity analysis of electrolyzer capital cost vs. capacity factor. It would be helpful to know what happens to costs if electricity is very cheap during the peak solar hours but the electrolyzers are run only at those times.
- While observations related to the study and inputs can be and were measured, it is not clear how the project itself can be measured, as clear and measurable performance indicators on the project do not appear evident. To that end, the lack of project assessment, rather than the inputs, is the project weakness.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- The use of the stakeholder webinars is an exceptionally good way to validate the approach, inputs, and scenarios. It would be good to reach out to multiple utilities; several seem to be looking at grid support and the potential of dispatchable loads.

- The workshop with industry participants greatly improves the diversity of collaboration.
- This is a difficult analysis project, and the team seems to have coordinated with other institutions quite well.
- The partners on this project are all DOE national laboratories. Evidently there is no cost share; DOE is paying 100%. The TV section of the MYRDDP states that projects are 50–50 cost-shared between the government and industry. On the positive side, project managers conducted two webinars, during which representatives from industry, academia, and government provided feedback and inputs. In response to a question, Dr. Wei indicated that project managers recognize the importance of sharing results with, and receiving inputs from, potential stakeholders. Project managers from the three laboratories involved are collaborating well on integrating the models and related activities that are important for this project's success.
- The grade assigned was a compromise, as the two partners undoubtedly worked closely with each other (supporting a higher grade), but there is little indication that the two partners worked sufficiently with others (therefore calling for a lower grade). While support from the Hawaii Natural Energy Institute (HNEI) is documented, little information is provided about who the other twenty or so webinar participants were or what the participants from industry, academia, private research (not defined), and government provided. Worse, there was a total of two webinars, and except for the support from HNEI, it is unclear what other additional collaboration existed for the $1.65 million effort beyond the work of the two laboratories.
- There is coordination of multiple laboratories as a result of so many models being integrated and used for inputs. The project could use additional industry or regulator input to ensure adoption outside of modeling efforts.
- The project should keep involving industry, especially the Electric Power Research Institute and utilities.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Because this is a difficult topic to analyze, systematic analysis has been limited. Better understanding of how various modes of production can integrate with grid demands is key to successful hydrogen implementation. Thus, this project is relevant and will have a significant positive impact.
- This project strikes at the heart of the discussion in California and is appropriately scoped to evaluate that early market. This project has significant relevance and potential impact.
- As summarized in the presentation (slides 3 and 4), this project is clearly relevant in the context of better understanding the potential for hydrogen and fuel cell systems. While not particularly relevant for TV objectives, the results promised by this modeling project should certainly help achieve FCTO's SA objectives. If realized, the objectives stated on slide 3 will provide valuable inputs for decisions by both public- and private-sector stakeholders.
- The project certainly supports some goals of the Hydrogen and Fuel Cells Program but recognizes that a greater need may exist to develop research for product advancements that promote the use of fuel cells.
- A utility company like Southern will be very interested in these results and methodologies.
- Grid integration and support using electrolysis as dispatchable loads is a key element of H2@Scale. The analysis needs to expand beyond just vehicle hydrogen fueling stations and include other value-added uses of hydrogen.
- Specific case studies could be more targeted to real-world problems to somewhat validate initial results. The integrated approach could have significant impact if adopted in the future.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The remaining challenges and proposed future work, summarized on presentation slides 17 and 18, seem logical and reasonable. Applying the model and related analysis to "real-world" conditions and scenarios, e.g., those associated with utility regions in the Western interconnect, is a good plan.
- Future work to explore liquid hydrogen delivery will be important to starting to match or calibrate results to current industry experience. It will be interesting to see more Plexos integration and industry input to help validate results.
- Future work is reasonable, although it seems like more could be done with the model beyond what is proposed.
- The future work is in line with the plans.
- Sensitivity studies related to different hydrogen usages and to different capacity factors would add value to the project.
- This project should find an answer that resolves the questions of why station providers are not realizing the significant benefits demonstrated by this work, what the gap is, and what will help address this gap. Improvements to the models and promulgation of the results are interesting, but there are real-world examples either deployed or in development that could inform a discussion around these key questions.
- Before a decision is made about additional work, it might be worthwhile to ensure that the money would not be better spent elsewhere.

Project strengths:

- Project strengths include the modeling and analytical expertise available in the three national laboratory project partners: Lawrence Berkeley National Laboratory, NREL, and Idaho National Laboratory (INL). The H2VGI Model utilizes and integrates the results of previously developed models and analyses. Results of the work are beginning to be applied to actual power generation and transportation scenarios and to be used to answer questions related to the future of hydrogen and fuel cell technologies. The project has significant relevance in the context of overall FCTO objectives.
- The team has pursued an ambitious analysis project that entails a wide breadth of geographic and production scales. The approach is logically constructed and explained. The team appears to be well balanced for the work needed.
- The project provides a good overview and tools for assessing the value of grid support services in conjunction with vehicle hydrogen fueling to reduce the cost of fuel. The project can be strengthened by considering other uses for the hydrogen produced and by including sensitivity studies where appropriate to gauge the effects of varying different parameters.
- The project is well aligned with important issues in a very critical early market.
- The project is comprehensive and builds on existing science.
- There is strong laboratory integration across multiple models from NREL, and collaboration with INL.
- Laboratory data are plentiful and well organized.

Project weaknesses:

- Additional assumption details need to be included to assess the reasonableness of the results. The cost difference between central and distributed is substantial, but the cost analysis seems to be divorced from the other aspects of the project. Conclusions as to the cost impact on the system are not discussed. The project is a substantial investment ($1.6 million), yet the results are that electrolysis has only a limited impact on flattening the duck curve. It seems that modeling apparatus could be used for other studies, beyond those listed in future work. Finally, the future work activities do not seem that interesting or likely to have a large impact.
- The stakeholder webinars cited in the presentation are a positive step. However, the project managers should increase the focus on, and intensity of, collaborations with organizations having an interest in H2VGI modeling results. Assuming funds are available, workshops should be planned to (1) present the

model's capabilities and results, e.g., case studies; (2) receive feedback on methodology, assumptions, etc.; and (3) ensure agreement regarding model priorities and questions to be addressed.

- Beyond the coordination between NREL and INL, there appears to be minimal collaboration with outside activities. Outside collaboration appears to be limited to data from HNEI and two webinars consisting of about twenty people per seminar, of which about half were from industry, academia, and government activities—indicating that about half the webinar attendees were from one of the laboratories. Also, the pressing need for this project is unclear.
- This is a large project that has many assumptions built into the various models. Continuing to validate the assumptions and identifying/understanding the discontinuities/inflection points in the results will be challenges.
- The results are inconsistent with industry experience and industry opinion. The project needs to find out why that is the case and identify the barriers.
- It would helpful to connect this project to TV-031 and to demonstrate that the benefits ascribed are possible with control systems that have been identified and validated.
- The project is overly reliant on laboratory modeling that is coupled without intermediate validation.

Recommendations for additions/deletions to project scope:

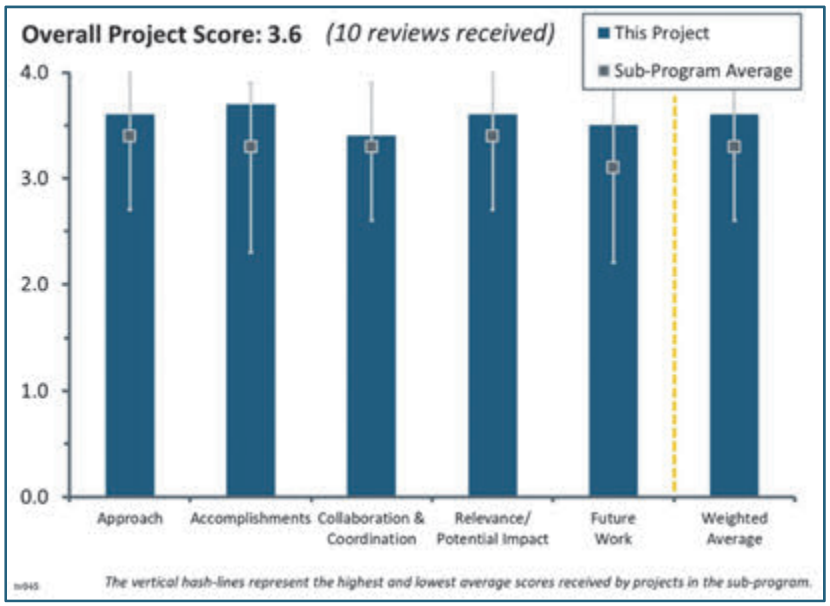
- The hydrogen refueling amount in slide 7 is curious; inquiry should be made as to why so many people refill only 1–2 kg at a refueling. Future work tasks should be increased to make better use of the model. Additional assumptions should be included in future presentations (specifically related to the cost analysis—some of the electrical usage values between central and distributed are surprising and not explained). The question of whether central vs. distributed has any effect on the shape of the duck curve should be analyzed.
- The results of this project have good potential to assist in making decisions relating to investment of private and public funds. However, with limited funds available for analysis, FCTO's SA team should continually ensure that this project is not duplicating or overlapping other modeling and analysis work being funded by FCTO and other organizations.
- The project should undertake additional case studies and validation of potential for forecasting cost and demand by region or hydrogen vehicle placements.
- While the discussion of using an H2G two-way fuel cell to reduce the power peak is interesting, the technology may not be technically feasible at this time. While the discussion might inform decisions as to whether to focus resources on developing such hardware, it is not likely useful for near-term design and investment decisions, as no efficient large-scale equipment that can do that exists, and the round-trip efficiency of grid–hydrogen–grid is poor.
- The recommendation is to minimize this project in favor of industry research.

Project #TV-045: H2@Scale Analysis

Mark Ruth; National Renewable Energy Laboratory

Brief Summary of Project:

H2@Scale is a concept that explores the potential for wide-scale hydrogen production and utilization in multiple energy sectors in the United States. The objective of this project is to improve the fidelity of the H2@Scale value proposition. The analysis seeks to quantify the potential economic, resource, and emissions impacts from wide-scale hydrogen production and utilization. In addition to conducting nationwide analysis, the project will also identify regional opportunities and challenges. H2@Scale analysis integrates many transportation, industrial, and electrical sector analyses and tools.



Question 1: Approach to performing the work

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

- The project has a solid connection with the DOE goals and objectives for H2@Scale. This effort gives perspective to the project's significance. The speaker noted some of the material presented is "already outdated," and this is a realistic perspective, to a point. Some of the supporting data may be "dated," but the approach(es) to performing the work can be used for a long time. The approach started with the relevance of the project: analysis makes the projection of light-duty vehicle penetration (with low-cost renewables including electricity). The analysis hinges on the economic potential of the H2@Scale concept, overall. Findings are based on resource potential (resource requirements): geographic locations and markets, and real-world performance. The project team compared to last year's efforts, which focused on economic potential. The team started with market sizes, first for industrial markets (existing markets, but opportunity costs were not explained); electricity markets (which are much like natural gas—flexible, although the team did not explain this); and transportation markets (seven-year-old National Research Council [NRC] reports were used) (this study should be blended with others and not used alone). The project team explained how the electricity source can be replaced with hydrogen. The technical potential was defined (although for transportation, it was based on an outdated NRC study). It is recommended that the project update this study, then the economic potential. The overall approach is excellent.
- It is encouraging to see the U.S. Department of Energy (DOE) making these efforts to understand the underlying economics of the hydrogen supply chain through modeling of supply- and demand-side pressures. With this body of work, a common methodology for these economic evaluations can be made. From an industry perspective, this is an important step for DOE as it enables industry engagement without relying on proprietary industry market analysis and without the concerns of market influence based on such proprietary evaluations.
- The approach taken on this project is very robust in the way that it is not only relying on transportation models and tools but also integrating these with models associated with the industrial and electrical sectors that are essential for the H2@Scale concept realization. The parameters being provided for the technical and economic potentials are well aligned with the overall goal of this analysis work.

- Overall, the approach appears to be strong, and the results are well presented and cover the major areas of interest. This is a nationwide, economy-wide piece of analysis, so there are inherently many assumptions and choices that need to be made. The analysis seems to be reasonable in its assumptions, which of course can always be probed in more detail or shifted.
- The approach is well explained. The project makes use of existing analysis tools that have already been vetted. The differentiation between technical and economic potential is key to this project's approach. The demand–supply curve evaluation is ambitious.
- The project team presented thorough coverage of analysis for support of the H2@Scale concept and use of all DOE tools. The project addresses a key need in explaining and supporting technical and economic benefits.
- This is a very ambitious project with much input and many variables. The communication across all sectors is key. To the extent possible, the project team should keep a finger on what is happening in the "real world," i.e., what industry is doing and how the actual market is playing out.
- The approach used is stepwise, logical, and comprehensive. The approach first understands what is possible, then reduces it to economic considerations.
- This project is an excellent analysis on a very important assessment.
- Establishing the scenarios of future demand and supply for hydrogen that goes beyond transportation is a positive step. However, after finding the economic equilibrium price, there is no mention as to whether this price is economically feasible, given current technology. These curves should point out which industries and applications would be able to deliver hydrogen at the equilibrium price and which ones would be willing to pay that price. Also, it is not clear whether the hydrogen supplied includes transportation and distribution to the final user.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project used a wide range of situations in the United States, an overall DOE goal. The project included examples from the San Francisco Bay Area and rural United States (Appalachia), with an emphasis on electrolysis. The project made a good connection with the target price point of hydrogen dispensed and moved to "beyond the target" price. That price was a little too high: $3.00 for the hydrogen price for the demand curves. However, it was explained that this is the amount that needed to be paid. The project team reviewed the different ways hydrogen is produced—curtailed electricity, nuclear, and steam methane reforming (SMR)—and gave various values in the sectors.
- This project has a good analysis of hydrogen demand across sectors across the geography that was presented. The project team completed a broad range of scenarios that were analyzed for hydrogen economics. This gives a more fair comparison of what cost renewable hydrogen has to meet to be competitive.
- The project team has done excellent work on the accomplishments and progress shown on this work this year. The development of the demand and supply curves was key to understanding the potential economic potential of the H2@Scale concept, which now provides a more complete picture by building on last year's results on the technical potential.
- The analysis clearly made progress toward answering the key questions articulated at the start of the presentation. Assumptions are inherent in this type of analysis, but progress was definitely made.
- This project has made very good progress going from technical potential to economic potential.
- The depth of evaluations made in this project is impressive.
- This project is in full alignment with DOE goals.
- This project has made good progress; the development of supply and demand curves for four different scenarios is significant. It would have been good to see an actual case study or the initiation of an actual project as well.
- The integration of geographic analysis and market potential is very good. It is not clear how the technical potential demand was calculated. It was also unclear in what year the demand was calculated.
- In slide 10, the project team should provide the actual link to the data source, as one cannot readily find it on Google or the National Renewable Energy Laboratory's (NREL's) site. It would be nice to understand

how/where the assumptions were derived (e.g., light-duty-vehicle transportation). While the technical potential of renewable hydrogen from photovoltaics or wind for every county in the country is perhaps interesting, it is not very helpful if it does not consider any economics or realistic scenarios. Policy is a very important factor in all of this, and the project team should take this into consideration.

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- One of the main strengths of this project is the expertise provided by world-recognized analysts, all of them from different entities, working as a very strong team. It is great to see that there is also feedback provided by DOE's Office of Nuclear Energy.
- The project team demonstrates good coordination with DOE national laboratories and mentioned a need for the example business cases. It seems likely that the private sector will want to collaborate with this project, since it is comprehensive and relevant. The project team mentioned technology transfer, but specifics are needed here.
- The laboratories appear to have stitched together their various analyses in reasonable ways and have worked together well.
- This project is very well integrated with several DOE laboratories.
- This reviewer looks forward to offering comment on the forthcoming report.
- The team needs additional collaboration with industry and government to initiate a project that can validate H2@Scale. It is encouraging to see that the team is partnering with the state of Texas to conduct a case study. The team is encouraged to look also at California, where the project would be more likely to get financial support for projects.
- The industry input may be a bit light. With all of the hydrogen activity in California and the Northeast, it is possible that getting input can be a challenge for the project.
- The project team did not explain the interactions with collaborators. Workshops have been held around H2@Scale to provide input, but it is not clear what mechanisms are being used in between to obtain industry input.
- This project has interesting preliminary results that are generally described clearly. The "hydrogen price" needs to be clarified as a production-only price. The project team concludes that if natural gas prices are low, only SMR will be used to supply hydrogen; but if natural gas prices are high, then SMR plays only a modest role, and electrolytic hydrogen generation is dominant. Plus, the price of electrolytic hydrogen must be about $1.5–$1.75/kg. However, assumptions as to whether and when electrolytic hydrogen can reach those cost levels are not shown.
- The project team could potentially improve the approach to validation in the market. It is unclear how, for example, the market predictions will be evaluated against actual costs that are seen in the field. Again, it is not clear whether there will be a long-term owner of these models who will have the responsibility to maintain and improve them as economic data is gathered and compared. It is not evident who this long-term owner would be (industry, trade organizations, DOE, etc.). The team should provide clarity about who will own/use these models in the future and how that will become part of industry reporting, as it is an important aspect of this project. The project could be strengthened by having the long-term owner of the tools/data/reporting on the team.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Past studies have examined individual aspects, but this project pulls them together into a combined assessment firmly set in an economic supply-and-demand framework. The project provides very relevant analysis that will explain/validate whether the hydrogen economy/H2@Scale concept is feasible.
- The project gave realistic scenarios of hydrogen production and the varied the price of natural gas, both base case and upper bound. This is good, for the increased demand for hydrogen in California shows a need

to keep planning for the upper bound. The project supports pipelines to bring hydrogen to the coasts (forward-thinking).

- This level of analysis is hugely important at this time when hydrogen is at a tipping point internationally. While it is good to look at an electrolyzer cost that can make the cases competitive, it is also important to provide a case more representative of today's technology.
- This project is in line with the [former] Market Transformation sub-program; the project is enabling and accelerating expansion of hydrogen and fuel cell system use by lowering the life-cycle costs of hydrogen and fuel cell power and by identifying and reducing the barriers impeding full technology commercialization. The work presented in the slides, together with the projects that DOE has selected to demonstrate hydrogen integration, is an important step toward lowering hydrogen costs using existing resources.
- This analysis is of extreme importance for a clear picture of the potential and impact of the H2@Scale concept. Understanding both the technical and economic potentials is definitely key to assessing the hydrogen implications beyond the transportation sector, which has been the main focus over the last several years.
- This project is very much aligned with the research and development R&D goals, and the potential impact of the results is significant.
- This is clearly critical to the overall mission of the Fuel Cell Technologies Office, and the results will contribute to future R&D efforts and setting R&D targets.
- This project is fully aligned with DOE goals.
- This type of analysis will really help in thinking about the future. In a subsequent project, it would be good to look at hydrogen technical/economic potential in terms of scale required to make an impact on the grid (such as the ongoing Lawrence Berkeley National Laboratory [LBNL] study by Dr. Saxena).
- The biggest concern with this project is that the project team does not consider the effects of policies on the markets. While DOE cannot advocate for policies or policy outcomes, it is imperative to understand how policies will affect the supply and demand sides of these evaluations. Particularly in early market stages, it is policies, not free market drivers, that will establish the supply and demand curves and their evolution in time. It is irresponsible for DOE to take the position that an economic market study will be completed without taking the effects of policies into consideration. It is unclear how one could make good policy decisions if there are no economic models that can show the effects on markets. A secondary concern is the accessibility of these models to users outside of DOE. It is unclear what access will be made to the tools being developed and how that can be best bridged to potential users in industry or markets.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The remaining challenges and barriers have been clearly presented, and the project team has clearly identified the necessary future analyses to address these challenges.
- The project's completion is moving forward as planned, and the ongoing updates are desirable.
- A qualitative analysis of a Texas transition plan would have some benefit, but a quantitative analysis would be better. Doing a Texas-only study might be good in that it is smaller than a national study and may better identify pros and cons of the approach.
- It is important to conduct a regional analysis to determine appropriate strategies for each area.
- The future work should also include more opportunity for industry input—webinars, surveys, etc.
- The presenter mentioned the need for more funding to support "deeper research." It is unclear whether the presenter can work with the concept of just-in-time production and distribution of hydrogen so that the fuel is where it is needed and the increased "real" access leads to price-at-the-pump decreases. It is unclear what the presenter's best-case scenario, or utopia, in the future would be. While the presenter has many answers and has already broke things down and studied them intensely, presenting his idea of the utopian scenario, market sensitivities, and the results would be appreciated and respected.
- The project should integrate overcapacity of either electricity or hydrogen production with a hydrogen refueling station or something similar. The logical next step is coordinating with government and/or industry to prove the models.

- The project team should continue to refine this work and narrow toward economic feasibility, as well as narrow the scope to specific regions.
- The continued use of these models in evaluating the various case studies banding the range of hydrogen market penetration is recommended, and the time when researchers can compare actual market data to the model predictions is happily anticipated. When at this stage, the tools will have real market value by giving stakeholders a common reference for these economic factors.
- The project is over, as the presentation said that there is no funding in fiscal year 2018.

Project strengths:

- Fundamentally, H2@Scale is a version of the "hydrogen economy" idea, and this analysis does a nice job quantifying, at the scale of the U.S. economy, the generation sources and uses for hydrogen across sectors. The supply and demand curves are important, even though there are plenty of assumptions, and provide a clear basis to assess research goals and understand when hydrogen could start to win on economics alone, for particular applications. The presentation was clearly put together and did a nice job of communicating results. A number of major questions that would be interesting to look at in future work follow:
    - It looks like hydrogen from nuclear will not happen, because the price per kilowatt-hour for current nuclear is just much too high. If this is correct, it could be stated in a more transparent way.
    - It is unclear whether it is realistic to build the types of hydrogen pipelines shown. There are lessons from the natural gas pipeline industry that could be applied. It is also unclear whether it is reasonable to permit and finance the types of pipelines shown. It would be good to know how big that investment would be compared to the annual build of natural gas pipelines today.
    - The assumptions and analysis that led to 28 MMT/y of hydrogen for storage were not clear. It would be helpful if the project team explained that in more detail, likely through a publication.
    - More information on electricity supply would be helpful. Presumably, curtailed electrons are free, and the rest of the electricity is bought at the denoted wholesale prices.
- The project's breadth and scope are huge. The resulting potential impact and value of the project are similarly large. The opportunity for presenting very compelling graphics based on the data generated is very high. As a word of caution, however, there have already been discussions in which the figure on slide 20 is interpreted as DOE's prediction for where hydrogen pipelines will be needed.
- This is a large, complicated undertaking that the NREL team appears to be handling in a methodical, clearly stated manner. The use of supply and demand curves is an excellent approach.
- This project has a highly complex set of data that the team explained well in the slides and orally. The analysis provides valuable data to support H2@Scale rationale and strategies for deployment. There is a good deal of data here that could be leveraged.
- The project is founded in solid approaches, including assumptions. The team presented clearly, with a passionate speaker, a strong presentation, and a broad approach. The project is providing needed work and needed results and insights.
- Overall, there is an abundance of "brain power" and information associated with this project, and there can be some information impactful to the industry.
- Starting from what is possible and narrowing to what is feasible is a strength of this project.
- This project has an excellent evaluation that should be completed as planned and, in the future, updated and further expanded as needed.
- The project team has strong technical knowledge. Data availability is a project strength.
- This team has strong modeling capabilities.

Project weaknesses:

- There are no evident weaknesses.
- The project just needs a scenario for utopia. It is already there, but it needs to be brought forward.
- In an analysis like this, there are always many assumptions to target, but it is clear that the team could vary assumptions, and the team clearly understands the different scenarios and can present on them as requested.

- Given the complex nature of the analysis, it is difficult to clearly explain the assumptions that go into the analysis. It is not clear that the team's planned reporting will have all the detailed assumptions necessary to challenge the analysis results. The creation methods (and details) of the supply and demand curves are not clear. Without confidence in those curves, the results are meaningless. There is no sensitivity analysis to assess the extent of change in the results due to changes in the critical assumptions. There is no identification of the critical assumptions or drivers.
- The underlying assumptions will be a challenge for this project. Another challenge is ensuring the economic analysis adequately captures the risk mitigation costs of industrial/utility investments.
- The likelihood of availability of hydrogen overcapacity is unknown, and the team did not assess the significant shift in the demand–supply curves. Also, the project lacks involvement of stakeholders that can build out infrastructure/initiate H2@Scale projects.
- The models do not consider the effects of policies on outcomes. This is a critical, if not fatal, weakness in the models in the early market stages when policies are much more likely to drive behaviors, prices, and market directions than in the open supply–demand curve modeling used here.
- The project team needs to keep in mind the policy comment as it affects the numbers and the "believability."
- The collaborations and follow-up with industry could be more thoroughly described.

Recommendations for additions/deletions to project scope:

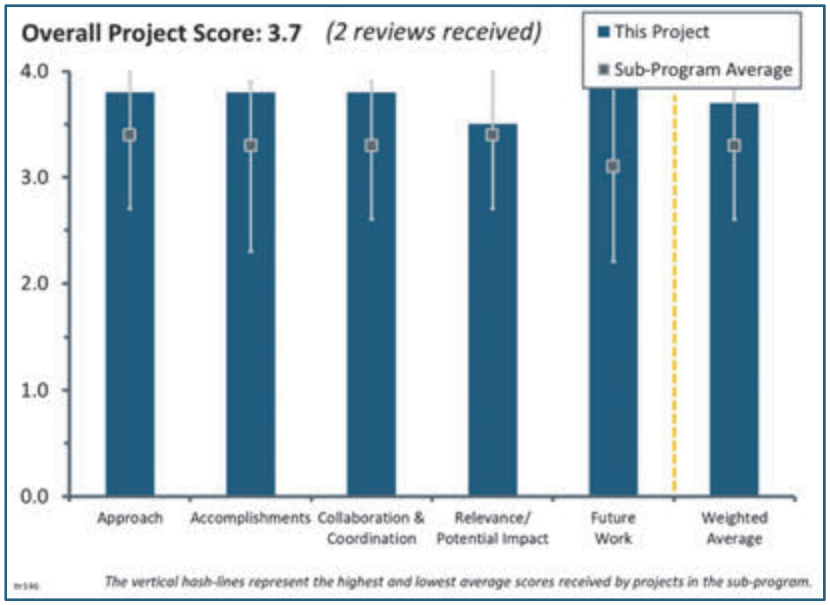
- This is a very valuable and potentially marquee project for the H2@Scale effort.
- The proposed future work will provide significant information.
- This project is over, but a number of additional scenarios could be assessed. The practicality (permitting) and economics of building a huge hydrogen pipeline system is of particular interest.
- The project needs a sensitivity analysis. The dollars-per-kilogram from electrolysis seems optimistic. It would be of interest to understand the team's exploration of how the supply curve changes with an increase. Also, the team should identify critical assumptions and analysis drivers. The project needs details and complete documentation of assumptions and a better description of how the supply and demand curves are generated.
- Connecting the dots between this analysis and R&D needs and impacts is critical for continuing; such an effort is needed to quantify how much technology advancements could reduce the cost of hydrogen and manage the gap to natural gas. It is important to analyze how policy also affects these models, while not endorsing any particular policy.
- The team should involve government and other stakeholders that can build out infrastructure and integrate demand and supply of hydrogen; initiate case studies and on-the-ground projects; assess whether it is cheaper to build high-voltage direct current (DC) lines to deliver electricity from the wind belt to the east and west coasts, or to build hydrogen pipelines to transport hydrogen from the middle of the country to demand centers; and assess potential shifts in demand and supply curves.
- The team should consider helping some of the other zero-emission-vehicle states, such as Oregon.
- The project team should add best-case scenarios.
- The team needs to periodically update on this project.

Project #TV-146: H2@Scale: Experimental Characterization of Durability of Advanced Electrolyzer Concepts in Dynamic Loading

Shaun Alia; National Renewable Energy Laboratory

Brief Summary of Project:

This project aims to evaluate electrolyzer durability with dynamic loading and assesses the ability of electrolysis-based hydrogen production to be cost-competitive while maintaining performance with extended operation. Los Alamos National Laboratory (LANL) will support the National Renewable Energy Laboratory (NREL) in (1) establishing baseline performance as a guide to catalyst/ electrode development and (2) evaluating the influence of low loading, intermittency, and system controls on durability.



Question 1: Approach to performing the work

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

- This project addresses technical barriers cited in the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan (MYRDDP). In particular, relevant barriers include barrier G, Hydrogen from Renewable Sources, in the MYRDDP Technology Validation (TV) section, and barrier F, Capital Cost, in the Production section. Project objectives are clearly stated. The project approach is well developed and logical. Electrode materials are fabricated, tested, and characterized at NREL and LANL.
- The project approach is good and described well by the principal investigator (PI). It is clear that the team understands the project goals and how the results will have relevance and impact.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Slides 7 through 15 provide evidence of significant activity and results since the project began on October 1, 2017. During the relatively short life of the project to date, the impacts of multiple variables on membrane electrode assembly performance and durability have been measured and quantified. These variables include iridium and iridium oxide loading, intermittency, wave type, ramp rate, and water quality. Materials characterization of single-cell test samples, using microscopy and X-ray diffraction, provides detailed information on metrics such as catalyst layer thickness, porosity, and equivalent diameter of pores. Selected results of microscopic studies show the impact on membrane durability due to changing test conditions. There has been outstanding progress in achieving project objectives. To date, the iridium and iridium oxide catalyst materials have been tested. The PI noted that no conclusions regarding "bigger-picture" issues can be drawn yet in regard to the implications of results so far for overall electrolyzer performance and cost.

- Not only are the accomplishments founded in strong science, but the results are well described. The presentation of the information is easy to understand, and the direct relevance is clear. The project evolution is easy to follow, and it is clear why the research work is following its current path and what impact the results have on the overall objective.

Question 3: Collaboration and coordination

This project was rated **3.8** for its collaboration and coordination with other institutions.

- This project is being carried out through a partnership between NREL and LANL. The responsibilities of each partner are clearly defined. Each week, single-cell MEAs, which have been tested at NREL, are sent to LANL for analysis and characterization. The presentation does not address or clarify how this project coordinates with other H_2@Scale projects, initiatives, and activities.
- The research has just started, but it is clear that there is a strong link from the research to the potential users of the information. The project should seek to maintain this level of collaboration as it proceeds.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is very relevant, and how the research will achieve an impact is clearly demonstrated.
- The relevance section of the presentation relates more to the overall H_2@Scale program, and water electrolysis hydrogen production, than to this specific project. The project being reviewed is evidently considered an element of H_2@Scale. The project's scope is limited. While it is hoped that results will inform electrolyzer design, materials selection, and operation, the project will likely contribute to cost-competitive hydrogen production only when combined with other, more robust development and testing projects.

Question 5: Proposed future work

This project was rated **4.0** for its proposed future work.

- Future work would build on the foundation established during the initial year of the project. The work described is a logical next step. The activities proposed should result in information that is beneficial for designers, developers, producers, and operators of equipment for hydrogen production by electrolysis.
- The project's future work should include the communication and collaboration efforts, not just the research tasks.

Project strengths:

- NREL and LANL investigators have been productive. Results and information produced to date have been plentiful and detailed. NREL and LANL have state-of-the-art testing and diagnostic capabilities/equipment. Project objectives are clearly stated, and the approach to achieving them is logical.
- This project is well focused and well communicated.

Project weaknesses:

- The project could fall into a common trap in which the research efforts are the only focus. The project team should ensure that an increased amount of effort is spent on communicating results to both the academic and commercial communities.
- The project's scope is limited. The project scope will likely contribute to cost-competitive hydrogen production only when combined with other, more robust development and testing projects.

Recommendations for additions/deletions to project scope:

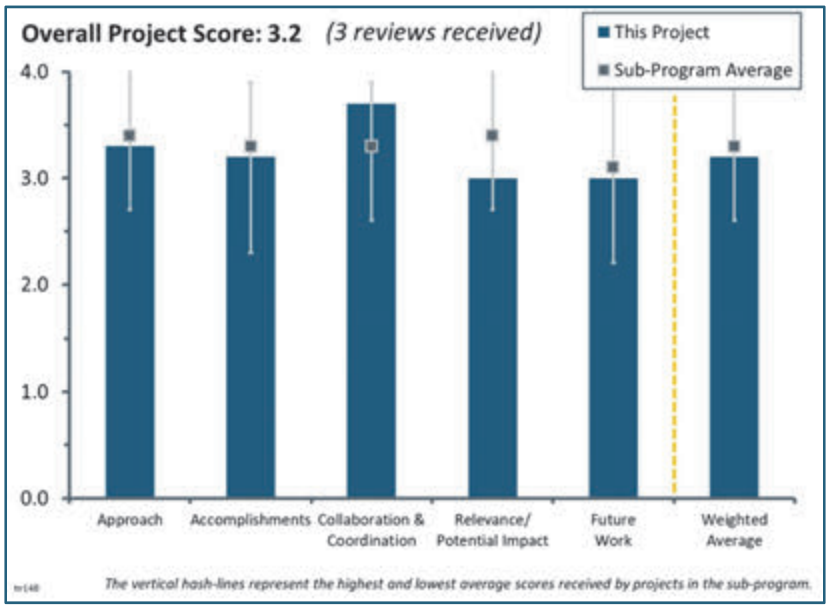
- Presumably, project continuation beyond the first year is dependent on additional funding of about $400,000 annually. Therefore, it can be assumed that continuing for another year is warranted and reasonable. After that, however, a critical assessment should be done to determine the probability that results achieved will contribute substantively to FCTO's goals of improving hydrogen production performance and lowering costs. How well this project is integrated and coordinated with other activities (e.g., other H_2@Scale projects) should also be factored into the continuation decision. It is recommended that the presentation at next year's Annual Merit Review should address this issue.

Project #TV-148: Hydrogen Stations for Urban Sites

Brian Ehrhart; National Renewable Energy Laboratory/Sandia National Laboratories

Brief Summary of Project:

The primary objective for this project is to create compact risk-informed and performance-based liquid hydrogen reference station designs that are appropriate for urban locations and permit hazard reductions, as well as improve near-term technology. Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST), a Sandia National Laboratories–National Renewable Energy Laboratory collaborative project, will partner with industry stakeholders to identify methods of reducing physical station footprints and address the possibilities for station layouts within urban sites.



Question 1: Approach to performing the work

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

- The approach is clear, and the relevance of the information is well understood by the project team.
- While the goals and deliverables for this project are well-laid-out and clear, it is not clear what value will come from attaining these goals. As a station developer, for example, each site considered has its own layout and offset requirements that are very specific, making the results of this analysis too generalized. Footprint requirements and layouts at stations are very much dependent upon the permitting offsets, the existing station equipment and layout, and the accessibility to vehicles, refueling, service, etc.
- The project team should consider starting with a base case that focuses on what needs to be done to build a hydrogen station on a greenfield site and achieve the same footprint as a gasoline station.

Question 2: Accomplishments and progress

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

- The project is closely aligned with industry challenges; thus the accomplishments and progress are very relevant. The clear communication of assumptions provides a strong basis and trustworthiness for the results. The project team selected an appropriate level of detail with which to communicate research work and impact.
- The team has made good progress, especially in the area of identification of code issues. However, there are too many hypothetical assumptions—the project needs to take on an existing gasoline station site and take all issues into consideration (existing local requirements/preferences, adjacent structures, etc.). By the time this project is finished and the results are published, 600 kg/day can be expected to be on the low end of station capacity sizes planned for implementation; even if the project appears to push the envelope, it may not be pushing the envelope hard enough.
- The project is in its first year; to date, the results are very general and not particularly usable by a station developer or site planner.

Question 3: Collaboration and coordination

This project was rated **3.7** for its collaboration and coordination with other institutions.

- This project appears well aligned with industry leaders, public safety officials, and code development organizations. The collaboration is clearly demonstrated in the project presentation.
- The list of collaborative partners is very good and includes developers, operators, DOE, trade associations, etc.
- The project team needs to have closer collaboration with hydrogen station developers/operators in industry for practical/real input to test actual challenges by taking an existing or planned site and applying effort. This will add significant value for both industry and national laboratories.

Question 4: Relevance/potential impact

This project was rated **3.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is reaching its potential with regard to impact on relevance and scientifically defensible public safety requirements.
- The project has reasonable relevance/potential impact. The level of impact would change very significantly (in a positive direction) if the team took an actual gasoline or greenfield site and went through the same exercise.
- Evaluating design options to reduce the footprint of stations is very much in the purview of station developers; thus, it should not be a high priority for DOE. It is not clear what the DOE Hydrogen and Fuel Cells Program can bring to the evaluation that is not already under consideration by station developers.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Of the proposed work, the performance-based evaluations have the most value. If a performance-based evaluation can be shown to significantly reduce offsets, and if a standardized methodology can be developed, this could be a useful tool for developers.
- The project team may want to consider eliminating rooftop storage as an option and focus all future efforts on underground storage.
- The proposed future work lacks specificity.

Project strengths:

- The project has good collaboration and input from a wide range of stakeholders. Performance-based design methodology may provide developers with an approach to reduce offsets.
- This project is very strong, both technically and in terms of relevance, and includes strong participation from industry.
- The project's strength lies in its potential impact. It is necessary for the team to assess how to reduce the footprint of equipment from hydrogen stations.

Project weaknesses:

- The project could better characterize the key concerns of public safety officials and better represent the challenges presented in the significant code changes. The team does not state how fast codes normally change, nor does the team address the concerns of local officials, despite changes in the code. It is unclear what information is needed to prevent "losing" the support of local officials, despite the code.
- Much of the project's scope is being done by developers on a project-by-project basis and will probably be too general to be applicable to any specific site.

- A weakness of this project is the modeling effort with hypothetical site scenarios. There is a need for practical applications to obtain data quickly and add value.

Recommendations for additions/deletions to project scope:

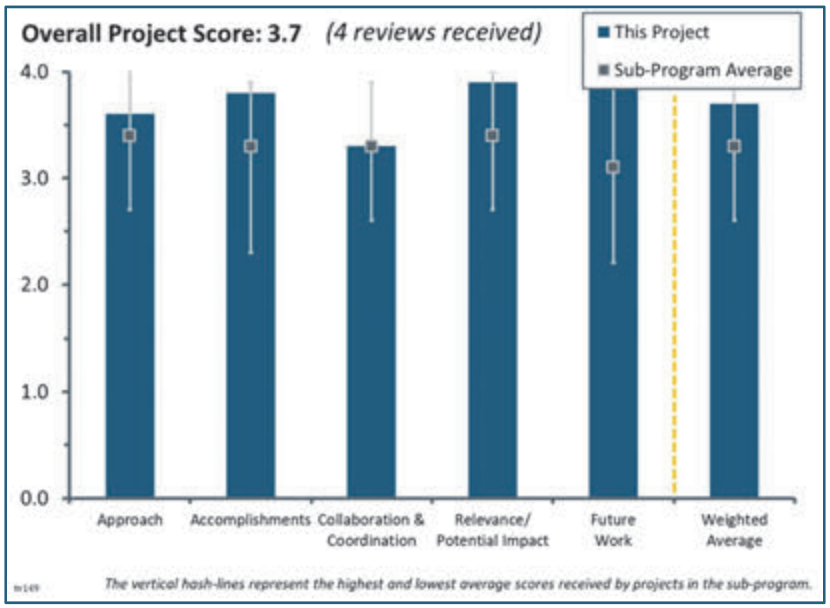
- It is recommended that a practical application to an existing or planned site be added. Rooftop storage should be removed as a future research topic; instead, the team should focus on underground storage. Instead of a national impact study, it is suggested that the team focus specifically on California and one state in the Northeast (the most challenging one)—this may help narrow efforts.
- It is recommended that the team focus future efforts on the development of a standardized approach to the performance design evaluations.

Project #TV-149: Mirai Testing

Henning Lohse-Busch; Argonne National Laboratory

Brief Summary of Project:

Argonne National Laboratory (ANL) is partnering with Transport Canada to investigate the 2017 Toyota Mirai fuel cell electric vehicle (FCEV) and provide in-depth independent and public access data for the research community. This project will utilize effective and established testing methods adjusted to the 2017 Toyota Mirai to yield real and open-source data outcomes from cutting-edge transportation technology. The team will examine energy consumption, emissions, and performance and operation at the vehicle and component levels.



Question 1: Approach to performing the work

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

- The 2017 Toyota Mirai is the first production FCEV and thus merits particular scrutiny. The project team's approach of testing and publishing actual performance data is spot-on and much needed. Testing in the ANL facilities seems very well suited for FCEVs. The team's separate supply of hydrogen prevents performance evaluation of the hydrogen supply system, but that is acceptable since the focus should rightly be on the fuel cell system.
- The project team tested and produced data from FCEV systems and subsystems. Extensive research was applied in testing and evaluating other vehicles, and the team was able to obtain the test vehicle. The project team applied its expertise in reverse engineering in this project.
- Data-gathering and public reporting are important to keep car companies honest and to allow the public to understand the vehicle's performance before buying/leasing.
- This project has a well-developed test plan that includes testing at different climate conditions. The vehicle is outfitted to maximize learning from all components.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The data presented is excellent and grants an unbiased, objective assessment of vehicle performance. The display of data, graphs with arrows, and comment bubbles was effective in illustrating key points. The definition of various efficiencies was well presented. Fuel economy was assessed at a variety of drive cycles. This is key, as results vary considerably, and comparisons between drive cycles illustrate important aspects of the power system performance. The team's evaluation at cold and hot temperatures is valuable data.
- The use of the FCEV and the infrastructure relates to DOE's H2@Scale. This project evaluates how well the car systems (i.e., the fuel cell stack and energy efficiency systems) function. These are important items to the user community at large, whether or not they understand this at the current stage of technology

adoption. The satisfaction of the user community with the FCEV is integral to the community's keeping the cars and driving them reliably. This project addresses that potential.
- It was interesting to see the energy distribution across the temperature chart, as well as the fuel efficiencies for different test cycles and the fuel cell stack efficiency and output. Also, it is interesting to understand the fuel cell behavior while the vehicle is idle to assess how much hydrogen flows out of the tanks. The test methods were appropriate.
- This project is complete and has accomplished the planned goals. Third-party assessment is essential to understanding vehicle performance. This will aid the industry in moving to fully commercial products for the market.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- Because ANL has the right expertise and adequate testing facilities, collaboration with Transport Canada and other national laboratories to acquire the vehicle and evaluate the results, respectively, is sufficient.
- Collaboration with Transport Canada is a foundation for this project. The poster (verbal) presentation did not mention other partners, but others are very likely to want to become involved.
- The collaboration with Transport Canada and the Advanced Powertrain Research Facility seems reasonable and effective.
- The project has a good collaboration with partners in Canada.

Question 4: Relevance/potential impact

This project was rated **3.9** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The adoption of FCEVs could be related to the reliability of the vehicle. At the beginning of adoption, early drivers may tolerate the need for more checkups and repairs, perhaps because they are enthusiastic. However, later on in the adoption cycle, drivers may become more critical if reliability equal to gasoline cars is not present. This ANL project gives a proactive review of the potential of reliability, which is very much needed, so that the manufacturer can benefit from a second set of eyes.
- An unbiased, open-source assessment is relevant and impactful in that it creates a base of objective facts that all can see and reference. Public dissemination of performance status allows the community to collectively identify areas that have been successful and areas that require further work.
- The project validates a state of the art of fuel cell systems in transportation and assesses technology status. These are both goals of the [former] Technology Validation sub-program.
- This project is well aligned with DOE goals and provides much-needed data and analysis on FCEVs to both DOE and the industry.

Question 5: Proposed future work

This project was rated **4.0** for its proposed future work.

- The perspective is one of planning to evaluate more FCEV models. This is extremely important. Perhaps a progression of the models as they are released would be possible. ANL discoveries and recommendations could be fed back to the manufacturers, industry analysts, and hydrogen refueling station developers so cars of the future achieve the reliability of commensurate cars with internal combustion engines. Potentially, this analysis could be used to design hydrogen refueling stations.
- This is not applicable, but it would be good to get the same results for the Honda Clarity.
- The project is complete, and no future work is planned.
- The project is complete.

Project strengths:

- The project team has a well-established facility and the capabilities to conduct testing. The plan is well-thought-out and addresses data collection under differing climates to determine how the FCEV performs.
- This analysis is necessary. How and how well the FCEV systems and subsystems work is very important to the consumer community and to hydrogen station developers.
- This project consists of professionally executed vehicle performance assessments, with the results made available to the public.
- The project's main strengths are its testing facilities, the technical expertise of the team, and its information-sharing concept.

Project weaknesses:

- The only weakness is that the user community, which can be generally intrigued with the FCEV, could have used the results of this analysis sooner. Be that as it may, the ANL approach and expertise are very good (great), and it is worth waiting for the results.
- There are no material weaknesses.
- There is no information from other hydrogen FCEVs on the market.

Recommendations for additions/deletions to project scope:

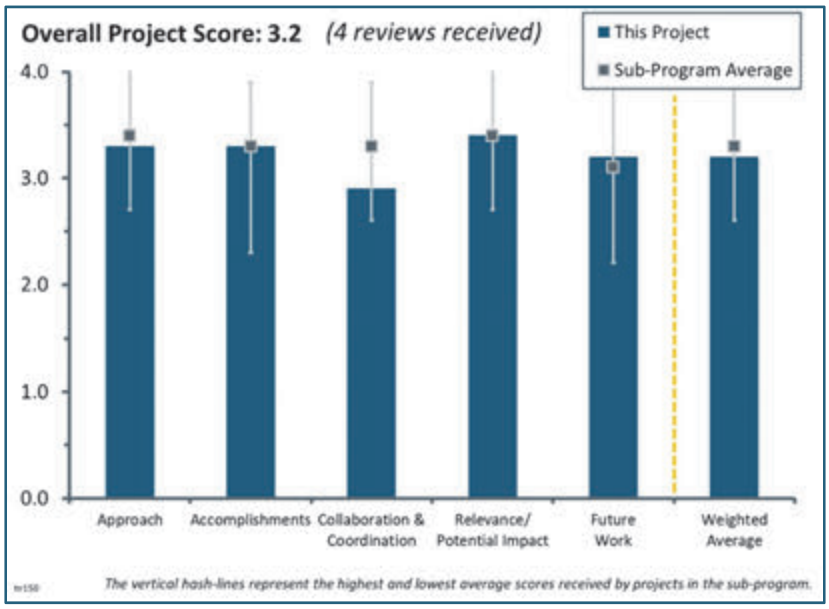
- This project would benefit from comparing vehicle performance simulations to the actual dyno results, particularly to evaluate what is happening at low and high environmental temperatures. More examination of cold weather power system performance would be beneficial. The source of energy losses during cold weather, while measured, is not identified. The team should address where the energy is actually going.
- It is recommended that the project team add more vehicle types to this project and future analyses. The project should investigate whether models can be evaluated prior to becoming leased or sold.
- It is recommended that the project team compare results to the Environmental Protection Agency window sticker. Other than that, the project has been completed. No additions or deletions are necessary.

Project #TV-150: Analysis of Fuel Cells for Trucks

Ram Vijayagopal; Argonne National Laboratory

Brief Summary of Project:

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



Question 1: Approach to performing the work

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

- This project is a modeling optimization activity. It draws upon previously vetted models of vehicle performance and optimization algorithms, which are then used to produce believable and valuable results. The approach is excellent.
- The use of the existing Autonomie tool was appropriate, especially for the low project budget. The use of real cost of ownership (RCO) is appropriate for an overall objective function.
- The approach is appropriate, but that is not apparent in the slides provided to reviewers, as results are only for a hydrogen price of $4/gallon of gas equivalent (gge). Fortunately, the poster also had results for $12/gge, and by speaking with the principal investigator (PI), it became known that the team also ran a case for $16/gge. The PI explained that for the final results, fuel cell electric vehicles (FCEVs) and battery electric vehicles with range extenders would be compared against a diesel internal combustion engine.
- The project represents a good first step in determining methodology. Some of the assumptions (such as miles per year) might need to be looked at as variables, rather than fixed inputs.

Question 2: Accomplishments and progress

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

- The optimization between the sizing of the hydrogen components (fuel cell, hydrogen tanks, etc.) and the battery components (size, number, etc.) is a very important issue, particularly when balancing performance, operation cost, etc. This project was modestly funded, yet the results produced are important to the design to yield a well-balanced system to reduce cost of ownership without compromising on performance. The accomplishments are an excellent return on investment.
- The project team has illustrated the general approach by walking through a medium-duty truck case study. The graphs of the design space nicely illustrate the optimization process.
- The project represents a viable method for determining what commercial applications offer competitive opportunities for fuel cells. It would be good to show how the method can/will be expanded for use on larger classes of trucks in the future.

- The progress achieved by the team with only $25,000 is impressive. However, the slides were not up to date and thus did not do justice to the work. It is recommended that the team publish the results for the $12/gge hydrogen price, along with the original $4/gge.

Question 3: Collaboration and coordination

This project was rated **2.9** for its collaboration and coordination with other institutions.

- Given the size of the project, consulting only internally with the ANL Fuel Cell Team is appropriate. Since the project is small and builds on past analyses, it is well within the project team's capability to conduct the study with only minimal outside collaboration.
- It would be beneficial to see collaboration with auto manufacturers to get feedback and perhaps collaborate for future medium-/heavy-duty truck designs.
- An important next step would be to involve input from both truck makers and (very important) truck users/ fleet operators.
- There is some coordination between this project and outside entities (the U.S. DRIVE Partnership and Oak Ridge National Laboratory), but there are no collaborations (one cannot collaborate with oneself; i.e., this project [ANL] cannot collaborate with the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation [GREET] model [also ANL]). This project is mature enough that it needs to collaborate with an original equipment manufacturer (OEM) that is actually building hybrid fuel cell/battery trucks. Input from OEM truck builders is important to making sure the assumptions used in this effort are reasonable for the companies' needs and designs. This project is very modestly funded, but having OEMs review the assumptions used should not be a financial burden; such a review would be very valuable, establishing credibility for this effort to industry. It is the lack of this type of collaboration that resulted in a 3.0 numerical scoring, particularly since this comment was made in the previous Hydrogen and Fuel Cells Program Annual Merit Review.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- It is very important to understand this type of optimization in the vehicle design architecture and the design of the system (in this case) to minimize the cost of ownership. Other optimization parameters could be used, which might yield different results, so having such a capability is very powerful and important. This project is very relevant to the growth of this hybrid truck application.
- The fuel cell industry is starting to see trucks and commercial vehicles and equipment as more economically viable starting points for fuel cells than light-duty vehicles, so this type of analysis/toolset will enable a more rapid study of alternative approaches to enabling those applications.
- Sizing the vehicle components, while maintaining performance and minimizing cost to the consumer, helps one understand the advantages of medium-/heavy-duty vehicles, compared to the incumbent diesel technologies. This, in turn, can help one understand potential market uptake.
- The issue of fuel cell dominant versus fuel cell range extender has repeatedly come up in the analysis community. This project is timely and contributes significantly to the discussion.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The stated next steps of expanding the classes of trucks that the tool can look at and verifying the analysis process are appropriate.
- Expanding the work to additional hydrogen prices and vehicle types and comparing them against diesel trucks will be key to forecast market segmentation and potential technology adoption. Unfortunately, that was not reflected in the slides—this information was obtained from the PI.

- To date, only a single case has been analyzed. The proposed work will extend the analysis to 13 vehicle vocations. The plan to "include control parameters [within the] optimization problem" is unclear and requires further explanation.
- This project is scheduled to be completed by August 2018.

Project strengths:

- This project leverages previous validated modeling and optimization work at ANL, which increased credibility and allowed for valuable work and results to be performed in a timely and cost-effective manner. The results are excellent, as is the productivity for the very modest funding this project received. The project also used publicly available models developed as a mechanism to disseminate the results of this work; the increased capabilities of the models used in this and previous work have created value. This project is excellent.
- This project has a generally straightforward expansion of past analysis to cover the optimization of FCEVs on the basis of local ownership cost. The computational tools are well matched with the analysis requirements (i.e., the team selected the right tools for the project).
- This project addresses a key element of system design necessary to enable cost-competitive commercial applications.
- The project team has expertise in the field, particularly in the use of Autonomie.

Project weaknesses:

- The assumption of 5% depreciation loss per year may not be appropriate for fuel cell trucks. The time value of money (i.e., the discount rate) is not clearly taken into consideration in the RCO equations. It appears that the time value of money appears only in some terms. The use of the capital recovery factor is not fully explained.
- The project would have benefited greatly had there been collaboration with an OEM working in this hybrid powertrain area. The collaboration could have been a simple review by an OEM of the input parameters and assumptions made in framing the analysis.
- The project's weaknesses include low levels of funding and poor communication through the slides provided to reviewers.
- So far, the analysis has not really been validated.

Recommendations for additions/deletions to project scope:

- A sensitivity analysis would be beneficial. The optimization results should clearly identify the fuel cell power level. It is implied that fuel cell size is set by sustained highway cruising power, which implies a nearly constant fuel cell power for all configurations, but this should be explained and made clear. The cost assumptions for the fuel cell and battery need to be identified (and included in the sensitivity analysis). The meaning of the statement "the [plug-in hybrid electric vehicle] should run 50% of the daily driving distance with electric power alone" is not clear.
- It is recommended that the team look into whether there is a vehicle demonstration project or any projects that could be used as data points for the validation of the model/analysis.
- Before the slides are published, the team should ensure that results from the $12/gge and $16/gge are included.
- Recommendations for additions/deletions to the project scope are not applicable; this project is scheduled to finish up on August 2018.