2019 – Infrastructure and Systems R&D
Summary of Annual Merit Review of the Infrastructure and Systems R&D Subprogram

The Infrastructure and Systems R&D subprogram aims to reduce the cost of hydrogen production, storage, use, and transport to enable H2@Scale. The subprogram includes three project categories: Hydrogen Infrastructure R&D, Technology Acceleration, and Systems Analysis. The Infrastructure and Systems R&D areas in 2019 included (1) low-cost, high-efficiency liquefaction, pipelines, chemical carriers, and tube trailers; (2) low-cost and reliable compressors, pumps, dispensers, and stationary storage; (3) grid integration of hydrogen production; (4) novel methods of manufacturing and improvements in durability of hydrogen technologies; and (5) heavy-duty fueling technologies. R&D priorities are informed by crosscutting systems analysis. The subprogram collaborates with state and local organizations and other federal offices and agencies (such as the U.S. Department of Defense, U.S. Department of Transportation, and the U.S. Department of Energy Offices of Science, Fossil Energy, Nuclear Energy, Wind Energy, Solar Energy, Geothermal Energy, and Advanced Manufacturing) to leverage outside activities, coordinate efforts, and build opportunities for new technology applications and deployment.

Summary of Infrastructure and Systems R&D Subprogram Reviewer Comments

The Hydrogen and Fuel Cells Program (the Program) reviewers commented positively on the level of industry and stakeholder engagement and participation within the Infrastructure and Systems R&D subprogram. Most notably, the subprogram was lauded for the progress and success of the H2@Scale initiative, though more work is needed. Suggestions for future H2@Scale research topics included further assessment of value chains, such as co-produced oxygen and renewable hydrogen for various applications, especially on a regional basis. There is also a need to identify near-term value propositions to support the transition to H2@Scale.

Program reviewers commended the increased emphasis on reliability and cycle life of infrastructure technologies. Specifically, the work on hydrogen dispenser hoses was called out as an example of successful technology transfer, which is needed to reduce the cost of dispensed hydrogen. In addition, the work on magnetocaloric liquefaction is recognized as having the potential to be high-impact. While Hydrogen Infrastructure R&D was considered to be well balanced, reviewers suggested that there be more research on hydrogen compression technologies. It was also recommended that Hydrogen Infrastructure R&D be expanded as a way to address the near-term priority of low-cost hydrogen.

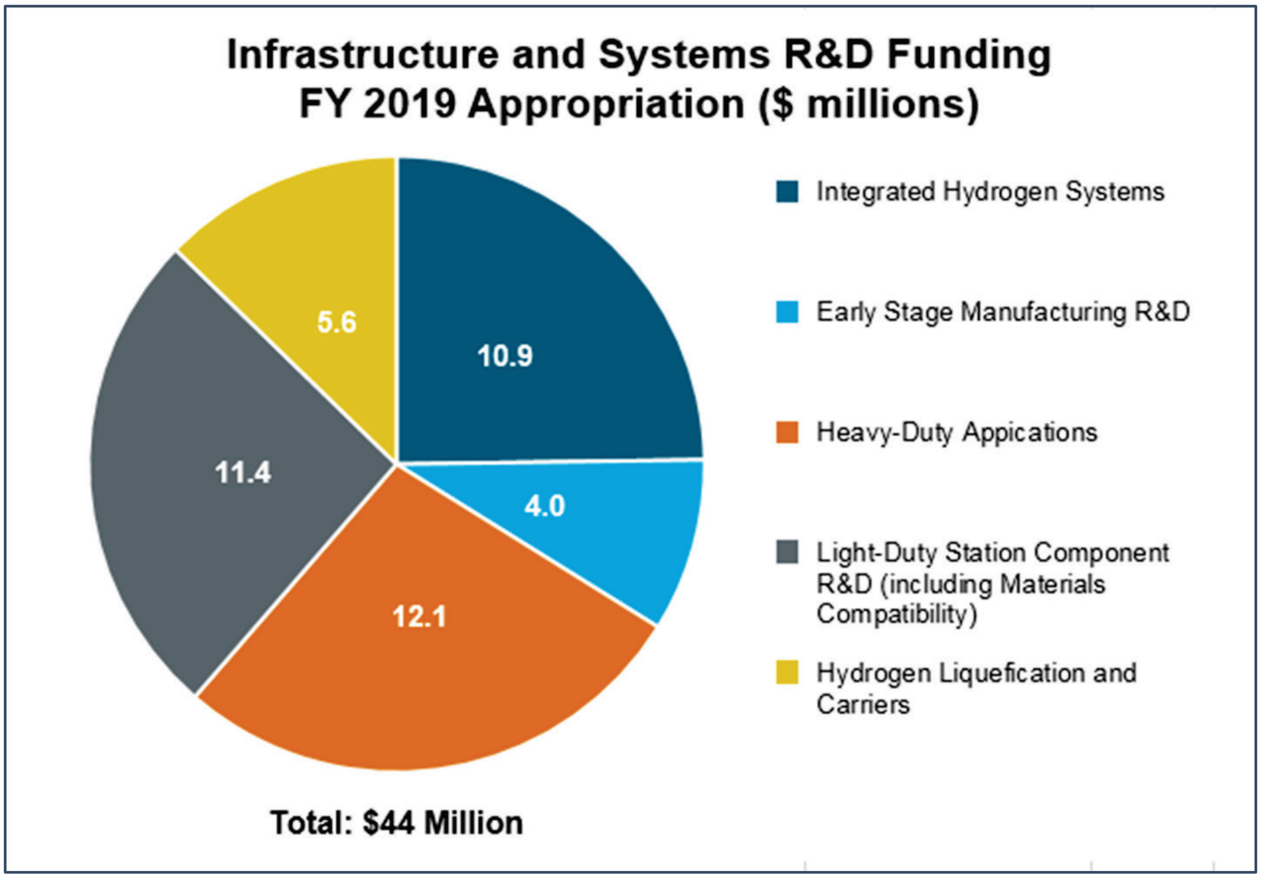
Within the Technology Acceleration activities, reviewers applauded interagency collaboration, as well as stakeholder engagement on new hydrogen and fuel cell applications, such as with the H2@Rail workshop. In addition, the Technology Acceleration project on advanced hydrogen refuelers was recognized for its high impact potential. Reviewers also pointed to the progress made on membrane electrode assembly (MEA) fabrication methods as one of the most significant accomplishments of the entire Program. Reviewers suggested that additional early-stage R&D be focused on manufacturing of hydrogen technologies, in particular low-temperature electrolyzers, to support cost reductions and value chain maturation.

Systems analysis, including technoeconomic analysis, on medium- and heavy-duty fuel cell applications was cited as a strength of the subprogram. Reviewers recommended that the technoeconomic analyses be expanded to assess renewable hydrogen production. The Systems Analysis activities were praised for providing a benchmark for business cases, a tool for measuring progress in market development, and guidelines to the global community. Suggestions for future research topics included life-cycle analysis of various e-fuels, analysis on reducing material consumption to support moving toward a circular hydrogen economy, and energy transition analysis.

Nine Hydrogen Infrastructure R&D projects were reviewed, receiving scores ranging from 2.8 to 3.7, with an average score of 3.3. Nineteen Technology Acceleration projects were reviewed, receiving scores ranging from 2.8 to 3.7, with an average score of 3.3. Under Systems Analysis, five projects were reviewed, receiving scores ranging from 3.0 to 3.6, with an average score of 3.4. The individual project reports in this section contain a summary of the project, the project's overall score and score by question, and the project-level reviewer comments.

Infrastructure and Systems R&D Funding

The fiscal year 2019 appropriation for the Infrastructure and Systems R&D subprogram totaled $44 million. The breakdown between Hydrogen Infrastructure R&D, Technology Acceleration, and Systems Analysis funding is shown in the figure below. The funding is expected to reduce the cost of hydrogen delivery and dispensing, support wide-scale hydrogen production and use, and enable resilience of power generation and transmission. Future work in the subprogram is expected to focus on applied and early-stage R&D for the H2@Scale initiative related to hydrogen production, integrated energy systems (including nuclear hybrid energy systems), advanced manufacturing, and hydrogen energy storage. For Systems Analysis, funding is focused on the hydrogen value proposition for H2@Scale, the levelized cost of hydrogen from renewable and nuclear hybrid-integrated hydrogen production pathways, the impacts of hydrogen delivery/onboard storage/fuel cells on R&D needs for onboard hydrogen storage options and associated costs, emissions from hydrogen pathways for fuel cell medium- and heavy-duty trucks, and hydrogen fueling station business assessments.



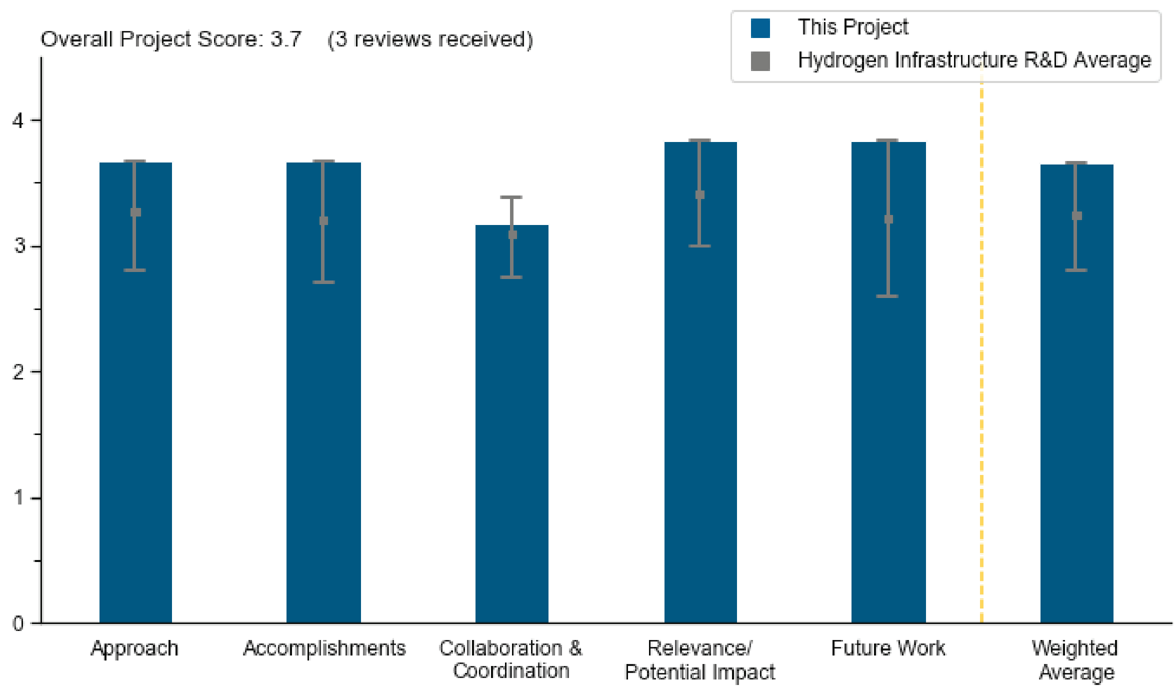
Project #IN-001: Hydrogen Materials Compatibility Consortium (H-Mat) Overview: Steels

Chris San Marchi, Sandia National Laboratories

Brief Summary of Project

The primary objective of this project is to evaluate the potential for modern, high-strength steels to facilitate reductions in the cost of hydrogen pipelines. Specific goals are to (1) characterize fatigue performance of high-strength girth welds in the presence of hydrogen gas and compare performance to that of low-strength pipe welds, and (2) establish models that predict pipeline behavior as a function of microstructure in hydrogen to inform future development.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure R&D projects.

Question 1: Approach to performing the work

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

- The approach is very well founded: focusing on microstructure understanding and then bounding the project with focus on three specific materials and their behavior, with regard to specific behaviors (crack nucleation and cryogenic behavior). There is much to look at here, so this approach will, one hopes, keep it manageable. Also, the approach of defining each task with a “Science Question” provides a great metric to make sure that the work being done ties back to that question.
- This effort is addressing important aspects aimed at understanding the mechanisms controlling the hydrogen embrittlement (HE) degradation process. The project has selected a subset of issues that are critical to informing relevant problems of material capability for hydrogen storage and delivery. Generally, there are multi-scale modeling and experimental approaches that take advantage of some of the unique capabilities at Sandia National Laboratories (SNL). The project’s approach to high-strength ferritic steel microstructures aims to have a mechanistic understanding of fractures and further understanding to inform

resistance in >950 MPa strengths. Further elaboration on the Fe-C-H (density functional theory [DFT] and molecular dynamics [MD]) models is requested. If this is for ferritic stainless steels, then it is unclear how relevant these models are if Cr is not incorporated. The work on the Kelvin probe is very interesting; however, it is unclear what question this is answering, whether the models will be linked to the actual material, and whether the Kelvin probe will be used to try to validate the models. The project's approach to high-strength aluminum alloys aims to understand the mechanism of HE in high-strength Al as well as the role of moisture on surface interactions. The details surrounding the DFT modeling and MD modeling are unclear. It is also unclear if there are any plans to look at the uptake behavior independent of cracking in the hydrogen and H_2O environment; this would facilitate seeing the extent to which hydrogen uptake will occur. Additionally, it would be beneficial to couple some of the MD simulations at the crack tip to the focused ion beam milling (FIB) of **transmission electron microscopy (**TEM**)** results by Gangloff and Ro that quantified the structure. The project's approach to transferability of damage and crack nucleation aims to generate an HE-induced crack nucleation prediction capability framework for fatigue. This looks specifically at models to hydrogen-induced deformation and damage. It is unclear if the team has a means of quantifying the initiation lives or if there is strong evidence that the hydrogen will actually affect the initiation life. This is of particular importance if the project team wants to move toward engineering applications. Oftentimes, large-scale defects (much larger than the atomistic or dislocation processes) will lead to initiation on engineering components. It is not clear how the team is defining "initiation," which is a big problem in the field. The answer to this problem may be dependent on how initiation is defined. This may be defined as the first slip step on the surface, to 1 micron, or to 1 mm. This depends on what resolution is being defined as "initiation." Additionally, the project team's approach to the microstructure of austenitic stainless steels aims to understand the physical process of HE in austenitic stainless steel, which would inform materials design. It is unclear how the team is incorporating the hydrogen into the crystal plasticity model. It is also unclear what parameters the team is modifying, as well as how the boundaries are being handled. It is unknown whether the project team is tuning this via constitutive laws gathered from polycrystals that have been hydrogen-charged or from single crystals. Finally, the team's approach for materials for cryogenic hydrogen service aims to establish metrics and materials selection for cryo-compressed hydrogen storage on vehicles.

- The tasks and questions being answered in this project are well defined. Separating the "science questions" from the "engineering goals" in framing the approach for each task is well appreciated. It is not clear, however, how these five tasks were selected as the focus—whether these were specified in the call or chosen by the applicant.

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.

- This project started recently, so technical results to date are modest. Interatomic potentials have been added to the Large-scale Atomic/Molecular Massively Parallel Simulator (LAMMPS), which is a big accomplishment. There is good progress on the "set-up" aspects of the tasks, and it seems like there should be many good results in the remainder of the year.
- Obtaining the stakeholder feedback and distilling that into a prioritized matrix of materials and failure conditions to test is a worthy accomplishment. It is recommended that the principal investigators do a sense-check on that matrix to make sure that they agree that no high-priority materials or failure modes have been omitted. Likewise, the initial tribology studies and the initial work on the test methods document represent significant accomplishments in the first year of the project.
- This is a new project, so there is not much progress; however, there are clear objectives that will be able to be tracked as progress is made.

Question 3: Collaboration and coordination

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

- There may be more industry and/or supplier stakeholders that could be involved. The discussion in the presentation about contribution from NASA was helpful. Companies like Parker and others are a possibility. This is related to the issue of "validating" the materials and performance criteria that the project team has chosen.
- This is a new project, so the extent of collaboration is yet to be fully established. However, several collaborators were engaged, and these plans are solid and will reasonably improve the project. Such collaborations could and likely will be expanded as the project moves on.
- Multiple laboratories are working on each task; the accomplishments indicate that there is good collaboration between the laboratories thus far. There is no collaboration from industry or academia yet, but it is reported to be in the works—there is a funding opportunity announcement out for industry partners.

Question 4: Relevance/potential impact

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

- Dedicating resources to the fundamental understanding of the materials interaction and degradation progress is very important. Such efforts will develop the data, understanding, and expertise needed to inform the design material selection and the ability to address or avoid issues in structural applications. These materials interaction issues will drive much of the economic consideration in transitioning and scaling hydrogen-based fuel economies. More specifically, by investigating traditional steel materials systems (with modifications) and candidate Al materials systems, this effort is addressing pertinent issues.
- This project is foundational for the goals of DOE and the industry, as it will underpin the design and deployment of safe hydrogen systems and also play a key role in improving the reliability of systems and equipment for hydrogen storage, dispensation, and compression.
- The presentation did not explicitly tie the materials challenges back to specific components in hydrogen storage infrastructure. While the relevance is clear generally, it could be more powerfully stated. The potential impact of this work on the field is demonstrated through the conscientious tying of microscale processes to engineering design. The project team works closely with codes and standards, and information will be disseminated to the industry through those channels. Additionally, advances in understanding of materials properties will be made available to the broader research community via Granta.

Question 5: Proposed future work

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

- The future work is well scoped for the resources of the project, and it would be pretty easy for the scope to grow too far, given the number of materials that could be considered and the daunting task of developing both models and test protocols for a wider range of failure modes. In particular, the focus on looking at the role of water in hydrogen on material degradation seems very valuable. There may be other likely impurities in hydrogen fuel that need to be studied.
- The project's future work directly addresses the challenges identified in each task and is aligned with answering the fundamental questions. It is worthwhile to note that at least two objectives of the project—the identification of a ferritic microstructure with sufficient hydrogen fracture resistance and the quantification of crack nucleation—may not be fully achievable within the scope of the project. However, these are important challenges that should be addressed, even if the ultimate research outcome is unsuccessful or incremental.
- The project team has a good plan; this project is just starting.

Project strengths:

- The project has an excellent technical plan addressing fundamental hydrogen material capability challenges. There is solid engagement in areas and materials systems that are relevant to engineering applications, excellent breadth in the different materials systems and issues, and multiscale modeling and an experimental setup that engages in many disciplines. The project takes advantage of unique experimental capabilities at SNL.
- The project approach is very strong and does a good job of focusing on different length scales and utilizing computational modeling in an impactful way. It also appears that the consortium is doing a good job of leveraging the strengths of various members and collaborating on tasks.
- This is a well-organized project with clear focus on issues critical to safety, reliability, and cost of hydrogen production, transport, and dispensation.

Project weaknesses:

- The project's collaborations are somewhat limited. It is likely that this limitation is a function of the new project and that collaboration is anticipated to grow. While each of the project tasks have finite and achievable goals, in aggregate, there is a good deal of proposed work. The total effort is ambitious.
- The project should have input from more industry collaborators to validate that the materials and impacts being researched are the most important to the industry.
- The broad nature of the tasks encompassed in the project make it somewhat difficult to quantify the impact of the overall effort.

Recommendations for additions/deletions to project scope:

- Specifics plans should be clarified for how the information and results will be disseminated and made available to industry working on component or system design and development. It is unclear whether the project team expects that the work will lead to any specific test protocol recommendations, similar to the polymers project.
- There are no recommendations, but this may change as results begin to be generated.

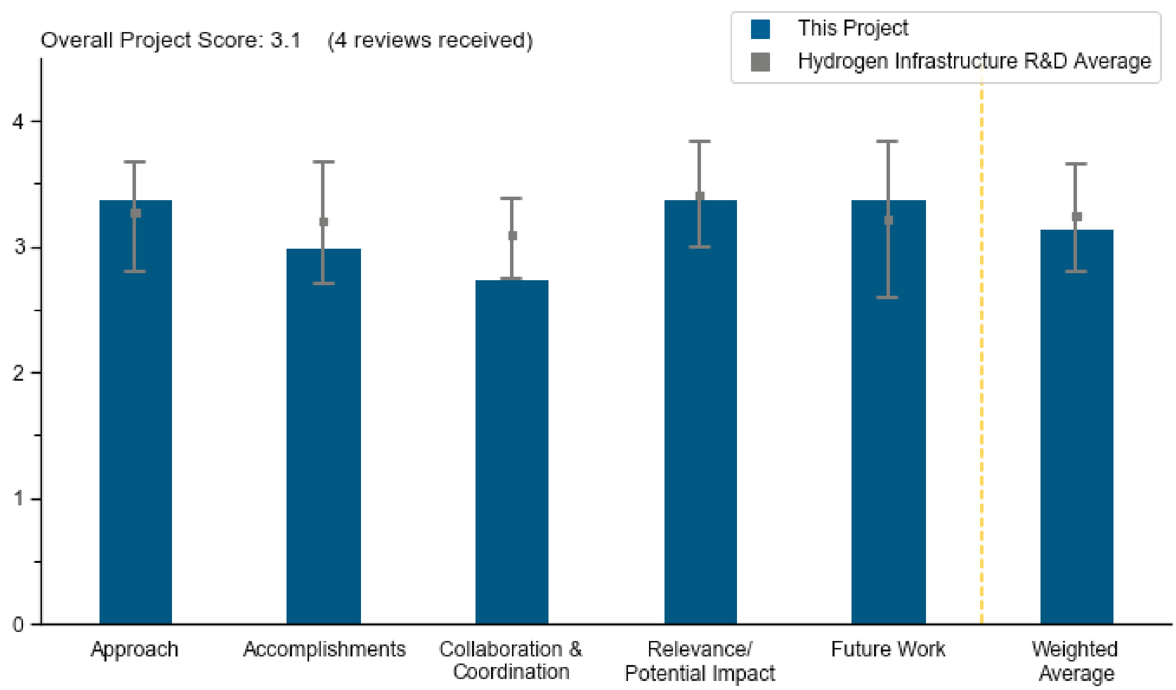
Project #IN-004: Magnetocaloric Hydrogen Liquefaction

Jamie Holladay, Pacific Northwest National Laboratory

Brief Summary of Project

The Pacific Northwest National Laboratory (PNNL) magnetocaloric hydrogen liquefaction system is expected to be considerably more energy-efficient than the Claude cycle. At 30 tons per day, the latter shows 40% efficiency, while the former is projected to be 70%–80% efficient. In this project, investigators will demonstrate the PNNL system liquefying ~25 kg/day. At industrial scales, the concept is expected to have a figure of merit (FOM) >0.5 (as compared to the Claude cycle system's FOM of <0.3). The project will also identify a pathway to a larger-scale system with an installed capital cost of less than $70 million.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure R&D projects.

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 relevant efforts.

- The project has a methodical approach to developing individual aspects of the technology. The project team identified a weakness in the design and applied new innovations to overcome it (i.e., length of magnetic field). The material characterization work by Ames Laboratory is very impressive progress for this application and possibly others.
- The project's approach—to liquefy hydrogen by way of magnetocaloric refrigeration—is very sound. Utilizing the bypass approach is a great way to gain efficiencies by reducing the approach temperature in gaseous hydrogen.
- The project's approaches to increasing the FOM, reducing system cost, and meeting the U.S. Department of Energy's targets are correct. The only suggestions for improvement would be to try to use the system equations on slide 29 to see what other knowledge can be gained from a sensitivity analysis. Much effort

went into the theory and background discussion to justify needing to change the designs to increase the aspect ratio for length to distance (L/D) for an FOM equal to 0.65.
- The presentation focused more on the technology's "potential" than actual progress to prove that potential. This is a concern. The project update presentation jumped around, ran out of time, and did not necessarily focus on the challenges going forward. Two key aspects are recommended for the approach:
    - The project needs to narrow its focus on proving that liquid hydrogen (LH2) temperatures can actually be realized with this technology, and at the efficiency stated—in other words, whether the technology will actually function, and function at the power levels stated.
    - There may be gaps as to the expectations of both power efficiency and capital effectiveness. Both should be critically reviewed this year to have a balanced assessment when compared to reality of actual operation and competing technology. Ultimately, the project must determine the "spigot" cost for LH2 with the capital and operating costs, as well as whether it offers a meaningful reduction in overall cost. This is not stated in direct terms.

  It is encouraging to see that the stated approach is to focus on the lower-temperature regime based on last year's comments, but there does not seem to be actual progress to date, even at the warmer temperatures. Next year's report will be critical to understand if progress is being made on this approach. There are significant deviations from "theory" to "reality," and it is unclear that this project understands.

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 principal investigator has mapped out a clear path demonstrating how his project is aligned with DOE's goal and how it is working toward meeting those objectives. Increasing the FOM from approximately 0.3 to >0.6 was clearly stated and communicated during his presentation. Progress was clearly demonstrated via the use of a "bypass" approach in the two-stage design, and the performance models were validated.
- The project has been able to make significant improvements to stage one of the process by reducing the layer count from eight to five. The presenter mentioned that stage one and stage two will continue developing as separate projects moving forward. It is unclear how the project will capitalize upon the accomplishments of stage one.
- Empirical testing is driving to the liquefaction goal. Understanding material characteristics is revealing the nuances of the magnetic technology. Recognizing the need to target and deliver the 20 K goal is prudent.
- Progress has been slow on actual demonstration of the technology. Even the higher-temperature work encountered issues preventing testing from being completed. There are significant hurdles to the technology, as well as commercializing into an actual industrial project. To a certain extent, the challenges that delayed progress this past year are indicative of the types of issues that will be encountered on a much larger scale as the project continues. There seems to be a "don't know what we don't know" aspect to the work when it comes to actual experience with LH2.

Question 3: Collaboration and coordination

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

- The project has shown good progress with materials work from Ames Laboratory. Collaboration with Washington State to introduce supporting technology is important. Developing a relationship with an organization that can support commercialization efforts, particularly economics, would be a good step in 2019.
- The collaboration with PNNL and Ames Laboratory appears to be really strong. The project does list collaboration with the Hydrogen Delivery Technical Team (HDTT), which includes three energy companies, but it is not clear how or what value HDTT has brought to the project.
- While valuable partners are involved, there are no partners that can provide valuable feedback and input on the actual installation or operation of a LH2 plant. This collaboration is critical to getting the initial system

to work, getting it to scale up to an industrial level, and understanding some of the basic limitations of operating hardware, particularly cryogenic systems. Most important, it is unclear whether it would actually reduce the "all-in produced cost" of LH2 to an extent that warrants the technical risk.
  - There should be a review of competing technologies for capital and electrical efficiency. For example, the work published by Integrated Design for Efficient Advanced Liquefaction of Hydrogen (IDEALHY, a European Union program to develop hydrogen liquefaction capacity in and for Europe) in terms of efficiencies of existing facilities and other cycles (e.g., mixed refrigerants) can also substantially improve existing technologies.
  - The assumptions within the presentation could benefit from critical input from the existing operators of LH2 plants.
- It seems like it has been the same partners for several years working on this effort. The opportunity exists to reach out to others and see what additional partners could contribute to this very important effort.

Question 4: Relevance/potential impact

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

- Applying this technology, particularly for stranded hydrogen streams, has very high potential, assuming reasonable packaging. Large-scale applications might be attractive if the economics are more competitive than traditional liquefiers. International markets where demand is in isolated pockets may be a perfect fit for the technology.
- Alternative forms of hydrogen liquefaction are very relevant when considering the future hydrogen supply requirements for the fuel cell electric vehicle market. Such systems will be key for filling the hydrogen supply gap in areas where distribution is less reliable.
- The principal investigator has mapped out a clear path demonstrating how his project is aligned with DOE's goal and how he is working toward meeting the associated objectives and impacts.
- To the extent that hydrogen liquefaction can be improved from a capital and operating efficiency perspective, these new technologies offer a path to lower-cost production and distribution of hydrogen, which is critical to the success of the market. The challenge is whether this work truly will have a meaningful impact on overall cost. The material has not shown that. Stating unproven reductions in power from 10 kWh/kg to 5 kWh/kg (where 5–6 kWh is the theoretical limit based on exergy) does not provide the potential reduction in overall cost of produced LH2. It is unclear what percentage of overall cost that represents. Similarly, the capital cost numbers as presented are questionable.

Question 5: Proposed future work

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

- The principal investigator has done an excellent job in documenting his past effort, and future work for this effort is based upon sound engineering and scientific approaches.
- It is great to see the focus on 20 K temperature. Credible economics are an important achievement before the next DOE Hydrogen and Fuel Cells Program Annual Merit Review. Proof of design and material changes recognized in 2018 are necessary.
- Future work for this project will focus on the design, build, and demonstration of stage two. The demonstration results from stage one will likely increase stage two development efficiencies. It would be good for the project to clarify the plans to align the stage one and stage two development activities.
- To the extent that the project is focusing on lower-temperature performance and testing, that is good. The project should, in parallel, better quantify the "produced" cost of LH2 to show overall potential of the technology based on what is known today.

Project strengths:

- The overall project strength is high. This technology challenges conventional, inefficient design. The technology may have multiple spinoff applications. Proof of 20 K is vital.
- The project has a strong accomplished principal investigator who is willing to push the FOM for hydrogen liquefaction by pursuing innovative system approaches: two-stage system and advanced technologies such as bypass, layered, and aspect ratios (L/D).
- The project's strengths lie in its ability to deliver a technologically advanced product that has the potential to support multiple markets.
- This is a substantially different technology to liquefy gases to cryogenic temperatures. This is a strength in that, if successful, this technology offers breakthrough potential.

Project weaknesses:

- No major weaknesses were identified, but the project could be strengthened by having more system modeling and a sensitivity analysis of the whole system and its major subsystems that could be optimized or further insights into the overall system performance that could increase the FOM, similar to the knowledge gained from the aspect ratio learning.
- There has been limited progress to demonstrate that the core technology can actually produce the desired temperatures needed to liquefy hydrogen. This will be a critical milestone. The next milestone would be whether the technology can be built to operate at an efficiency to justify its investment. The next milestone would be whether it can be built on an industrial scale, cost-effectively. None of these has been demonstrated yet.
    - There is a lack of actual operating and industrial experience that established companies can provide.
    - Counter to its stated intent, the project presented a cost estimate that does not show a decrease in capital cost. The estimate excludes critical cost elements that are usually included in other published costs. On an apples-to-apples basis, the equipment costs do not compare favorably to existing hardware. The cost estimate is missing costs for land, site infrastructure development, utility feed, hydrogen production, hydrogen pre-purification, equipment installation, truck loading facilities, and adequate product storage. Some portions such as "piping and valves" and "process controls" are substantially less than would be required to integrate a 30-tonne-per-day facility to modern, safe, industrial practice.
- The project's weakness rests in the complexity of the design and the product's reliance on the rare earth materials.
- The economic analysis seems weak and hard to defend. This needs more work by a credible partner.

Recommendations for additions/deletions to project scope:

- The expectations of both power efficiency and capital effectiveness should be critically reviewed this year to have a balanced assessment when compared to reality of actual operation and competing new/improved technology. Ultimately, the project must determine the "spigot" cost for LH2 with the capital and operating costs and whether it offers a meaningful reduction in overall cost. This spigot cost is not stated in direct terms. If a benchmark analysis has not been done with competing new technology as published by other work, such as IDEALHY, then that should be done in parallel with the above technology validation to understand the potential benefit.
- The project should focus on demonstrating that the core technology can work to 20 K temperatures and can approach the desired efficiency. This is a key "stage gate" to pass prior to proceeding further and should be accomplished as soon as possible, especially after four years of work so far.
- The project should maintain the course.
- No additions or deletions to the project scope are recommended.

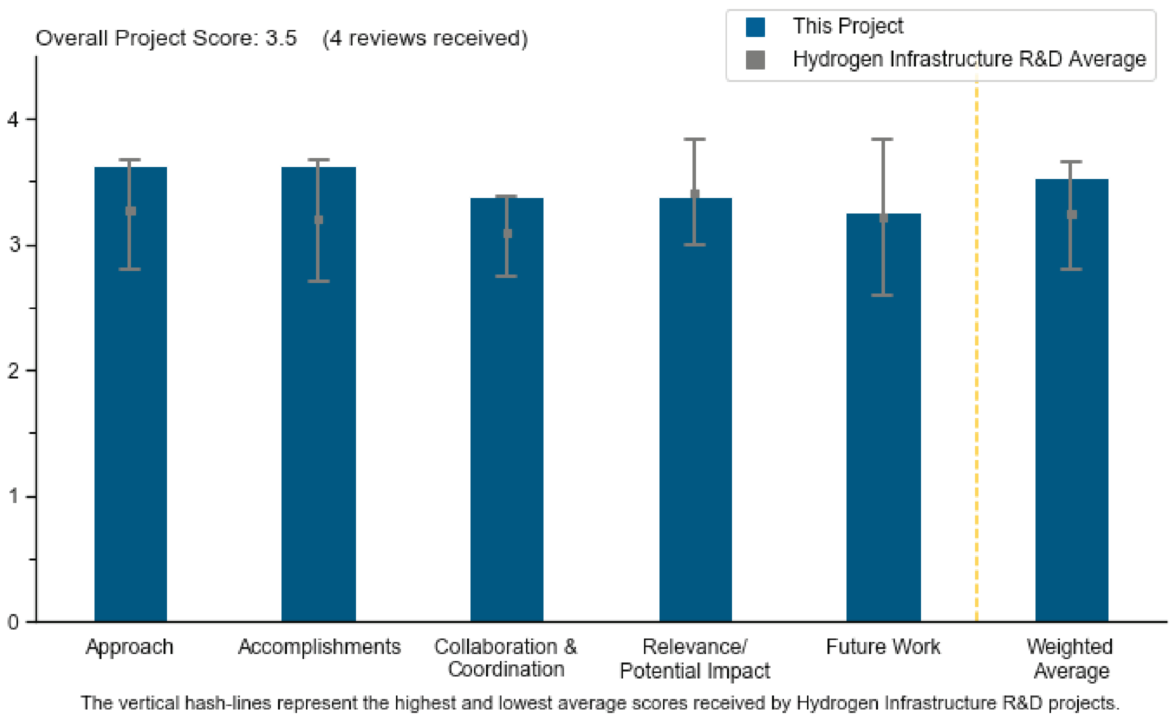
Project #IN-005: Electrochemical Compression

Monjid Hamdan, Giner ELX, Inc.

Brief Summary of Project

This project will develop and demonstrate an electrochemical hydrogen compressor (EHC) that is lower in cost, higher in efficiency, and more durable. Specifically, the project will (1) fabricate hydrocarbon membranes with enhanced properties for use in EHCs, (2) improve EHC water and thermal management, (3) optimize stack hardware and demonstrate cell performance, and (4) build a prototype system. Development of reliable and low-cost, high-pressure hydrogen systems is needed to enable market penetration of fuel cell electric vehicles.

Project Scoring



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 relevant efforts.

- The proposed approach is based on the use of electric potential in polymer electrolyte membrane (PEM) stacks, instead of mechanical compression to compress hydrogen to the pressure necessary to fill up fuel cell vehicle tanks. This technology potentially has higher reliability, lower maintenance, and smaller energy consumption compared to the incumbent technology. Two major differentiations of this project are using solid supported membrane that allows for much higher pressure difference and replacing Nafion-type perfluorosulfonic acid (PFSA) with an aromatic-based PEM that delivers lower cell voltage.
- The work is outstanding. It is very clear that the researcher has approached this work systematically. The project team first achieved 200 bar (compression ratio 10), then 360 bar, and then 875 bar, with a stepwise increase in performance. The team has solved core issues, demonstrated a working system, and increased the technology readiness level (TRL) sequentially, achieving project objectives.
- The team has scaled up the membrane size 6x, which is a good step toward overall scale-up of the EHC technology. The team has also developed a new membrane and a better membrane support (solid supported

membrane) that has demonstrated sealing up to 20,000 psi. Thus, the effort is well directed toward addressing the technical barriers and meeting U.S. Department of Energy targets.
- The project team had a clear presentation, a well-presented approach, and nice modeling work to quantify the performance gaps and tie them into the approach. The project has a good approach for overcoming challenges across various tasks and project elements.

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.

- All of the project's major technical and design milestones have been met, and the project progresses well toward DOE goals. The project team demonstrated a scale-up to 300 cm^2 membrane electrode assemblies (MEAs), which gives confidence to the team's successful project outcome.
- The project team has made excellent progress with the development of a new support structure for the membrane, as well as a new chemistry for the membrane. These achievements have helped the team demonstrate both an increase in system efficiency and the EHC system operating at 875 bar.
- The project's approach and progress are sound. The 875 bar target was met. As the researcher indicated in his presentation, additional work clearly needs to be done to scale up the final system (which hit 875 bar) to a larger size and to lower operating voltage for the compression ratio indicated.
- It seems like milestones are being met and impressive performance is being demonstrated. The status of the project was well articulated for years 1 and 2.

Question 3: Collaboration and coordination

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

- Although the collaborators and their roles have been listed, the overall presentation gave the impression that the work was mainly done by Giner ELX, Inc. (Giner). Perhaps this is an indication of a very tightly integrated team, but it may be useful also to elaborate upon the team members' respective roles in individual aspects of the work and how often the team met, interacted, held discussions, and teleconferenced.
- Giner worked well with outside partners such as Rensselaer Polytechnic Institute. The project's achievements included substantial coordination and involvement from other partners, which demonstrates excellent teamwork.
- From presented data, close cooperation between partners and interaction with collaborators are clearly seen.
- There is good integration among the team members.

Question 4: Relevance/potential impact

This project was rated **3.4** for 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 making good progress toward the technical targets, but its operation seems to have been demonstrated mainly under steady-state operation and not start/stop or intermittent operation, which may create a different set of issues (e.g., thermal expansion and contraction, potential leaks). It would be useful to verify the suitability of the design—for example, with the 50 cm^2 system at 875 bar under intermittent operation—and fix any bugs; this will demonstrate the robustness of the project's EHC system under real-life operating conditions.
- Hydrogen compression is a critical issue that is very necessary in the development of the hydrogen energy infrastructure. Current mechanical compressors are unreliable and expensive. The potential benefits of electrochemical compressors make investment in this technology pathway compelling.
- The proposed electrochemical hydrogen compression could replace unreliable and expensive incumbent mechanical compression and reduce energy consumption. Though this is not critical in constructing

hydrogen fueling stations, this technology could substantially assist in the deployment of hydrogen infrastructure.

- There is a clear opportunity for electrochemical compression, and it is impressive how high the achieved pressures are. Cost may remain a challenge, but this work should be continued to see how far electrochemical compression can be pushed.

Question 5: Proposed future work

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

- Addressing how the system performs with "impure" hydrogen and under start/stop operation would be key to ensuring that the EHC can be a viable alternative to existing hydrogen compression technologies. If, for example, membrane robustness or sealing cannot be maintained, then the effort and labor to replace these, and the resulting downtime, may end up as the same issues that are listed as drawbacks for existing mechanical compressor technology.
- A substantial part of the project's future work is dedicated to stack optimization for 350 bar operation, while 875 bar operation was already demonstrated and is the final project goal. It seems logical to carry out the majority of optimization work for 875 bar. The durability of the stack pressurized operation, especially with the aromatic PEM, is not planned, though it could be one of the major selling points (or the showstopper) of the proposed technology.
- As the researcher indicated, the system needs to be scaled up. All "issues" related to scale-up need to be addressed. Larger active area, higher flow rates, cost reduction, etc. are all crucial to getting this system commercialized. The project needs to migrate to a higher TRL before commercial adoption.
- The project's next steps are clearly described and appropriate, given the current stage of development.

Project strengths:

- The EHC technology offers an attractive alternative to mechanical compression, owing to the lack of moving parts and therefore the promise of lower maintenance and possibly lower capital costs for station installations. The team has made good progress in scaling the system size and operating at high pressures. The team is solving the challenges associated with membrane development and sealing at high pressures.
- This is an important technology pathway and an excellent effort to lift the TRL of this technology. The work that was done in this project is excellent and has raised the bar for the technology. Units were built, tested, and validated, and good data was generated. This is a meaningful contribution to the advancement of this technology.
- The project has a good combination of component and stack/system technical work and technoeconomic analysis. The hydrogen compression data is compared with model work. The pace of the scale-up work is good.
- The project had a very nice presentation and slides, clear technical progress, and a clear plan for the next steps to advance this potentially promising approach to compression.

Project weaknesses:

- The system needs to be demonstrated under real-life conditions, even if at a low hydrogen flux rate of 0.5 kg/hr. With the design's current state of development, the team should be able to project how EHC costs may compare against those of competing technologies. With the estimated system endplate of 12-inch thickness (i.e., 1 ft.) for a 1000 cm^2 active area, a weight of several hundreds of pounds per plate with the additional weight of bolts, etc., is implied. Therefore, the system weight is likely going to be significantly high, which may complicate any potential field repairs. Thus, if the system is "down" because of issues with membrane or sealing that needs to be replaced, the time to bring it back up (unbolting, removing endplates, etc.) may require more than one person and thus increase maintenance costs.
- The durability of the EHC development is not addressed properly at either component or stack level. The reproducibility of large-size PEM and cells should be presented. The technoeconomic analysis lacks sensitivity analysis and comparison with the incumbent (mechanical compression) and emerging

(pressurized electrolysis) technologies on the basis of capital and maintenance costs, footprint, and safety. It is desirable to consider the effect of stack weight (i.e., endplates) on the capital and maintenance costs.
- Additional work needs to be done to increase the size and scope of the system. It needs further advancement before it can be commercialized.

Recommendations for additions/deletions to project scope:

- Rather than focus on embrittlement of the components, a focus on the effect of impurities on membrane operation may be more impactful and relevant to operation in the field.
- Ultimately, this technology will have value only if it is integrated into a commercial arena. The project needs to be supported with that goal in mind.
- A study of durability should be added to the work plan.

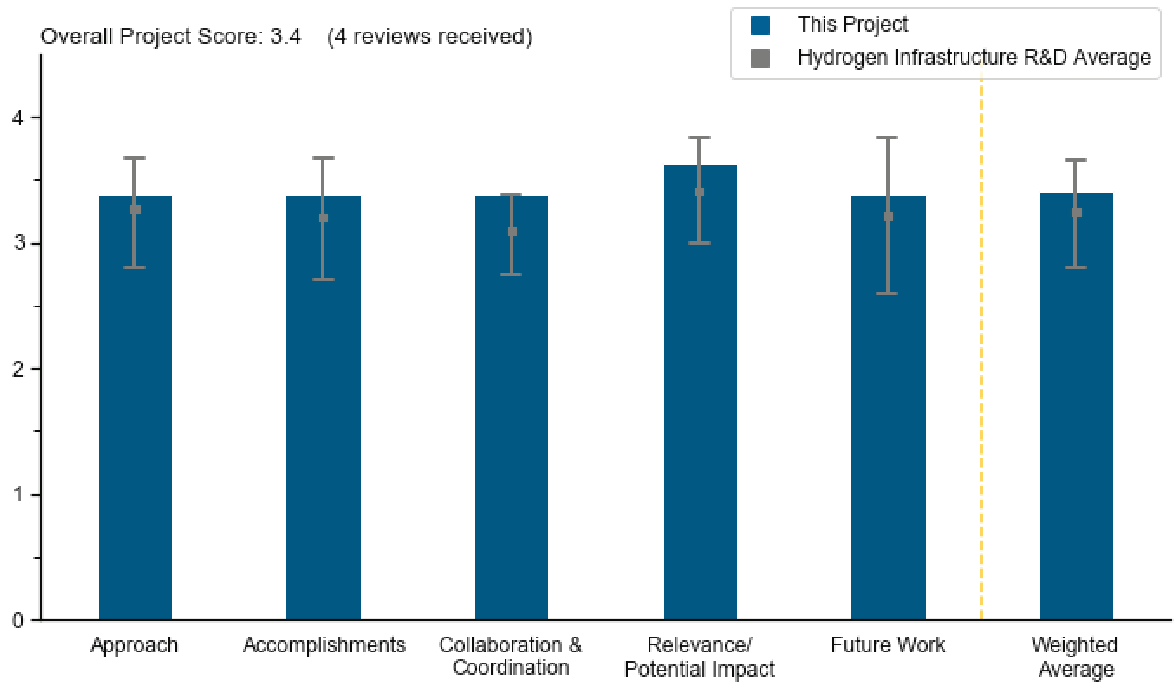
Project #IN-007: Metal Hydride Compression

Terry Johnson, Sandia National Laboratories

Brief Summary of Project

The project seeks to overcome barriers to improve the reliability and costs of gaseous hydrogen compression. The hydrogen compressors available dominate station costs (48%) and downtime (24%); metal hydride compression has the potential to improve the reliability of 700 bar refueling. The project's main objective is to develop and demonstrate a two-stage metal hydride compressor (moving from technology readiness level [TRL] 2 to TRL 5) with a feed pressure of 150 bar that delivers high-purity hydrogen gas at an outlet pressure of >875 bar. Each stage consists of 2–3 hydride beds with materials optimized for that stage. The experiments will be designed to demonstrate a scalable system with a pathway to meet U.S. Department of Energy (DOE) targets. The project will collaborate with synergistic project Hybrid Electrochemical–Metal Hydride Compression (PD-137) because both include a high-pressure metal hydride stage.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure R&D projects.

Note: This is a new project in 2019. Reviewers were given the option not to evaluate Accomplishments. In such instances, the other criteria were re-weighted to total 100% (see the Introduction section for details).

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 relevant efforts.

- The project team's approach is excellent in terms of compressor bed design; alloy material selection, characterization, and testing; and prototype demonstration. The principal investigator's (PI's) leveraging of the expertise of Greenway Energy (GWE), in terms of hydride materials selection and costing, is a very good idea. It ensures that the project progresses in a timely way and meets its intended goals.
- The work is good. State-of-the-art metal hydride systems cycle at a faster rate and hold smaller total volumes of metal hydride materials that are crucial for meeting industry cost targets. Most of the work done

was based on materials from literature review, rather than fundamental understanding of the materials and developing more advanced alloys that can more optimally meet targets. There is scope for this project to do much more, and there are exciting opportunities for the researchers to consider more advanced approaches.

- The project closely integrates system modeling, testing, prototyping, and cost estimation in a way that promises to make tangible progress toward DOE metrics. The barriers and objectives are clearly identified.
- The project's approach to developing a metal hydride compressor is sound and logical. It appears that it solves one problem but introduces other problems. Analysis is needed on how much maintenance the metal hydride compressor needs and on what the cost and frequency are versus conventional technology. The project team needs to investigate what level of conventional compressor improvements would be necessary to meet the hydride compressor, as well as whether that is feasible. Comparison also needs to be done over 10 years of full system operation, including energy inputs. The team needs to know if this would lower the required conventional compressor improvement required to hit break-even. Waste-heat scavenging is a good option, but it limits application of the technology.

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 PI is on track to meet the project milestones, despite the challenges usually associated with managing multiple teams with varying tasks and timelines that are interdependent. The project has managed to complete milestone 7.1 in a timely way. This is very encouraging, considering that the intelligent selection of hydride alloys for use with the compressor is one of the most critical steps for the success of the prototype demonstration. The project has developed a method at Ames Laboratory (Ames) and Hawaii Hydrogen Carriers (HHC) to produce about 4 kg of AB2 alloy for use on the compressor beds. This reproducible method of making the activated AB2 alloy will likely ensure easy scaling of the process at commercial scale. One can envision contracted commercial vendors using this method to make high-quality alloys for hydride compressors. Consequently, there will be fewer issues with variability in the quality of alloys bought from the selected commercial vendors.
- The team has done great work on solving the technical issues of getting a metal hydride compressor to work. This is excellent analysis and predictive work.
- The project has made excellent progress on components and prototype design. Delays from suppliers have led to late completion of milestones, but the project should not be held accountable for these delays. Still, it is a bit concerning that there is no target delivery date for the high-pressure vessels.
- To the extent the project has met its work plan, it has accomplished the tasks as provided. Therefore, it is on track with the goals it has set out. For DOE goals to be met, however, the project course needs to be adjusted to bring it to par with state-of-the-art systems.

Question 3: Collaboration and coordination

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

- There appears to be effective collaboration between the three groups (Sandia National Laboratories [SNL], HHC and Oak Ridge National Laboratory [ORNL]), as well as with Ames and GWE's project (PD-137). The project team is made up of companies that are world experts in the fields of hydride technology and prototype design and fabrication. These companies have previously performed related projects, potentially making it easier to conduct project communication, time management, cost estimation, and materials sourcing. All the project partners are fulfilling their objectives; for instance, SNL is on track to accomplishing the design and fabrication of compressor system components, and HHC and ORNL are completing the sourcing, ball milling, and characterization of the hydrogen storage properties of the alloys for use on the laboratory prototype.
- The collaboration within the team is very strong, and the project's close interactions with GWE appear to have been helpful, particularly for selecting high-pressure candidates. However, the team could benefit from stronger interactions with other DOE and university efforts on the materials side. The team has

excellent expertise in metal hydrides, and discovery of a better high-pressure candidate is outside of the project's specific scope. This is not in dispute, but there could be opportunities for broadening the selection efforts beyond literature reviews by partnering with other institutions.

- It appears the work is well coordinated within this area of expertise. Stepping up to a higher level through targeted use cases would be beneficial to bolstering those cases and providing justification for the energy inputs required.
- There is clear evidence that the researcher has worked well with outside partners.

Question 4: Relevance/potential impact

This project was rated **3.6** for 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 will enable reliable and cost-competitive hydrogen refueling at 700 bar, if successful. High-pressure mechanical compressors are available; however, they require huge capital investments and maintenance costs. Therefore, metal hydride compression could provide an economical, reliable alternative with longer life expectancy. Through this project, new metal hydride alloys for the high-pressure stage could be identified and tested under practical conditions, paving the way for the future discovery of alloys for two-stage 700 bar compression.
- Hydrogen compression is a critical issue within hydrogen energy infrastructure. Current mechanical compressors are unreliable and expensive. Alternate approaches are a must. Metal hydride systems offer an excellent pathway for hydrogen compression and should be explored as part of the overall technology portfolio.
- The project is very innovative and important for the Hydrogen and Fuel Cells Program. It has the potential to revolutionize the current compression technology, which remains one of the biggest cost drivers in hydrogen.
- The technical relevance helps solve issues related to conventional compressor durability and maintenance; however, it is difficult to see the relevance outside certain applications with excess heat available. General mechanics can service conventional compressors, but it is not clear how a hydride compressor is serviced (on the rare occasion it needs service).

Question 5: Proposed future work

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

- The project places high emphasis on prototype integration and testing of the complete compressor, which are logical next steps. Since performance and cost are ultimately related to the choice of materials, it is unlikely that high-efficiency targets will be achieved. However, demonstration of the compressor should still be considered a significant advance, and the plan for future work is well positioned for this.
- The proposed future work is a logical development from the previous year's work. Future work is aligned with the project's objective of demonstrating metal hydride compression at 700 bar to increase the TRL of this technology from TRL 2 to TRL 5.
- To the extent that the project has been mapped out, the researchers' proposed future work is consistent with the proposal. However, it is suggested that the researcher review other work in this field and channel his future work toward meeting state-of-the-art standards in this field.
- All future work is logical and relevant to demonstrating this technology.

Project strengths:

- The project is made up of teams who are experts in the field and who have performed similar types of projects. The project has managed to make significant progress in design and fabrication of components for the hydride compressor and in the selection, characterization, and testing of the hydride materials. The team has managed to make their own alloy combination for the laboratory-scale prototype, which is a significant step, given that the development of alloys was not a core activity of the project. The project has also managed to stay on track, even though it has been challenged by material quality issues from commercial

vendors prior to deciding to make the material in-house. There are no issues envisioned with the team's completing the remaining milestones. However, to achieve milestone 10.0 and be on track to meet DOE 2020 targets, the team should devote more time to prototype assembly, integration, and testing, as it usually involves dealing with unknown unknowns and requires numerous iterations to perfect the system.
- This is a very strong and innovative project with excellent expertise, a clear work plan, and potentially high technological reward. The team deserves credit for its focus on prototyping and demonstration, as well as its consideration of cost projections in the system analysis. The combination of system modeling, design, and technoeconomic analysis is an asset.
- The project team has done excellent technical work in identifying materials and characterizing performance. There are great models of performance.
- The researcher has good fundamental knowledge of this field. The work has been competently done, and the engineering effort is solid.

Project weaknesses:

- An inherent challenge of the project is its lack of focus on the development of a high-pressure stage material (250 to 875 bar). Materials development is outside the scope of the project, and the project is focused on the selection of literature-based materials, which in most instances would be extrapolations for the high-pressure stage; therefore, it is hard to fault the project when the literature materials do not practically behave as predicted. Ideally, separate and complementary efforts should be made to develop high-pressure hydride alloy materials that can be tested under practical conditions in this project. To ensure the project does not end because of lack of funds, better predictions or projections of the costs of materials and components are needed, as well as sensitivity analyses to mitigate cost overruns, especially when planning for future phases. The practical scalability and reproducibility of the Ames alloy synthesis method at large scale needs to be determined.
- Ultimately, the compressor technology's viability depends on the availability of a suitable high-pressure hydride material (which was also identified as a key challenge by the project team). Although the project rightfully focuses on technology demonstration rather than materials development, tighter connections could be made with external DOE and university projects (including international efforts) that are focused on materials discovery and optimization. The team should consider expanding their collaboration network to include researchers who could provide these materials solutions within the compressor design.
- For this technology to be economical, the researcher needs to improve thermal transfer rates, reduce material use, and improve cycling time. This is crucial to the success of the project.
- The project needs a fundamental justification or plan for reducing the energy inputs.

Recommendations for additions/deletions to project scope:

- There needs to be a comparison of metal hydride compressors to electrochemical compressors; a detailed analysis of the full system operational costs, including energy; and a break-even analysis on the required conventional compressor improvements needed to meet metal hydride operational cost.
- This project needs more aggressive targets to bring the work to industry state of the art.
- The project scope is good and attainable.

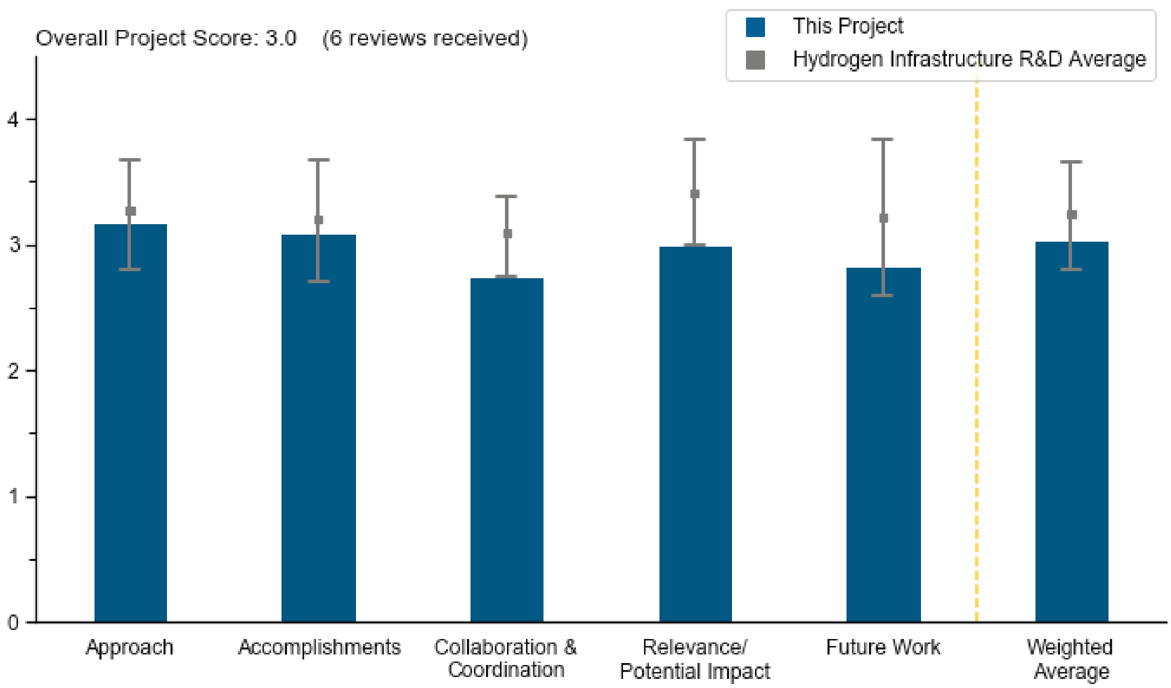
Project #IN-008: Dispenser Reliability

Michael Peters, National Renewable Energy Laboratory

Brief Summary of Project

Hydrogen fuel dispensers are a top cause of maintenance events and labor time at hydrogen fueling stations. This project seeks to identify the proper balance between dispenser costs—both capital and operations and maintenance (O&M) costs—and performance. The project consists of three major tasks: (1) a technoeconomic analysis of capital and O&M improvements to the chiller/heat exchanger, (2) reliability testing of dispenser components, and (3) development of an open-source and free hydrogen fueling model.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure R&D projects.

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 relevant efforts.

- The work represents an important step in the development of hardware and methods for testing component failures under simulated operating conditions. This is an important research topic, and the data generated will be important.
- The approach of using a device with consistent and realistic conditions (i.e., in low temperature and at pressure) is a great way to evaluate dispenser components.
- The project's approach to testing dispenser reliability is sound. Utilizing multiple dispenser subassemblies (i.e., valve panels) is a very sharp approach that will optimize the time and cost for testing and data evaluation. Of the 40 test samples or subassemblies, it appears that some of the components used may not be true representations of the components used at current stations. It would be closer to ideal to test components that are representative of the current market.
- The approach to evaluating dispenser reliability is sound, and, per the presentation and supporting information, the principal investigator (PI) went to lengths to drill down into the root cause of failures and

the causes of shutdowns in the dispensers. One piece of the approach that may be lacking is whether the project is actually using valves, for example, that are being used in the field and are having issues. The presentation was not totally clear as to this point. The high-cycling test setup and leak detection method are very good.

- The use of a fill profile similar to the National Fuel Cell Technology Evaluation Center's fill and the use of a Kaplan–Meier analysis seem to be an appropriate approach. However, it is impossible to operate and analyze the systems in all permutations and combinations of temperature, humidity, etc. Therefore, the approach of testing a few dispensers with a limited range of variables seems to have limited value. The materials testing effort, pre- and post-hydrogen exposure, will produce valuable scientific output. Perhaps such materials work could be performed under the Hydrogen Materials Compatibility Consortium umbrella instead.
- The project appears to cover all the bases that can be covered based on the funding available.

Question 2: Accomplishments and progress

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

- The project has successfully simulated numerous test fills that are aligned with the SAE International J2601 fueling protocol. This is key for establishing a quality batch of data. Additional progress has been made in identifying that the equipment installation requirements were also significant contributors to the failure life of the components (i.e., valve stem torque). These are both great accomplishments. Understanding the results of Sandia National Laboratories' (SNL's) material analysis for the failed components is what is missing for this presentation. It is understood that SNL has a separate poster presentation for this effort. It would have been nice to include SNL's general conclusion of the findings in this presentation.
- The researchers have accomplished a good amount during this time and found key areas of failure. The way to address this is less apparent, as they do not have a good closed feedback loop with the valve manufacturers specifically to find out why things fail as they do (beyond their own hypothesis). Closing this loop would provide invaluable feedback to industry. The team does have a good close collaboration with the makers of nozzles and breakaways. It appears from the data that the bulk of the issues are with valves specifically; after 800 cycles, it appears there is a 100% chance of a failure of some sort. The statistical analysis of the predictive failures of the valves is reasonable and correlates with the project data. Further testing would provide this, but with valves from a different manufacturer, it is not clear that this would still be predictive. It should also be determined whether the data would be the same and whether the predictive calculation would give the same results if the valve stem torques were checked out of the box.
- Leaks and dispenser downtime are costly and affect customer experience and the safety and integrity of the station near the user. By simulating the fill profile, conditions, and indicative component failure, the components that need to be improved can be identified. This is a good step in the right direction. The project team should be able to evaluate the types of valves and determine which ones are more robust under operating conditions. The reseal effect should be used to understand what properties may be permanently changing as the components heat up to cause a reseal and when they return to operating low-temperature conditions.
- The project's progress and accomplishments are good overall. However, it is not clear what serves as the benchmark for each of these individual component failure rates; it may be equipment experience from compressed natural gas or industry operator expectations for a certain failure rate. This should be clarified. As far as the difference for actual torque compared to the torque manufacturing set point, it is not clear what the industry experience is for any other valves or valve stems with a torque manufacturing set point (for any fluid and/or pressurized gas). Observations and claims mostly indicate that those that integrate components into full systems (such as dispensers) should adopt a practice of always verifying the torque of newly received components. It is also unclear how much leakage is realistically acceptable.
- The quantity of data is low, mostly owing to the extended time that is required by the testing, rather than to any lack of effort on the team's part. Perhaps it would be possible to add additional test bays or to create duplicate test stands to increase the rate of data generation. This is probably outside of the project budget, but it is worth considering for future testing.

- The team detected and recorded leaks and failures, but the project has not shown the entire range of data, e.g., what components failed (other than the leaks due to the valve stem torque). It is not clear what value the present form of the leak and failure data that was presented will provide to the community, other than the fact that the team has quantified the number of leaks and failures of a limited set of systems and concluded that low temperature and high humidity are "bad." Materials analysis is a good start.

Question 3: Collaboration and coordination

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

- Working with the valve manufacturer is a necessary and good step in the project. By providing the manufacturer with access to the test apparatus and data, the team is allowing for the validation of the testing methods and providing valuable feedback to the manufacturer on both the test standards and the field operation conditions; these may provide insights for future design and materials selections.
- The collaboration between SNL and the National Renewable Energy Laboratory (NREL) is well managed. The delegation of the hardware testing and the material analysis is a great way to ensure quality effort is being invested on each side. With the exception of Weh Technologies, Inc., and Walther–Präzision, additional collaboration with other component suppliers would have been ideal for comparing previous failure results. Overall, the collaboration is excellent.
- Although there seems to be good collaboration with certain manufacturers, there should be an opportunity to bring more component manufacturers into the mix as the industry grows. There may be an opportunity to bring third-party testing organizations into the project to help develop certification standards for critical components.
- It is good to have the main (current) stakeholders involved and engaged. However, including large valve and component manufacturers would help benchmark feedback for test observations; both current partners are boutique manufacturers compared to the market of conventional fuel component suppliers.
- Dispensers are made up of different parts: valves, instruments, nozzles, hoses, and breakaways. There is good collaboration for nozzles and breakaways. For the valves—which make up the bulk of maintenance needs and failures on this test setup—the project does not have a good feedback loop. Valves were chosen mainly for cost and, according to the PI, not necessarily because of their usage in the field. It is to be determined how the data will be made useful when it is non-attributable to industry. A good approach would be to work with willing participants (e.g., manufacturers) who want to improve their products and reliability in this specific market.
- Some coordination seems to exist between the two national laboratories in terms of failed components from testing that are being provided for materials analysis. Collaboration between the dispenser system provider and NREL did not seem to go beyond setting up their dispensing system for evaluation. It is not clear that the discussions with the system provider led to any meaningful progress in system design or material selection.

Question 4: Relevance/potential impact

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

- System reliability is and will remain one of the key issues facing station operators. Customers expect stations to be operating 24–7–365, without exception. Data like those being generated here can help in designing and maintaining components and systems to meet these targets.
- This project satisfies the targets for relevance and potential impact very well. Station reliability is a key driver for market stability. The results and findings of this project will help improve station reliability and, ultimately, customer satisfaction within the market as a whole.
- The project shows the challenges the industry faces as car deployment ramps up and the stations become fully utilized. Many of these issues were not readily apparent in the demonstration period with low station utilization. Having testing devices that simulate high-volume throughput is a good way to put components to test as the market matures.

- The relevance would be much better if the poor reliability of the valves could be tied to feedback to the manufacturer to improve the manufacturer's product and, if that was then included in retesting, to see whether there was improvement. It is not certain that this is a good baseline of understanding (1) when the manufacturer may not be representative of what is in dispensers and (2) when the chosen manufacturer does not care about the results, as was more or less expressed. This may be more the fault of the valve makers than the PI.
- The relevance of the statistical population for dispenser failures is barely acceptable when compared to the typical minimum population requirement used for scientifically acceptable conclusions. Because of the impact of heavy-duty (HD) hydrogen fueling stations on hydrogen cost reduction, it would be good to extrapolate the lessons learned for HD H70 high-flow fueling.
- The potential impact is not very clear.

Question 5: Proposed future work

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

- The project does a good job at identifying areas of concern for future work (e.g., the impact of humidity and ambient temperature changes). It is not clear that the project plans to address any of the identified concerns during future testing. The approach of conducting statistical analysis is a really great way to capitalize on the testing result and provide the industry with some tangible information that can be applied to existing stations.
- While the data for specific components will be an important deliverable from this project, a more impactful deliverable could be establishing a standard for the equipment and methodology used for component testing. The team should consider using this equipment and methodology to establish a testing standard, if they have not considered it already. The number of components needing testing will go well beyond what is covered in this study, and the methodology could become a service provided to component manufacturers, or it could provide a basis for a component certification process or design standard for the industry.
- It would be good for this project to continue and to integrate with the valve manufacturer to make either material or design changes themselves. A non-disclosure agreement with these companies would be invaluable. Feeding this information into the development of codes and standards for valves and fittings would also be supportive to providing a framework to allow the industry to follow some guidelines.
- The proposed future work should include hoses since these are a large cause of leaks and failures both at the fittings and at the hose itself. There could an opportunity to develop a test standard for hoses as well.
- This project should not spend time on a station operator's costs when a leak or failure occurs, as this is already part of project TA-014: Hydrogen Station Data Collection and Analysis. The project should stay focused on generating empirical and test data, not doing cost analysis and modeling. The team should consider including more details in the project report on specifics of where leaks occur and the potential observations of environmental factors' influence on leaks (even though this specifically would take much more time, possibly years).
- The proposed future work appears to be unfocused and very generic; it does not seem very impactful.

Project strengths:

- The strengths of the project include (1) that it recognizes how important it is to test components under operating conditions in hydrogen and (2) that it provides a consistent approach for testing and comparing alternative valve designs (e.g., plunger versus rotating) and the same component from different manufacturers.
- This is a very good and solid approach, with rigorous testing and modeling of predictive failures. The project has a great test setup; there is great potential if the team continues to provide valuable feedback to industry and standards developers.
- The project's strengths include the initial effort to generate data that can provide early indicators of failure rates for hydrogen dispenser components and information about where failures appear to occur first. This motivates the industry to put effort into designing and building robust dispensers with lower maintenance needs.

- The project's strength is the test bench. The test bench is closely representative of what hydrogen stations are experiencing every day, and therefore the resulting data has an extremely high factor of reliability.
- The project has generated valuable data by quantifying and statistically analyzing failures to provide real data for design improvements.
- The mathematical analysis of failures is a useful aspect of this project.

Project weaknesses:

- The number of cycles and data sets is relatively small. Also, the leak detection methodology may be overly sensitive in comparison with the way some leaks are actually discovered (i.e., a pressure leak test during fill). This could drive impractical solutions for small leaks that might be tolerable under normal operating conditions. Zero leakage from all valves and fittings would be preferred, but as long as the leaks are below lower explosive limits, zero leakage may or may not be practical.
- There is a lack of feedback channels with valve manufacturers. The actual use of these manufacturers in the broad hydrogen dispenser market seems uncertain. Better feedback from industry would be helpful to make sure that NREL is testing what is broadly used in the field. Going by the pictures, one of the manufacturers is not used by anyone.
- The project's weaknesses include the small number of project partners. It is easy to get distracted by topics other than generating failure testing results and data. Also, this project covers only light-duty dispensers; because of the low throughput, this effort may have a marginal impact on reducing the cost of fuel.
- The project's weakness is that not all of the components tested are truly representative of what is in stations today. The presenter mentioned that the project is using a "low-cost" valve instead of the more popular, more expensive option.
- The project is frustratingly slow in gathering sufficient data for a meaningful statistical analysis.
- The primary approach seems to be "try and see," which is not impactful.

Recommendations for additions/deletions to project scope:

- The project team should not include cost analysis efforts as part of this project; this is distracting and should be left up to the dispensers and station operators that are responsible for cost and economics. NREL labor hours should not be used for this. The team needs to assess when leaks are realistically unacceptable and redefine what is acceptable. The team should also provide dispenser integrators and operators with recommendations related to torque manufacturing set points for newly used dispenser components. The project team should also develop and/or research industry benchmarks for the failure rates of components, based on conventional failure rates.
- It is recommended that the project team create a feedback channel with codes and standards bodies based on data sets, and test other manufacturers in the set-up to correlate data among a broad set. There are currently at least six big players, with others trying to enter the valve market. These include Tescom Corporation (part of Emerson Process Management), Nova Swiss, GSR Ventiltechnik, Eugen Seitz AG, and Swagelok, none of whom are represented in this testing set.
- It would be nice for the project to test the unit under varying ambient temperature and differing dew points, something identified as a concern.
- The project should bring in hose manufacturers. The team should consider bringing in a third-party test organization in an effort to develop a certification standard for critical components to which manufacturers would need to conform.
- The project team should consider expanding the test apparatus to test more data and components.

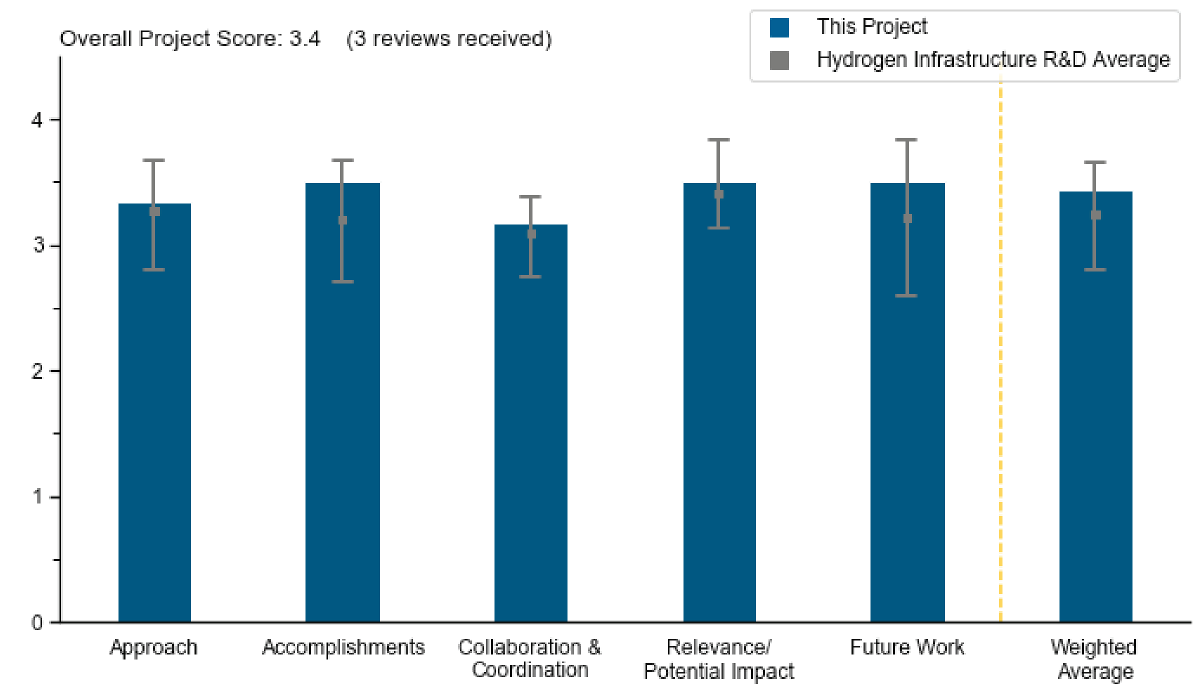
Project #IN-009: Advancing Hydrogen Dispenser Technology by Using Innovative Intelligent Networks

Darryl Pollica, Ivys Inc.

Brief Summary of Project

The primary objective of this project is to develop a robust and cost-effective system for dispensing and measuring hydrogen; the system is meant to further enable widespread commercialization of fuel cell electric vehicle (FCEV) technology. Key project activities include (1) development of robust sensor hardware and algorithms that improve accuracy based on empirical testing and enhanced meter temperature measurement; (2) development, testing, and demonstration of the use of dedicated short-range communications (DSRC) for use in vehicle refueling; and (3) simplification and cost reduction of flow control and hydrogen pre-cooling systems.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure R&D projects.

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 relevant efforts.

- This project's approach is excellent. The team has a clear plan to improve multiple systems within the dispenser. The systems they plan to improve consist of the Coriolis meter and the standard Infrared Data Association communication protocol.
- The approach to this work has been laid appropriately on foundations of safety, accuracy, and practicality. The effort has followed an appropriate plan to produce new results for applied technology in the hydrogen dispenser domain. Collaboration with industry and the National Renewable Energy Laboratory (NREL) has been beneficial. Field trials are being implemented.
- The project used an integrated approach, combining DSRC and an improved Coriolis meter, and built a dispenser system with a cooling system as well. The team used existing DSRC technology for this project

and claimed that it would be compatible with 5G standards in the future. The approach was to validate the work via a bench test prior to moving to field testing, which seems reasonable.

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 accomplishments achieved so far are great. The project has completed the manufacturing of the dispenser assembly, which included the high-accuracy flow meter. Additionally, the project has integrated a high-accuracy servo flow control valve in place of the standard pressure control valve that is utilized in stations today.
- The applied use of the DSRC system and the improved design of the Coriolis flow meter and heat exchanger have comprised advancement in accurate and safe hydrogen-dispensing design. The potential positive market impacts can be identified based on increased accuracy and benefits in cost and design. The field trial, when completed, will help support the validity of the concept.
- The team has been able to achieve metering accuracy of 2% at bench scale and has made progress toward a lower-cost heat exchanger. The team has also completed installation of the system at NREL's Hydrogen Infrastructure Testing and Research Facility, and it remains to be seen if the metering accuracy can also be achieved during field testing or if the heat exchanger performs as well as simulations indicate.

Question 3: Collaboration and coordination

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

- The project's collaboration and coordination with other institutions are very sound. The combination of leading institutions with knowledge in both hydrogen station system design and hydrogen metering technology is very advantageous.
- There is clear demonstration of coordination between the solution developer, the key suppliers of the specialized technology, the user community, and the national laboratory community. Opportunities for direct collaboration with the automotive industry for the on-board communication solution are ongoing, and the additional expansion, which is necessary, will need to be accomplished outside of the project.
- The presentation lists the areas in which the team is collaborating with other partners. Details of such collaborative activities would have been useful, such as those pertaining to the design of the dispenser enclosure (and an explanation for why it is the largest-cost component of the prototype) and the integration of the Coriolis meter.

Question 4: Relevance/potential impact

This project was rated **3.5** for 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 scope of this project has great relevance and impact for the FCEV market. All accompaniments will bring great efficiencies and improvements in terms of both cost and reliability.
- The benefit of the improved accuracy of hydrogen dispensing, with reasonable cost, supports advances toward DOE Hydrogen and Fuel Cells Program goals and objectives.
- The project has made progress toward improving the meter accuracy, using a DSRC system for communication, and developing a lower-cost heat exchanger. It seems that the improved accuracy is based on empirical testing to some extent, so it is uncertain how the algorithms (based on empirical testing) hold up during field tests. The adoption of the DSRC system by automotive original equipment manufacturers (OEMs) is uncertain, although the team claims that it will be transferrable to 5G systems. The practical implementation of the brine-based heat exchanger is yet to be seen, but it appears to have lowered the cost somewhat.

Question 5: Proposed future work

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

- A significant portion of the proposed future work is related mainly to the validation of the dispenser. Although challenges are likely to arise, the project has shown that these challenges can be overcome.
- Completion of the field trial, which is being implemented in the coming weeks under an extension, is quite important. Future work beyond that trial is not contemplated, as the project is scheduled to end in June 2019.
- The proposed future work matches the team's work plan, although they appear to have lost the field demonstration site, which will directly affect their ability to complete their work scope.

Project strengths:

- The project has integrated collaborative industry and national laboratory partners to advance design concepts for more accurate and cost-effective dispensing technology. This demonstrates that safety, accuracy, and practical deployment have been prioritized. The use of several innovative approaches to metering, cooling, and communications using practically grounded principles can be impactful for the industry (pending the outcomes of the field trial proof of concept).
- The strength of this project is the approach to improve existing dispenser features with more innovative solutions that station developers can implement into their designs.
- The work seems focused on addressing specific challenges, and the project has addressed them (e.g., metering accuracy, communication, lower-cost heat exchanger).

Project weaknesses:

- The field trial is critical and has not yet been completed (although it is being implemented). The practical scale and impact of the project will depend, to a degree, on support from the automotive sector in taking up the communication solution. This highlights the need for continuing the expansion into the automotive sector and amplifying awareness of the benefits.
- The details of what is novel about this project's dispenser system are not clear. The details of "cost-optimized hydrogen safety system" are not given. The use of brine may, over time, lead to scaling (e.g., salt deposit) that could lower the system's heat-transfer efficiency. There is a big risk as to whether the DSRC technology will be accepted by automotive OEMs.
- A weakness for this project is in the reliance on the OEMs' acceptance of the proposed DSRC hardware. There is no clear plan or strategy that has been shown to ensure an acceptable level of confidence to overcome this issue.

Recommendations for additions/deletions to project scope:

- Unless it was already shown in prior years via bench-scale testing, the team may consider tests to demonstrate the purported advantage of the DSRC system, i.e., that only one roadside unit is needed to communicate with multiple nozzles.
- During testing of the DSRC technology, it is recommended that the project request early participation from the OEMs. Presenting only a findings report may not suffice for their full acceptance.
- Additions to the project scope are not applicable, as it is concluding in June 2019. No deletions are needed.

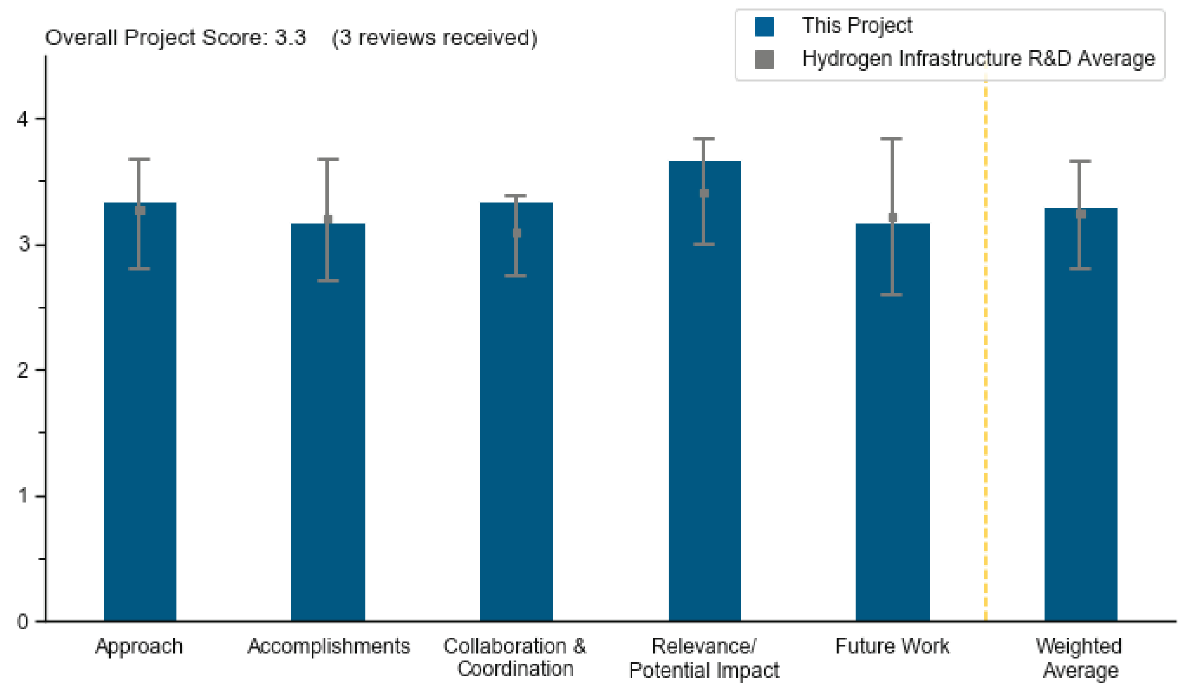
Project #IN-010: Cryogenically Flexible, Low-Permeability Hydrogen Delivery Hose

Jennifer Lalli, NanoSonic

Brief Summary of Project

This project aims to develop a hydrogen hose for fuel cell electric vehicles (FCEVs) that is (1) engineered to be flexible and enable hydrogen delivery at less than $2/gge, (2) durable in conditions of roughly -50°C and 875 bar for H70 (70 MPa) service, and (3) reliable and safe for conducting approximately 70 fills per day for more than two years. NanoSonic, Inc. (NanoSonic) is partnering with two national laboratories, a standards development organization, a local government, and industry to implement and test a cost-effective, metal-free, high-pressure hydrogen hose design that meets the above criteria, resists hydrogen embrittlement and contaminant leaching, and endures mechanical fatigue.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure R&D projects.

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 relevant efforts.

- The project is following a good, logical process to improve the design of the fitting/hose system.
- The project has a sound approach to the work, including well-developed ideas for overcoming obstacles.
- The approach seems fine, although the approach to finding an acceptable fitting to swage on the end seems problematic. NanoSonic states they do not design fittings, so they work with machine shops to come up with some to connect to the end. This is a large reason that a high mark cannot be given, as without this there is no dispenser hose.

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.

- Everyone would like to see the fitting–tube interface problem solved, and in spite of the ongoing difficulties, there is confidence that the team is on a good path. Results are never guaranteed in research and development projects, but the knowledge that is being developed by the team and the potential for a step-change improvement in cost or performance calls for continued support and potentially even extension of the project.
- The accomplishments in the materials science of the hose are good and well done. One of the keys to ensuring proper applicability is to have the hose tested on hydrogen gas. Until now, all testing has been done on hydraulic fluid and nitrogen, which are not indicative of how well it will react with hydrogen.
- Some obstacles were identified, including significant fitting failures that could hamper the work. However, alternate solutions were provided.

Question 3: Collaboration and coordination

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

- The project is well connected to collaborators who will ensure project success, including the National Renewable Energy Laboratory (NREL) and CSA Group (CSA). CSA could also potentially support future certification efforts for NanoSonic.
- NanoSonic has a great array of collaborators on this project who will be able to provide integral feedback to project outcomes. Beyond Cardinal Rubber & Seal, Inc., though, it is not totally clear who is doing exactly what.
- Given the ongoing challenges with the tube–fitting interface, it would be good to get a fitting manufacturer on the project, as the design, materials, and function of the metal fittings are not in the project team's expertise.

Question 4: Relevance/potential impact

This project was rated **3.7** for 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 development of alternative choices for high-pressure fueling hoses for FCEVs is critical to the success of the FCEV industry. Current products are not suitable for the mass market, and this technology is necessary to get us there.
- The development of a low-cost and long-life hose would work to address one of the biggest failure modes of current station operation. If the design and cost targets of the project can be met, this would be significant.
- Hose lifetime and cost are critical areas for dispenser reliability and cost; through this work, it appears the project can produce a hose at a very attractive cost point. Testing with hydrogen will be critical.

Question 5: Proposed future work

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

- The future work at Pacific Northwest National Laboratory and NREL is appropriate. Hydrogen testing is the critical path, but solving the fitting slippage will of course come first.
- There are good next steps planned in getting the laboratories involved in analysis of the failure modes.
- One minor weakness of future planning is the lack of direction related to actual tests using hydrogen gas. Much of the development efforts are using hydraulic fluid, and it is important that leakage, permeation, and gas-cycle testing be performed with hydrogen gas.

Project strengths:

- The project's overall strengths include the development of a critical piece of the fueling puzzle, which is currently a barrier to the commercial success of hydrogen as a vehicle fuel. Furthermore, this is a well-managed project that is poised for success.
- The project has a good, strong team with obvious expertise in flexible hose design. This is an important topic with directly impactful results, if successful.
- The project has strong materials science accomplishments and data. Other strengths include the strong reduction of permeation with special filaments and the project's methodical approach.

Project weaknesses:

- NanoSonic would benefit from seeking out a partner with deep experience in hose-crimp technology. There are countless companies with which to engage, not the least of which would be Swagelok or Parker Hannifin, among others. These companies would see the value this work provides to their business and would therefore make for a strong partnership that would push NanoSonic over the top.
- The overall project weakness is a lack of planning for testing with hydrogen gas, including leak, permeation, and impulse/pressure cycling.
- There is a weakness in expertise for fitting design and metallurgy.

Recommendations for additions/deletions to project scope:

- The team should add hydrogen-specific tests to validate the project: leakage, permeation, impulse/pressure cycling. The team should also examine the American National Standards Institute/CSA Heavy Goods Vehicles 4.2 standard and choose key performance tests to further validate the product.
- The team is on a good path and has shown great strength in working to solve the interface problems.

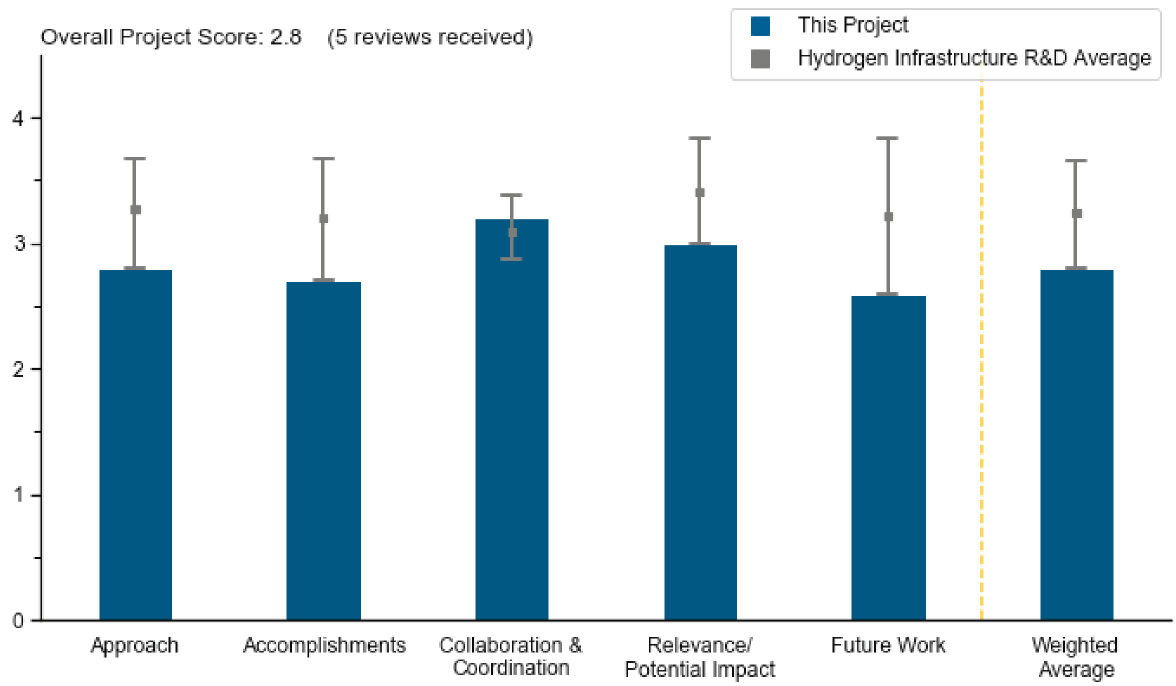
Project #IN-011: Coatings for Compressor Seals

Shannan O'Shaughnessy, GVD Corporation

Brief Summary of Project

Seal failure is a major contributor to hydrogen compressor maintenance, adding significant downtime and cost to compressor operation. The goal of this project is to improve seal life in hydrogen compressor systems by three to five times. The work focuses on two different types of coatings. For static seals, the project will develop barrier coatings that mitigate hydrogen ingress into the seals, which prevents premature failure. For dynamic seals, low-friction coatings that reduce wear and extend seal life will be developed. A room-temperature polymer vapor deposition process will be utilized to produce thin polymer coatings for both types of seals.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure R&D projects.

Question 1: Approach to performing the work

This project was rated **2.8** for identifying and addressing barriers, project design, feasibility, and integration with other relevant efforts.

- Hydrogen station reliability is a critical topic regarding the future success of the fuel cell market. This project's objective is to make tangible improvements to seal life with vapor-deposited coatings. The approach taken constitutes two types of coatings, targeting both static and dynamic seals. Existing station reliability data were used to determine the strategy. The plan is dynamic and provides a high probability for success.
- Seal wear and hydrogen leakage are important problems that need to be solved, and the barrier coatings and lubricious coatings approach has merit. The team seems to have started addressing production issues (e.g., inclusions, uniformity) but did not provide data to support the statements on success in solving these issues. The work to test the coated seals in a compressor is a good start. The work scope seems very similar to prior years, and the presentation did not provide specific milestones or stage gates against which project progress could be evaluated.

- The approach of the project is interesting—to apply thin vapor-deposited coatings on O-rings to create a barrier and lubricious surface—but it is unclear that this effort has any chance of improving the critical issues with elastomeric seals. The barrier coating has a high likelihood of capturing the hydrogen in the elastomer, which would result in explosive decompression. The lubricious coating could be helpful, although there could be other options for the design, such as the surface finish specification.
- The approach is sound but could use some improvement. The justification of the helium results as a surrogate for hydrogen was not clear. More time should have been spent rationalizing this. There were some data that indicated the hydrogen permeability data did not correlate with the helium permeability data; more time should have been spent discussing this discrepancy.
- This talk and presentation were a little hard to follow. It sounds like the hydrogen barrier coatings work has not gone well, and the project is shifting to the low-friction seals for piston heads. A good deal of background material was included, but the specific relevance to this project was hard to follow. It sounds like the work on hydrogen barrier coatings is still on helium, and hydrogen testing has not yet started. Improved clarity on what exactly the project's approach is would be helpful.

Question 2: Accomplishments and progress

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

- The project has made significant progress in regard to the overall objective to improve seal life by three to five times. The coatings have demonstrated the reduction of helium permeation and mass loss for dynamic seals. Although helium is a comparable gas to hydrogen for testing, it will be interesting to understand the coating's true ability to reduce permeation in high-pressure hydrogen applications. Nevertheless, the results show that successful high-pressure hydrogen testing is achievable.
- The work with a national laboratory to demonstrate the usefulness of the coated seals during compressor operation is good progress. Likewise, the connection with additional industry customers is a step in the right direction. It would have been useful if the team had presented data that supported the claims that the project increased the deposition zone by 10x through changes in chamber geometry. Likewise, the results of the permeation tests would have been useful to support the team's claims of success in solving inclusion-related problems.
- The accomplishments are well-defined, but the discrepancies with the test data need more explanation.
- Progress toward the overall project and DOE goals appears to be slow. In fact, the hydrogen permeability function of the coating did not provide positive results because of issues with applying the coating. Because of these results, the project has decided to stop effort with the barrier coating evaluation and focus on the lubricious coating. This change in direction seems to acknowledge the coating's lack of ability to provide the barrier function, which is more important to the DOE goals than the lubricous function.
- From the presentation, it sounds like the hydrogen barrier coating work has failed. It does sound like there is some promise for the low-friction coatings, although apparently only 50 hours of testing have been done so far. Specific quantitative metrics for the low-friction coatings were not seen in the presentation, nor was how well GVD Corporation (GVD) is doing in meeting those metrics.

Question 3: Collaboration and coordination

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

- The team has a good balance of original equipment manufacturers and testing facilities. This will allow for quality test specimens and data validation. Overall, the collaboration and coordination is well covered. Additional collaboration with active station owners would be an added benefit.
- It sounds like testing is taking place at NREL, which is a good partnership.
- The team has a good list of collaborators that will support the success of the project.
- The collaboration with the national laboratories (e.g., National Renewable Energy Laboratory [NREL] and Oak Ridge National Laboratory) is good. Additional collaboration with industry partners beyond Takaishi Industry Co., Ltd., would have been useful for obtaining feedback regarding the application and failure

modes. In addition, the project should have contacted Pacific Northwest National Laboratory (PNNL), which is leading the Hydrogen Materials Consortium effort on polymer compatibility with hydrogen.
- Various partners seem to be providing support, mainly through testing the coated products rather than participating in an integrated effort. It was not clear how the total funding was distributed across the partners or how to evaluate the level of support that each provided. One of the tests that was being run at the national laboratory was cut short because of equipment failure, but no plan was presented regarding whether the testing will resume or what the schedule might be.

Question 4: Relevance/potential impact

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

- DOE's objectives are in support of systems that are both "reliable and affordable." This project is aligned in both aspects. As stated in the project's objectives, the goal is to improve maintenance frequency and decrease hydrogen cost per gasoline gallon equivalent (gge). This is excellent.
- Compressor reliability is significant weak link in the fueling station system. Any improvements to minimize down time and increase reliability and durability are critical to the success of the fuel cell electric vehicle industry.
- Hydrogen permeation and the lubricity and wear of the seals are important aspects to preventing equipment down time in hydrogen infrastructure. However, the properties of the polymer of the base component (e.g., the O-ring or a gasket) also play a role, and it is possible that the O-ring/gasket performance is not mitigated (or mitigated to only a limited extent) by utilizing the project's coatings. Although the project's coating technique could theoretically be applied to a large number of components simultaneously and for components of shapes other than O-rings/gaskets, the project has not shown data supporting these potential attributes.
- The need to evaluate hydrogen compatibility with polymers is important. The project appears to significantly overstate the relationship of seal failures with the cost of hydrogen. It is not clear how improved seal performance would ever reduce hydrogen compression, storage, and dispensing costs from $3.50/gge to $2.00/gge. The project makes statements about the impact of seal failures without any evidence or other supporting information.
- Because there were not clearly defined metrics in the presentation, it is hard to determine the impact. Clearly, there could be a benefit, but the potential for this approach to provide the full benefit for compression was hard to follow.

Question 5: Proposed future work

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

- The project has achieved an acceptable level of success during testing, and it plans to expand the testing soon. Additionally, the project has already begun to supply the product to industry stakeholders for testing and plans to increase that effort in the future.
- There is a definite need to pursue hydrogen permeation testing and other performance tests using hydrogen gas. It is unclear whether the team has considered explosive decompression in hydrogen environments.
- The team is focused on field trials and building commercial partnerships, which overall are good and reasonable steps. However, a significantly greater scope of technical work than just partnership-type activities was expected, based on the level of funding for the team's Phase IIA work.
- There were not many specifics in the future work.
- The proposed future work for this project indicates dropping the barrier coating effort and focusing only on the lubricious coating. This change of direction will further reduce the relevance of this project. The wear of O-rings has not been identified as a critical barrier for the industry. Certain suppliers may have issues with the wear of O-rings, but this may be due to their design or incorrect selection of O-ring material.

Project strengths:

- A key strength of the project is that it is addressing a major low-reliability component in the fueling station system: compressors. The technology offers promising results, as shown with the data from Powertech Labs, Inc., and HydroPac, Inc.
- The project's strength is having multiple approaches to improving seal failures (i.e., barrier coating and lubricious coatings).
- The company is leveraging barrier-layer technology to mitigate down-time issues in hydrogen infrastructure equipment.
- The project's strength is thinking "outside of the box" to improve the failure modes of elastomers in hydrogen applications by using a coating.
- It sounds like NREL will do testing of the low-friction seals, which is a good step.

Project weaknesses:

- The project activities, milestones, and stage gates are somewhat poorly defined. Although the team seems capable, the work presented is missing the scientific depth and understanding relative to other projects within the Fuel Cell Technologies Office.
- It is concerning that there is little supporting data showing that the improved seals are actually effective in hydrogen environments. There is a need to explore testing at higher temperatures and higher pressure (1000 bar).
- The weakness for the project is the fragility of the barrier coating application. As mentioned during the presentation, "Hydrogen permeability did not match the helium permeability due to particulate inclusion in films caused by modification of deposition chamber." If this application can be improved to withstand minor defects, the barrier coating application will be considered excellent.
- The project weakness is the focus and overstatement regarding the impact of seal failures. The lack of data indicating the improvement of the barrier coating and the sensitivity of the application process are weaknesses of this project. In addition, the test conditions to evaluate the permeation were only at ambient conditions and low pressure. The project has notable weaknesses in the approach and execution of developing a robust seal to address the seal failures. A response was also provided during the presentation that this coating is intended for applications that are not in constant exposure to hydrogen, which is a weakness because of the limited application of this project effort.
- This presentation and set of slides were hard to follow. It is unclear what the metrics are, how far along GVD is toward achieving them, or what the specific approaches are to improvement.

Recommendations for additions/deletions to project scope:

- The project should consider analyzing coating efficacy on different polymer systems, since vendors may use a variety of different formulations for their respective seals and O-rings. Such data could possibly show the efficacy and/or generality of the approach for different polymer systems and may help guide manufacturers in polymer selection. The team could consider verifying the uniformity of coatings when a large number of components are coated simultaneously (for higher throughput), as well as when coating components with more complicated geometries.
- A recommendation is that the project use failure mode tools (e.g., failure mode and effects analysis) to examine the potential of the coating to provide the necessary functions in the application. The project team should contact PNNL regarding evaluating polymers in hydrogen applications. The project should not dismiss the barrier application, even though it will be difficult because the lubricious coating is less interesting and less impactful.
- It is recommended that the team conduct sample-level permeation testing using hydrogen, evaluation of explosive decompression, and evaluation of the material's resistance to higher temperatures (operating) and pressure (up to 1000 bar).
- The project should evaluate the possibilities of modifying the barrier and lubricious coating application methods for other materials and surfaces (e.g., sliding surfaces of compressor piston chambers).

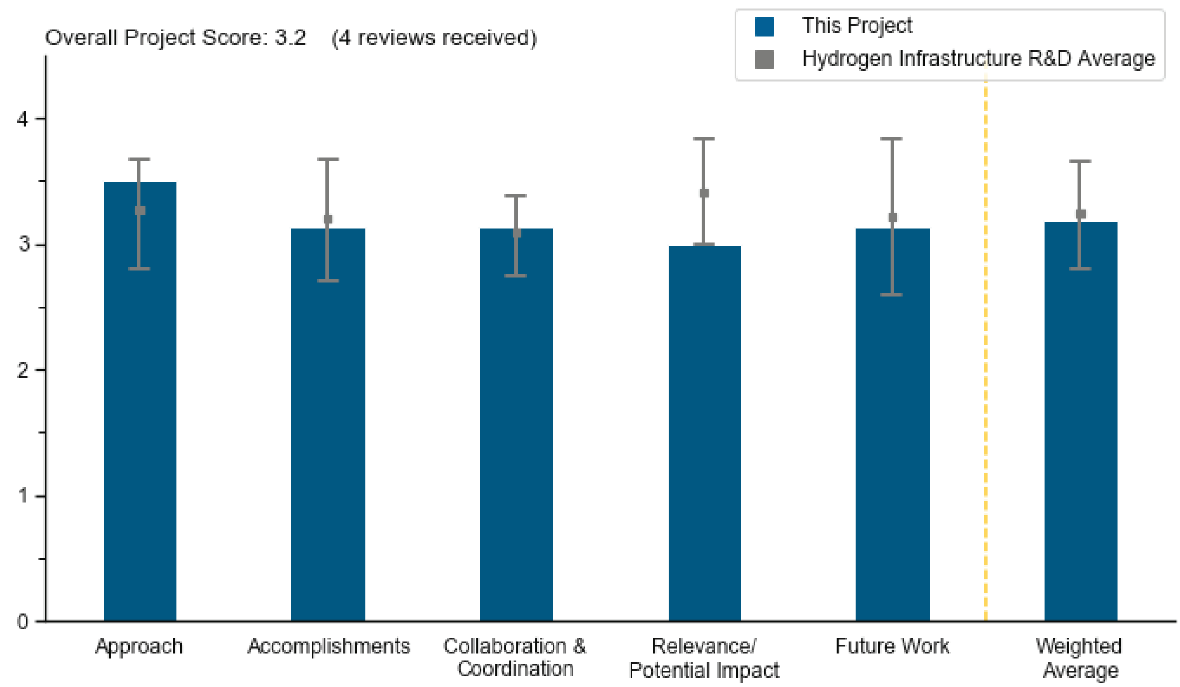
Project #IN-012: Low-Cost Magnetocaloric Materials Discovery

Robin Ihnfeldt, General Engineering & Research

Brief Summary of Project

Hydrogen is less expensive and safer to transport and store in liquid form. However, converting hydrogen and keeping it in liquid form is not easy. The energy required for hydrogen liquefaction at the point of production is high, and hydrogen boil-off from cryogenic liquid storage tanks needs to be minimized. This project seeks to address the high cost and low energy efficiency of hydrogen liquefaction. To overcome these barriers, this project is developing a low-cost, energy-efficient magnetic refrigeration technology for hydrogen liquefaction. The project objective is to discover, develop, and commercialize low-cost, high-performance magnetocaloric effect (MCE) alloys to enable magnetic refrigeration to move from prototype to production.

Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Hydrogen Infrastructure R&D projects.

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 relevant efforts.

- The principal investigator's (PI's) approach is strong and sound. The approach of focusing on a low-cost and small-scale hydrogen liquefaction system has many merits overall. The focus on MCE material cost versus magnetic field cost is nothing new to the field, so there was a need for some additional insight into why the approach, which focuses only on materials with a second-order-only response and uses low-cost rare-earth materials, is going to maximize the search for better MCE materials. Overall, there is confidence in the approach and the PI's ability to deliver a few promising MCE materials.
- The characterization of the materials and the application of the doping solution to enhance performance are impressive. The development of casting techniques is important work for materials development. Achieving high stability for MCE materials is vital for the development of magnetic liquefaction.

- The project's approach of avoiding rare-earth materials is a good strategy to narrow options and improve efficiency. The project also does a good job defining the material requirements for conducting the research, much of which is based on what exists in the commercial market today.
- The approach to date seems good and is focused on material research. However, task 2.4, to develop a "small-scale" hydrogen liquefier, seems to be a significant deviation from the objective of discovering and commercializing MCE alloys. The "materials" skills to evaluate and discover MCE alloys are significantly different from those for producing an operating refrigeration system that utilizes those materials as only a part of the device. This step does not seem to fit with the stated objective and should be part of a redefined project with a different purpose and potentially different or additional skills.

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 progress on the stated objectives appears good, as shown by the presentation materials and the "percent complete." The true evaluation of the project's success would be implementation by the magnetocaloric hydrogen liquefaction (MCHL) project led by Jamie Holladay (IN-004).
- The materials development and characterization are impressive. Material functionality is vital work.
- The material synthesis was successful, allowing the project to commercialize a product in small quantities.
- The accomplishments for this effort are strong. The team demonstrated the performance of several low-cost second-order MCE compositions for a wide temperature range (9 K–325 K) and showed that anneals are required to achieve good MCE properties. More was expected from the material discovery at this stage of the project. It is too early to comment on DOE's targets since the project does not have a prototype yet or a system model based on the material's performance.

Question 3: Collaboration and coordination

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

- The team presented a long list of partners and their roles. As part of a small business, the team understands the importance of leveraging resources and knowledge from others.
- The project has exhibited great collaboration with universities and other related DOE projects.
- It is not clear how closely this project has worked with the MCHL project led by Jamie Holladay. Presumably, that project is the logical beneficiary of this work, but that project is not listed as a collaborator. The team should clarify whether connections have been made such that these are the materials that will be used by that project. Also, in terms of the next step for developing a "small-scale" hydrogen liquefier, performing this seems better suited for the MCHL project as a first step to validating the technology, not by the project that was tasked with materials development. The partners listed will not have meaningful input into the technology needed or the ability to integrate into an actual system. During the presentation, there was a comment that some potential future partners have been "engaged," but until they are formally part of the project, it is a risk that there will be no meaningful technology input for handling liquid hydrogen (LH2), nor input to commercial application. For example, a 300 kg liquefier is small-scale from the perspective of "production," but it would be very large from a perspective of "boil-off" recovery.
- It was good to see a diverse set of partners, but this technology needs more exposure to a wider variety of applications to secure help with further funding. The project lead needs to expand potential applications in the energy field to underpin development support.

Question 4: Relevance/potential impact

This project was rated **3.0** for 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 materials being developed within this project have a strong relevance to the application of liquefying hydrogen. For the fuel cell industry, the use of LH2 in transportation minimizes cost and logistics. It would be advantageous for the project to identify other direct or indirect applications to utilize the materials.
- This is a blended score. The relevance is high (3.5) with respect to developing adequate materials to validate the MCHL technology, although its value is predicated on successful results that prove it to be substantially better than existing LH2 production. The relevance is low with regard to the "boil-off recovery" extension of the project. It is not clear how the boil-off recovery advances the DOE targets for 30 tons per day (tpd) and 300 tpd production of LH2, nor how it achieves a production cost of $3/kg. Boil-off recovery is an after-the-fact "system improvement" tool for a fueling station and has no impact on production cost or efficiency. Its process parameters would be different, and the economics are substantially different from production. Boil-off efficiency can also be (and has been) approached via other existing technical approaches. It is not clear this would have any benefit until a preliminary economic evaluation is completed.
- Addressing the high cost and low energy efficiency of hydrogen liquefaction is critical to the DOE Hydrogen and Fuel Cells Program goals and objectives. This performer brings some uniqueness to the DOE's research and development portfolio by focusing on small-scale systems. The researchers claim that the modeling results for their small system look promising and their system could be used as a low-cost solution at fuel stations for preventing boil-off losses, but few details were presented, and what was presented was presumably preliminary findings. There is much anticipation for next year's presentation, in which the team might elaborate on these modeling results and the approach.
- Striving to achieve high-efficiency hydrogen liquefaction is an important goal; however, there must be other applications that can utilize this technology.

Question 5: Proposed future work

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

- The proposed future work is strong. There is much anticipation for the prototype activities, focusing on having an optimal design determined from the team's model efforts this fiscal year (FY). The potential Phase IIa and IIb will be based heavily on the outcomes from the FY 2019 activities, but building a small-scale system is a natural progression if the project is successful with the FY 2019 activities.
- The project has a clear strategy for scaling up the MCE materials production line.
- The focus on driving for lower-cost materials is appreciated. Improving low-temperature performance is good. The project needs to identify new sponsors in liquefied natural gas, cryogenics for super colliders, and space or satellite applications.
- This is a blended answer. The future work proposed to complete material evaluation is good. The proposed future work for item 2.4 needs significant evaluation as to scope, need, and technology prior to being included in this project.

Project strengths:

- Their biggest strength is that the project is focusing on a low-cost and small-scale hydrogen liquefaction system. Hopefully, the team is not biased too much from larger systems and instead learns from them and approaches this challenge with an innovative solution that leverages the fact that the system is small; this could be a game-changer if the project is successful.
- The identification of materials to enable magnetic refrigeration is core to that technology. This project seems to have made progress in that area and has been successful. The project can likely be closed when this work is completed.
- The project's strength rests in its support from the project collaborators, such as the hydrogen liquefaction design team.

- The project is high in strengths.

Project weaknesses:

- There was hope that this material discovery approach might have been broader in techniques and results, but overall, this is a strong project.
- It is not clear that the MCHL project is benefiting from this work; it might be, but it is not clearly stated. Transitioning from a "materials expertise" project to a "system" project is a significant change that does not align with the original objective. It is recommended that this work be done as a separate project or integrated into the MCHL project since it requires substantially different expertise and experience from the materials work. It is also not clear that any evaluation has been completed that would indicate that developing a "boil-off recovery" unit is economically justified or technically possible.
- The project's weaknesses are in expanding potentially high-value applications.
- The project's weakness is the lack of access to equipment for larger-scale processing of materials.

Recommendations for additions/deletions to project scope:

- The scope is strong.
- It is recommended that the team complete the materials work. For the boil-off work, it is recommend that it be deleted since it does not fit the original objective and is of substantially different scope and expertise. If there is desire or intent to proceed, then it should be separated into its own project to be evaluated on its merit. If the boil-off recovery work continues, then the team should (1) perform an economic analysis of the capital and operating costs of such a unit, (2) evaluate the optimal size of such a unit (i.e., whether 300 kg is the right size; it is probably not), (3) evaluate its benefit relative to DOE objectives, (4) evaluate existing technologies (e.g., cold heads and recovery compression) that are commonly used today for comparable applications to see whether a magnetic refrigeration system offers any benefits, and (5) develop partnerships that can meaningfully help with the technology evaluation, economics, and technology development needs and provide input into the potential deployment strategy.
- The team should maintain the focus on technology and expand the focus on applications.
- There are no recommendations for additions or deletions to this project.

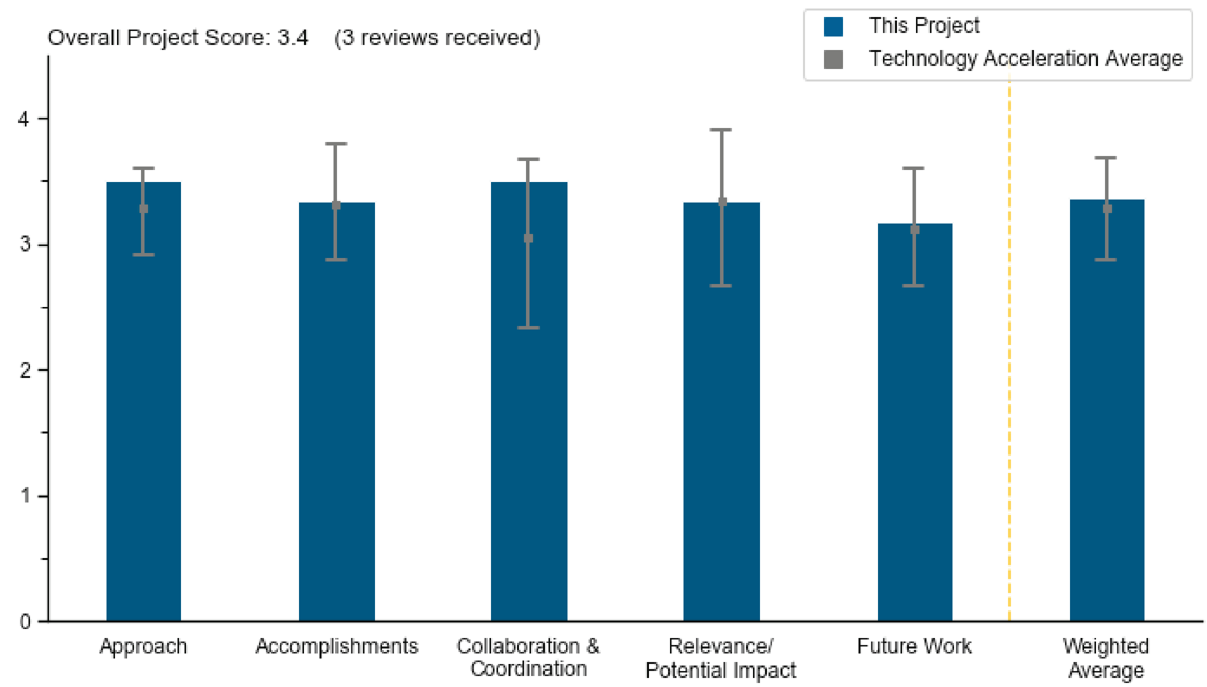
Project #TA-001: Membrane Electrode Assembly Manufacturing Research and Development

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.

Project Scoring



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

Question 1: Approach to performing the work

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

- This is an excellent project. A systematic approach is being pursued to determine the capabilities of various diagnostic tools for quality control/quality assurance (QC/QA) of membrane electrode assemblies. The team is working to understand industry needs fully and is designing project activities in response to those needs.
- Advanced on-line QC tests are a critical need. The use of optical methods is innovative. Efforts to measure impacts of defects from a quantitative perspective are strongly endorsed.
- The techniques are useful, particularly in looking for deviations in catalyst coatings. The pinhole characterization is not clear. Clearly, these are a problem, but the effort to find what size of a pinhole is acceptable is not likely to bear much fruit. Once there is a pinhole, it quickly propagates, so if the minimum acceptable size is unknown, it is hard to know whether the detection is good enough.

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 availability of QC/QA tools for full-scale manufacturing of polymer electrolyte membrane (PEM) fuel cell and low-temperature electrolysis membranes will be essential for achieving processing yields required for ultimate cost reduction. The team appears to be making steady progress toward the project goals.
- Optical methods for platinum loading are impressive. The use of membranes that are kilometer lengths allows NREL to establish a strong baseline database with respect to defect measurements. The goal for optical measurement was down to 0.05 mg/cm^2; however, the smallest step-size goal seemed to be 0.1 mg/cm^2, so it is unclear whether the technique can adequately cover the low end.
- The post-mortem work is good, but it seems many investigators have already published these techniques. For those techniques that might occur during processing, this would be helpful, but it is uncertain whether they can detect at relevant sizes. The catalyst monitoring is of more interest; however, here the correlations are not yet strong enough, though the team will likely close in and make this better.

Question 3: Collaboration and coordination

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

- The collaborative approach to working with end users is a major strength of this project. This is essential for this project to ensure that the team is developing characterization tools that industry will use. The team has also expanded to leverage capabilities of other national laboratories and universities.
- This is an outstanding assortment of industrial and association collaboration. The team has a very organized outreach campaign to understand what is needed.
- The team has an excellent team of collaborators, but it is unclear what the team is doing with General Motors. The work with Proton and Gore should maintain the focus on what is important to manufacturers.

Question 4: Relevance/potential impact

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

- A sign of a product's maturity is its level of QC and QC understanding. Thus, this work is critical to implementation of fuel cell electrolyzers for the hydrogen economy.
- This project supports the goal of reducing cost at full-scale production of membranes for PEM fuel cells and low-temperature electrolyzers.
- It is not certain that Gore or other PEM manufacturers currently have a problem with thickness mapping. Clearly, the thin-film industry has methods to measure this already. The catalyst loading is of interest, and the team is closing in on methods.

Question 5: Proposed future work

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

- Finding out what variances exist in the catalyst layer, membrane thickness, and pinhole size probably should have come before finding out if they need to be, or can be, measured. It is good that the team was able and allowed to adapt mid-project to address low-temperature electrolysis needs.
- The proposed project efforts are well aligned with the needs of the community. The team endorsed linking quantitative defects to accelerated stress tests and lifetime prediction.
- The proposed work is fine, but there does not appear to be a budget allocated for the work.

Project strengths:

- The use of "whole material" optical or heat methods that have 100% inspection is a project strength. Demonstration of on-line measurement and the ability to build up a library of defects are also project strengths.
- Collaboration is the strength of this project, as end users define needs and guide project activities, and other organizations expand the "toolbox."
- This is a good team with very appropriate collaborations that should steer the project toward the most important characterizations.

Project weaknesses:

- The team should have worked to define what size variations were acceptable before determining methods to find them. For example, if a pinhole of any size is unacceptable, the project will need to find methods that can find much smaller pinholes than the optical techniques now being developed. Without knowing this, the team might spend a lot of time developing a technique that is not relevant.
- The low end of optical platinum loading detection may not be sufficient for typical anode loading.

Recommendations for additions/deletions to project scope:

- There should be a pause on the detection techniques until the researchers have established the resolution that they need.
- At some point, it may be worth expanding the scope to other types of fuel cells (e.g., solid oxide fuel cells).

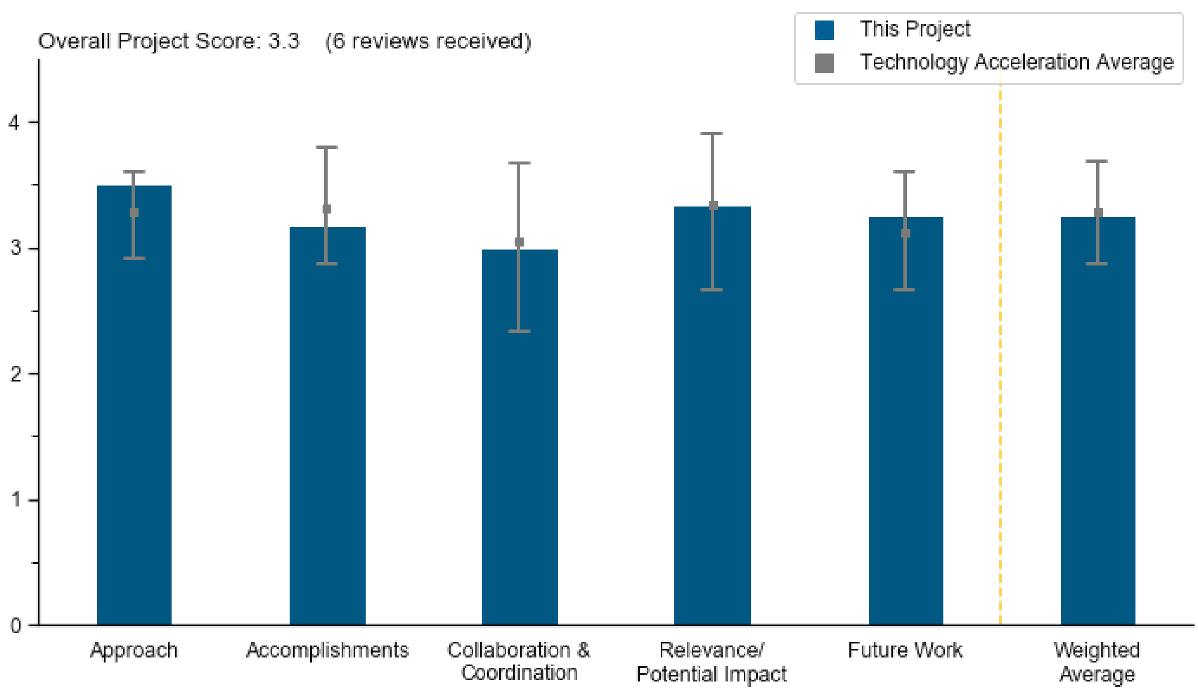
Project #TA-005: In-Line Quality Control of Polymer Electrolyte Membrane Materials

Paul Yelvington, Mainstream

Brief Summary of Project

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

Project Scoring



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

Question 1: Approach to performing the work

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

- The approach develops the methodology to identify defects in the major components of PEM cells. The approach includes transition of the analytical approach from small-scale offline to roll-to-roll (R2R) manufacturing. The team anticipates the development of a prototype system for industrial applications.
- The approach is a needed first step, which represents a significant advance vs. visual inspection of components, in both feature size and speed. This still requires some definition around data analysis to track back to defects, but the technique seems applicable to multiple substrates and components.
- The approach is valid. The team wants to see what the relevant defect size is, then find methods to detect it. The team is doing this for multiple categories, including membranes, gas diffusion layers (GDLs), and catalyst-coated membranes (CCMs).
- The project is not a "research" project but rather a development project based on compiling existing technologies into a system that can detect defects in a moving web. Thus, barriers and targets are not as

relevant in this project as compared to others. In fact, resolution on the cameras was reduced so that the quantity of data was reasonable.

- The goal of the project is to transfer a national-laboratory-developed non-destructive inspection technology into a commercial product. This objective is being met. The question is whether it is a product if no one buys it.
- The investigated approach is appropriate to address the main barriers and to reach technical targets.

Question 2: Accomplishments and progress

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

- There is very good progress regarding defect detection and the evaluation of the catalyst loading. Results on the impact of defect size on durability would have been appreciated, as some cost elements have an impact when moving from today 100 µm detection to the next step of 25 µm, and the ultimate to 10 µm.
- Good progress has been made toward the stated goals of the project. Reduction of false positive and false negative rates at 100 ft/min speeds is fairly impressive. Identification of catalyst layer thickness to within the error bars is probably sufficient. The more pressing issue is detection of voids or large agglomerates that could cause hot spots or high creep areas.
- Demonstrating measurement of defects in membranes, GDLs, and CCMs, the team is able to measure catalyst thickness and distinguish between a false positive and a true positive. The team is developing techniques to measure catalyst loading on CCMs and GDLs. The testing of industrial materials has been initiated.
- The project has made good progress and has a commercial system available for install at customer sites.
- The QC thickness measurement and defect detection system developed by Mainstream appears to be suitable for its intended purpose. The only real question is whether this product will find commercial acceptance. Developed without active involvement by commercial membrane manufacturers, the company pursued an "if you build it they will come" approach.
- Although the team stated that it wanted first to determine what defects and defect magnitudes were relevant, then find methods to detect these, the researchers are in fact operating in the opposite fashion: they are determining what their current system can accomplish while waiting to find out relevant defect size from the National Renewable Energy Laboratory (NREL). This can possibly lead to a large amount of wasted effort. There is a very weak correlation between catalyst loading and pixel intensity, which is disappointing and brings the methods into question.

Question 3: Collaboration and coordination

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

- Collaboration between Mainstream and NREL appears excellent. The involvement of more industrial entities as membrane electrode assembly (MEA) producers is appreciated.
- Collaboration with NREL is excellent, with coordination on defect creation and detection. However, this is to be expected, as this project originated from a technology transfer/licensing based on a Small Business Innovation Research topic. It would be good to see more interaction with potential end users to demonstrate the method on production or prototype components and work collaboratively on customer needs.
- The team reports collaboration with NREL, a leader in identifying defects in MEA materials and identifying the impacts of defects on fuel cell performance. The team identifies testing of industry samples. Industry interaction should be increased to get a greater variety of membranes, CCMs, and GDLs.
- The team is using NREL to determine the relevant defect size, which should have occurred as early as possible in the process but does not seem to have been started. As for the process development, the Mainstream researchers should be able to do this themselves, so extensive collaboration is not necessarily needed.
- There is minimal collaboration with other research institutions; however, the nature of this project does not require such elaborate collaborations.

- Although it appears that input from commercial manufacturers was solicited at the project onset, and commercial collaborations were pursued during the project, no commercial collaborations were established. This is a huge weakness of the project. By the end of the project, DOE will have invested $2.15 million dollars, and Mainstream will have developed a product that may or may not have a market.

Question 4: Relevance/potential impact

This project was rated **3.3** for 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 system will have the ability to eliminate defects in PEM fuel cell stack components prior to assembly of the stack or construction of individual fuel cells. The results of the analysis would be to discard faulty MEA components or MEAs prior to stack assembly, which should greatly reduce costs and increase durability of fuel cell systems. The methodology can lead to improved manufacturing processes and a reduction in scrap rate.
- Aside from NREL's work, this is the only project in the DOE portfolio focusing on automated defect detection in fuel cell/electrolyzer components. As these technologies are deployed in the market at larger quantities, QC is both a bottleneck and a larger expense, and this project addresses a key need.
- The project is relevant to the DOE Fuel Cell Technologies Office. In-line defect detection is critical for R2R processing to ensure concurrently lower scrap rates and thus lower membrane and MEA costs.
- There is apparent value of this QC product for MEA manufacturing. However, MEA manufacturers are apparently not showing interest. It would be helpful to know where the disconnect is.
- It is not convincing that a new method for determining membrane thickness is needed. Similarly, though QC methods are needed for online R2R fabrication of electrodes and MEAs, it is not certain that this method will be able to discern this. In addition, the team does not appear to have a "Plan B" if the camera does not work.
- It is unclear whether the industry is ready for such equipment.

Question 5: Proposed future work

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

- The proposed work appears appropriate to achieve the project targets. Quantified results of defect size on durability and a cost analysis should be presented.
- Clear direction for the development of a commercial product is the focus of this small company.
- The plan for future work is fine. The project needs commercial demonstrations, if not in the fuel cell industry then in other industries. There is a huge risk that Mainstream is developing a product that no one will buy.
- Future work addresses increasing sensitivity to observing smaller defects on a moving R2R system and scaling up the system to larger-size (commercial-size) components. Moving the prototype system to industry and finding manufacturing partners are important aspects of this emerging QC system.
- Transitioning to validation of the QC method (through performance testing) is a critical next step, as is working directly with customers and manufacturers.
- All of the future work is concentrated on improving the resolution and fidelity of the current process. There is no reference to establishing the actual guidelines or when the project will have this. The team has a goal of reaching a 10 µm defect resolution, which sounds very good; but perhaps the critical dimension is 100 µm, and anything smaller is fine. In that case, the researchers are wasting their time trying to improve. If the critical dimension is 1 µm, then the team clearly needs a new method. The researchers give a goal for web speed, but there is no basis to judge whether this is good or bad if they do not state how web speed adds to the cost of the process they are monitoring, and how this translates to total dollars per square meter of active area. If cost of the material is already down to $\$0.01/m^2$, the researchers likely do not need to focus on this area.

Project strengths:

- An important strength is ability to work with NREL to get materials with known defects and to optimize the NREL QC technology to a prototype for demonstration on industrial R2R manufacturing. The organization's experience in developing turnkey systems is a definite strength.
- Strengths include the approach to creating controlled defect sizes and catalyst loadings for quantification of detection limits and demonstration of method. Another strength is looking at the different electrode configurations and how different pinhole types would interact with the catalyst-layer configuration.
- The Mainstream/NREL team's efforts to speed up development and demonstration of this kind of technology are of high value.
- The team has clear focus and concrete results with commercialization efforts.
- The team has good capabilities and a good approach to face a relevant problem.
- This is a nice product being developed to meet an apparent need.

Project weaknesses:

- The cost of the equipment and the cost of using the QC process in a manufacturing process needs to be determined.
- Data analysis, given very large datasets, was a stated challenge that did not have a fully defined solution yet. It would also be interesting to expand the range of catalyst loadings/types analyzed for better relevance to electrolyzers, which are not platinum on both sides and are still at high loading.
- Project focus to date has been entirely on making it better and faster. This is, of course, admirable, but there is no basis to back critical parameters of needed defect size and cost. Without this, it is unclear how anyone can judge what is "good enough" or "fast enough."
- It is not certain that the industry is ready for this. The principal investigator has identified that the commercialization may be better directed at more mature manufacturing industries. No commercial interest is demonstrated.

Recommendations for additions/deletions to project scope:

- It would be helpful to see some cost information. Presumably the cost will be well within acceptability, but this information is needed. The team needs to accelerate the work with NREL to determine the critical parameters or tolerable defect sizes.
- The team should include the effect of the defect size on performance and durability. The team should also investigate the two-dimensional spatial mapping, in particular for the loading mapping.
- The team should expand the project and funding to install equipment on an industrial production line and add a large-scale (3M or W.L. Gore) manufacturer to project.
- It would be good to add a range of catalyst thicknesses and types for electrolyzers.
- The team should explore alternative markets for the product.

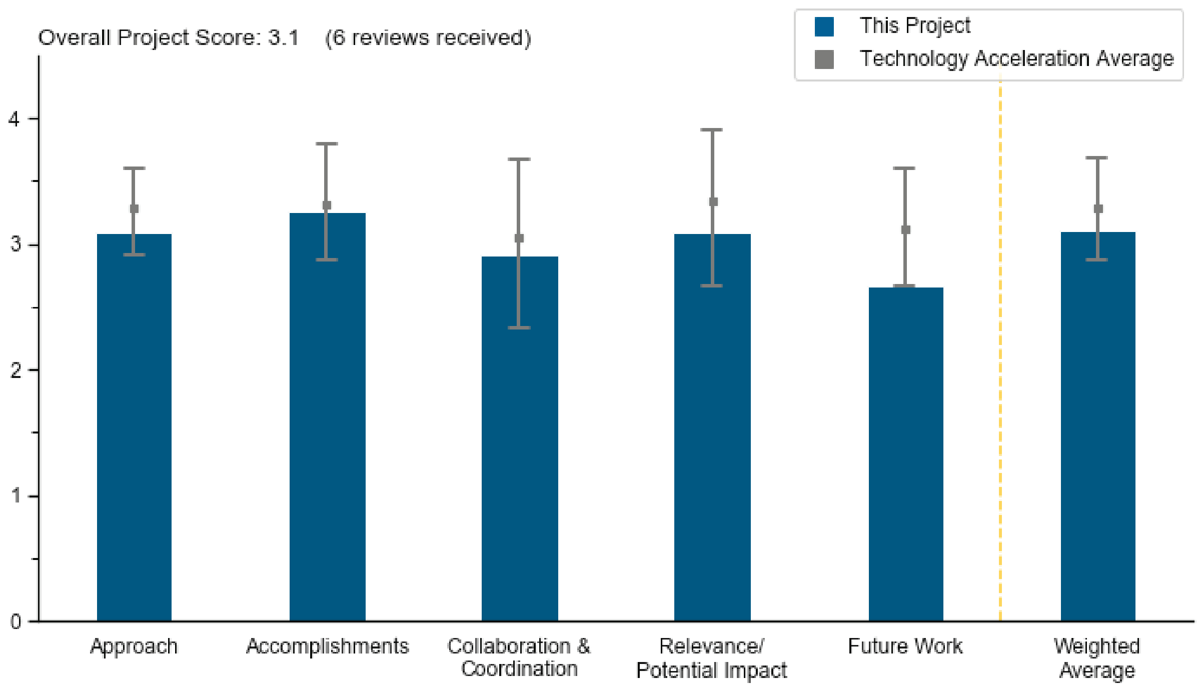
Project #TA-007: Roll-to-Roll Advanced Materials Manufacturing Lab Consortium

Claus Daniel, Oak Ridge National Laboratory

Brief Summary of Project

All U.S. Department of Energy-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.

Project Scoring



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

Question 1: Approach to performing the work

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

- The project has an excellent approach in the demonstration (and performance verification) of the R2R techniques that are required for high-volume, low-cost fabrication of membrane electrode assemblies and that have not yet been demonstrated by industry. Performance validation of the ensuing R2R products is essential.
- It appears that Oak Ridge National Laboratory established an extremely qualified team of national laboratory scientists and engineers to perform this work, and there is value to performing research aimed at reducing manufacturing costs. The only concern for the approach is how it will be broadly transitioned to industry when there appears to be only a single industrial partner.
- Although this project focuses on manufacturing, which should normally be left up to industry, some good and promising results have come from it. Most notable is that a significant amount of material

was used, allowing for good process control of the materials being made. This allows for low sample-to-sample variability when comparing the impact of different processing parameters on fuel cell performance.

- The basic approach of using the R2R manufacturing process is appropriate and has projected cost savings of 63%. One area that seems to be missing is an on-line quality assurance strategy. R2R could have savings only if the process is running near defect-free, with minimal scrap.
- The project team is putting a good deal of effort toward eliminating the ionomer overspray layer, and it is not clear that eliminating this layer is at all necessary. The researchers wrongly assume that adding this layer will double the cost of their R2R process. That assumes a full rolling and unrolling. In reality, it could easily be done in the same winding as a separate layer, adding only a small fraction to the cost. In R2R, the cost is generally proportional to how many times you have to roll and unroll, while extra processes are minimal.
    - The source of the cost reductions is unclear, but \$0.013/mile for a fuel cell or an electrolyzer MEA seems unlikely. An assumed 12" web of >6000 m^2 is enough for 300 MW of electrolysis. The cost of 300 MW of electrolysis is ~\$120 million. This project is an attempt to drop \$120 million from costs by lowering a process cost by \$0.47. The reasoning behind this is unclear. Over their lifetime, those 300 MW of electrolyzers should generate 300,000,000 kg of hydrogen, so this achievement will lower the cost of hydrogen by \$0.0000000016/kg. Automotive fuel cells require about 10 m^2 of MEA, so one mile can generate enough MEA for 600 vehicles. If the researchers reach their target, they will only drop the cost of each vehicle by \$0.0008. Clearly, any increase in performance with an ionomer layer or slower processing will be well worth it. Clearly R2R will be, and is, the method of choice, but the focus on increasing speed may be misplaced.
- The approach charts describe negatives for catalyst-coated membranes (CCMs) and identify some of the projected benefits of the R2R gas diffusion electrode (GDE) method of fabricating electrodes and MEAs. Not a lot of detail on experimental approach is given. The composition of the slurry for deposition of the catalyst layer (CL) was not discussed. It should be made clear whether the slurry had Nafion in it, as well as how the slurry was cured on the CL and substrate material. Several critical parameters were not discussed in the approach.

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 work on roughness was insightful and very helpful. The progress toward stated goals is good, but the metrics are in question. Adding an ionomer layer should not significantly increase costs.
- The team systematically evaluated key parameters relating to the R2R process; the performance achieved was better than that of the baseline spray-coated CCMs or GDEs, achieving the project goal.
- The coating and fuel cell performance shown is excellent progress. However, it is not clear how this is related to DOE goals, as these should be the industry's goals. It does show that the R2R coating technology does not have a significant impact on the cost of the MEA; it is mostly material costs. Also, this project team has made contributions to the state-of-the-art understanding of parameters for fuel cell electrode construction.
- The team has made substantial progress in better understanding and demonstrating GDEs with and without ionomer over-layers. The team has also established that smoother gas diffusion layers (GDLs) and hot-pressing are key to a good interface and good performance.
- The project team demonstrated improved performance with modification of CL surface roughness, and the work is predicted to improve GDEs made by R2R. The team demonstrated the use of slot-die coating with a smooth microporous layer. The team also eliminated the ionomer over-layer. It was not clear why the project was successful in eliminating the over-layer.
- It seems like much work has been performed, but a huge investment was made with minimal industrial involvement. If the objective was to establish a national-laboratory-wide capability in R2R manufacturing, then the objective was met. If the objective was to develop technology that will ultimately be practiced by industry, there is a long way to go.

Question 3: Collaboration and coordination

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

- The project team has the correct partners on the processing and characterization side. The addition of Proton OnSite should help the team focus on the requirement needs, but this is for low-temperature electrolysis (LTE) applications, which will be lower in volume than those of fuel cell electric vehicles (FCEVs). The project needs to add an automotive original equipment manufacturer (OEM) to help guide priorities.
- The project seems to have a very solid DOE laboratory collaborative team. With the notable exception of the industry cooperative research and development agreement with Proton OnSite (which is not yet implemented), there appears to be a lack of industry involvement. Collaboration would be stronger with more industry input.
- The project has strong collaboration with other national laboratories but is limited to one industrial partner that works with electrolysis, not fuel cells. A majority of R2R processes are meant for fuel cell catalysts or membranes consistent with fuel cells, but not with electrolysis. The project should find a fuel cell collaborator.
- This project, by its very nature, is a laboratory collaboration, with five partner laboratories and two companies involved. The laboratory partners' roles are well defined. It is not apparent from the presentation if the number of collaborators is a source of delay or management complexity.
- The project appears to be an entirely DOE laboratory effort; an industry partner in the water electrolyzer marketplace has been added to the project.
- Large-scale MEA manufacturers need to be involved in this project if any value is to be derived from it.

Question 4: Relevance/potential impact

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

- As stated in the presentation, R2R processing is required to achieve high volume and low cost. Therefore, it is highly relevant for the project team to pursue basic advancement and increased understanding of specific R2R applications that are not otherwise being conducted.
- The project has met its performance goal using the R2R process and may very well meet the eventual cost reduction targets of 63%. The ability to control the process and attain high product yield will be a critical next step.
- Defining the parameters and better understanding the processes during R2R formation would be much more important than trying to increase throughput. In general, the latter is more easily achieved. Understanding the structure, property, and performance issues as a function of the drying rate and solvents used would be a better use of effort.
- The project very quickly down-selected one particular manufacturing process and then went on to study how to optimize MEA performance using that manufacturing approach. Industry standards are done with the CCM approach, not the GDE approach. The project team could do a better analysis of different CCM manufacturing approaches.
- The description of the slot-die coating process is not adequate to fully understand how a 63% cost reduction is achieved. The $1.30 for the slot-die coating process should be broken out into individual stages (coating, drying, and bonding) and their respective costs.
- It is hard to get over the level of investment made in this project without industry involvement. There can be no impact unless the technology is transferred to a manufacturer.

Question 5: Proposed future work

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

- Examining multilayer coatings is a particular focus area worthy for future work. It is key to integrate drying and curing into both the procedure and performance research, as well as the cost computations.
- The proposed work is broadly defined to include multilayer coating, ink formulation, drying and curing, and flow modeling. The areas to be added should include the effects and causes of defects, strategies for defect detection and process control, and leveraging other ongoing projects' technologies where available.
- The team may continue some work for Proton OnSite, but roll speed is far less important with LTE than it is for FCEVs.
- The project focused in on one process (direct coat catalyst on GDL) and excluded another (coating catalyst on membrane). The basis for this was a flawed processing cost analysis, assuming single-use expensive (Kapton) transfer liners and discrete transfer liner hot-pressing steps. One could envision a CCM decal transfer manufacturing process that would not consume the "liner" but simply re-use it. Also, the transfer process of the catalyst to the membrane could be in an R2R heated laminator, again eliminating the discrete hot-pressing cost step. The point is that the project eliminated one approach for MEA manufacturing over the other too quickly, and with a shaky foundation.
  - Instead, the project team could focus on the question of the CCM versus GDE approach. The Pt catalyst utilization was long ago (in the 1990s) determined to be worse for the GDE approach versus the CCM approach. This is why the industry shifted away from the 1990s GDE approach in favor of the CCM approach. This could be different with today's new GDL materials, as alluded to in the presentation. However, that would be a valid factor for determining the outcome between the GDE versus CCM approach.
  - Also important would be an entire supply-chain-wide manufacturing cost analysis. It needs to be understood where the supply chain breaks between different types of companies. The team should consider whether it makes sense for a membrane manufacturer to make, package, and ship a 10-micron membrane, just for an MEA manufacturing company to unpack that membrane and use a similar coating machine to apply catalyst, and then repack it for a stack manufacturer to cut and assemble it as discrete components into a stack. On the other hand, the team should consider whether a fuel cell system OEM has access to the know-how and best materials needed to manufacture MEAs from bulk raw materials. Industry-wide common breaks in the supply chain would yield the best results, along with pricing competition at each supply chain break.
  - In summary, it appears that this project has transformed itself from one focused on issues and trade-offs surrounding manufacturing MEAs into a project focused on optimizing the performance of a fuel cell MEA by changing its construction parameters. However, credit is due to the team, as they have a done an above-average job at the latter.
- The proposed work is not descriptive enough. It appears to be a shopping list of topic areas with no description of the approach to solving or defining future tasks. For example, it is not clear what the project is going to flow-model.
- More industrial involvement is essential for this project to have any value.

Project strengths:

- The DOE laboratories are uniquely positioned to perform this work, as they have the resources and expertise, the work is not being done elsewhere, and the topics are pre-competitive and beneficial to multiple vendors. The cost impact of the various processes is key to their evaluation. The cost projections are very much appreciated and should be included even more in future work.
- The project team has five national laboratories with broad, comprehensive capabilities. The R2R approach seems to be technically successful thus far. The cost model shows a potential of 63% cost savings; it would be beneficial to see the cost breakdown or savings realization based on the current project status.
- Good progress has been made on improving MEA performance and understanding of the mechanism.

- The project team has good capabilities in processing and characterization.
- The project's strengths include the talent and capabilities of the team.
- The cooperation of all the national laboratories is a strength of this project.

Project weaknesses:

- The cost of the over-layer may be overstated in that (1) its net additional equipment cost may be low if the coating station is added to an existing process train, rather than being a stand-alone process, and (2) it may be desirable to lay down the membrane on a wet over-layer rather than a dried overlay (and this may eliminate the hot-pressing operation).
- A weakness of this project is that there are no fuel cell MEA manufacturers participating in the project. Proton OnSite is a manufacturer of electrolysis equipment.
- The overall objective of how the project advances the DOE Fuel Cell Technologies Office mission is a bit unclear.
- The team's goals do not seem to make economic sense. The current roll-speed costs are not significant, and neither is the cost of adding an ionomer overspray.
- The project's weaknesses include a lack of industrial involvement.
- The future work should address defect detection and process control.

Recommendations for additions/deletions to project scope:

- The project team should include specific cost analysis for each examined process. The team should explore the upper speed of each process, recognizing that the optimal line speed may be determined by economics (as high line speed may lead to long dryers and high capital cost).
- The project should add in-line process control and defect detection. The team should update the cost model based on the current process and set priorities based on future savings potential.
- The project would have a greater impact if a fuel cell manufacturer would participate in the effort.
- Broader participation by industry is needed.

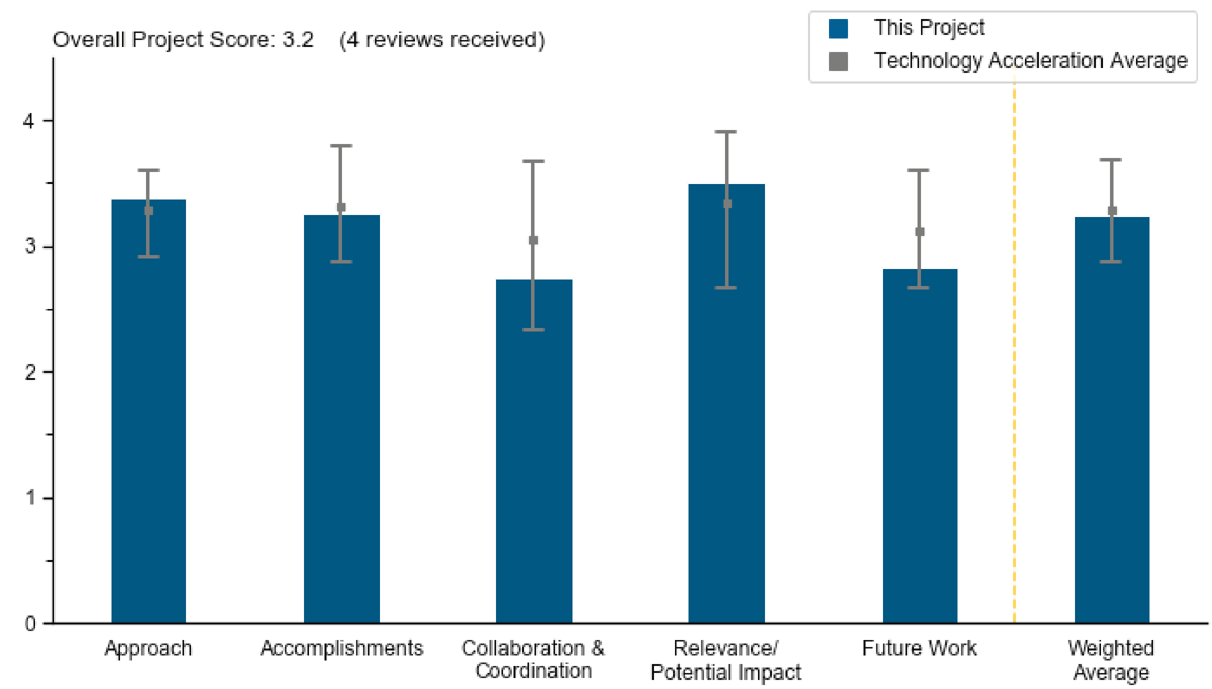
Project #TA-008: Material–Process–Performance Relationships in Polymer Electrolyte Membrane Catalyst Inks and Coated Layers

Michael Ulsh, National Renewable Energy Laboratory

Brief Summary of Project

The objective of this project is to study the material–process–performance relationships for roll-to-roll (R2R) polymer electrolyte membrane fuel cell (PEMFC)/electrolysis cell materials to understand the coupling between process science and material properties and performance. The project team seeks to understand the impacts of ink formulation, coating and drying physics on ink microstructure, coatability, film morphology, electrochemistry, proton conduction, and mass transport. The project team accomplished the following tasks: (1) determined that slot-die coating results in higher-performance membrane electrode assemblies (MEAs) than gravure coating, (2) related catalyst ink microstructure to electrode microstructure, (3) improved methods for dynamic light scattering and zeta potential to better understand catalyst–ionomer interactions, and (4) initiated work on electrode cracking, showing that microporous layer cracks can induce catalyst layer cracks.

Project Scoring



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

Question 1: Approach to performing the work

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

- A systematic approach is being used to assess different ink formulations and coating processes, with a good mix of materials and coatings characterization and electrochemical performance testing.
- The project's approach is good: to study how ink behavior relates to manufacturing processes and ultimate fuel cell performance.
- The individual pieces and the approach to quantifying and improving ink and electrode methods are promising.

- The approach is solid and instructive to the community. It would have been good if the team had done some fairly simple experiments to determine the amount of ionomer coating on the catalyst. Determining whether the isotherms change based on the solvent system will really give insight into what is leading to performance differences.

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.

- Given the limited amount of funding, it seems like this project has made much progress. Good correlations are being made between coating process, coating morphology, and electrochemical performance. What seems to be missing is research into explaining the "whys." For example, it was observed that electrochemical performance was better with slot-die coatings compared to gravure coatings, and this was correlated to morphology differences. It should be made clear whether these are differences that are intrinsic to the coating process or whether they are due to coating inks being more or less optimized for one process compared to another process.
- The project did not have any targets or go/no-go decision points, so it is more of a supporting analysis of the catalyst inks project.
- The project progress is good, but the need is less clear. The original equipment manufacturers and electrode manufacturers have excellent electrode knowledge; it is not clear that the national laboratories should be trying to develop this knowledge.
- The project's progress is impressive compared to the budget but not at all impressive compared to the start date; it is hard to see how this took two years.

Question 3: Collaboration and coordination

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

- The level of collaboration on this project is exemplary, especially given the limited funding.
- There is not much industry interaction. The team could use more industry interaction on the inks; however, this could be an intellectual property issue.
- It is not completely clear what the other organizations did. It is also unclear how $200,000 was divided among the partners, or that it was very effective.
- It was not clear what, if any, of the work presented was in support of projects.

Question 4: Relevance/potential impact

This project was rated **3.5** for 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 supports the development of low-cost, high-yield manufacturing processes that will be essential to the long-term commercialization of PEMFCs.
- This is good, practical work that many groups will find useful. To make it more useful, more characterization to understand the differences the team is seeing will be needed.
- The project showed how important the ink parameters are to fuel cell performance, and also how unexpected simple adjustments on ink deposition techniques can have a large impact on performance. More study should be done here.
- Since improving electrodes and manufacturing is a goal for DOE, this project is well aligned and effective, especially considering the small funding level.

Question 5: Proposed future work

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

- While the approach is great, the performance is still so much lower than fuel cell state of the art that relevance is hard to judge. However, for electrolysis and platinum-group-metal (PGM)-free fuel cells, this seems to be a more valuable effort.
- The proposed work makes sense, but no additional funding appears to be planned for this project.
- It appears that the proposed work on PGM-free inks would be taking place too early to study any of the manufacturing aspects of these catalysts, as they are not at the technology readiness level needed for manufacturing.
- The team talks about working with K.C. Neyerlin to help understand the differences in performance. It is not clear how this work would be funded.

Project strengths:

- The project's strengths include the quality of the work, the connection of measurable characteristics to observed and measured performance, good higher-level analysis, and consideration of R2R issues.
- There is a focus on process and property relationships, with appropriate materials characterization being used to support interpretation of the results. The team is also collaborating with other national laboratories that have unique capabilities and with end-user companies that can benefit from the results of the project.
- The team shows good characterization of several different ink systems.
- The project demonstrates the large impact of the interaction of ink properties and application methods on performance.

Project weaknesses:

- The project's weaknesses include the lack of scope or follow-through. In all honesty, the work is quite good, considering the budget, but much more could have been done. It is not clear how the team worked together. There are many MEA characterization methods that are readily available to this group and that could have been used to try to discern the differences in performance from the various inks.
- The poor fuel cell electrode performance casts doubts on the conclusion's relevance to fuel cells. The project's connection to other efforts is unclear.
- Better industry interaction would be useful.
- The project has insufficient funding.

Recommendations for additions/deletions to project scope:

- It would be great to see the isotherm work on the catalyst inks as a function of ionomer loading and how that varies with the solvent system. It would also be good to see MEA characterization, especially mass transfer analysis and impedance, to determine what is going on with the different inks and methods.
- Focusing on electrolysis and PGM-free catalyst systems seems like a proposition with higher added value, as the electrode structures for those are less well developed and the need is there. Better integration with existing projects may be helpful. The integration is in progress but was not reported.
- This project should be continued, or a similar scope should be added to future projects.
- The project team should add more industry interactions.

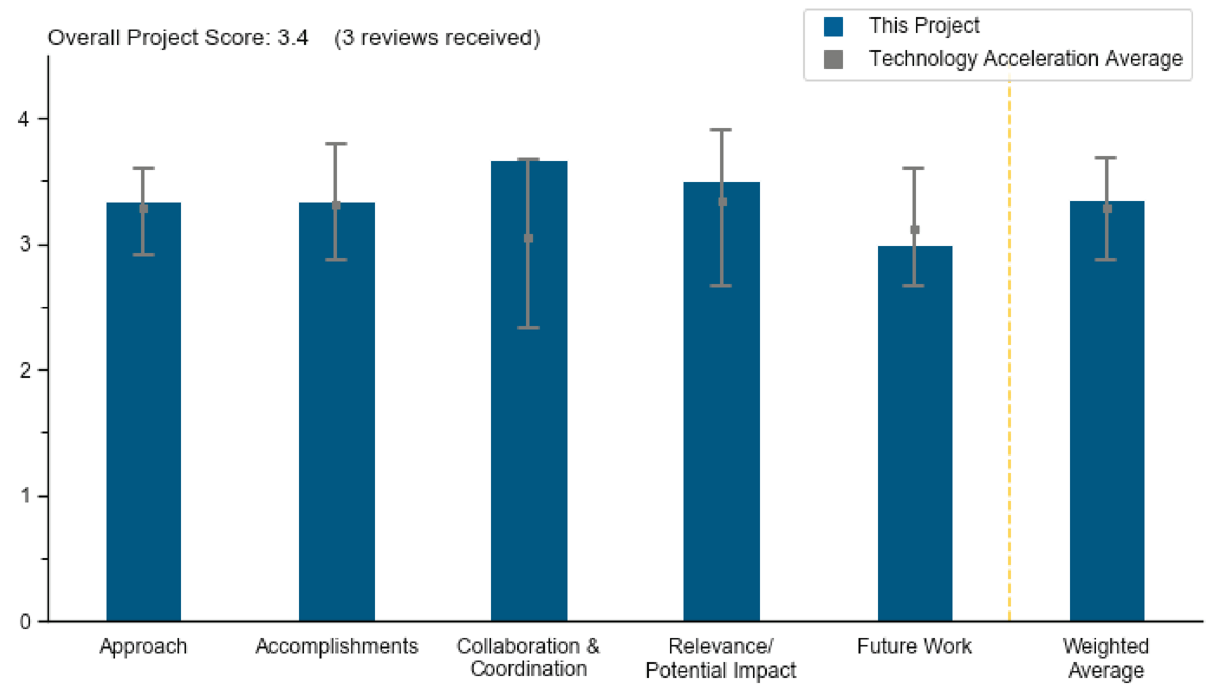
Project #TA-009: Maritime Fuel Cell Generator Project

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.

Project Scoring



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

Question 1: Approach to performing the work

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

- The approach is very sound, including upgrading the unit to provide 480 VAC to meet Scripps Institution of Oceanography (SIO) requirements and ensuring that the unit and its operation meets all other local requirements.
- The approach identifies the objectives and barriers, is well designed, and appears feasible.
- The project’s strategy shifted from reefers to ships at dock. It is unclear how power requirements break down, how many reefers can be powered from one fuel cell container, or what the limitations are for a ship at dock.

Question 2: Accomplishments and progress

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

- The project has significant accomplishments and appears to be able to demonstrate the use of fuel cells to power the SIO vessel. However, it is not clear what concrete steps are being taken to lower investment risk and to enable permitting. Perhaps certain stakeholders are on board and willing to move forward with regulatory documentation.
- Progress included exploring the Curtin Maritime site at the Port of Long Beach and the SIO site in San Diego for test deployment, as well as upgrading the unit to meet deployment needs at the SIO.
- It is not clear how the project is addressing the identified objectives from slide four: lowering technology risk and investment risk and improving permitting acceptance.

Question 3: Collaboration and coordination

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

- The project has good partners for the execution. Although it did not work out, having Curtin Maritime and the Port of Long Beach on the team is a good partnership to better understand issues and site requirements. The SIO partnership will provide a good collaboration.
- Collaboration and coordination among the existing partners is outstanding, as seen in the progress discussed at the Annual Merit Review.
- It is apparent that the project is coordinating with other institutions.

Question 4: Relevance/potential impact

This project was rated **3.5** for 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 a few stationary applications to maintain the overall Hydrogen and Fuel Cells Program's momentum. Mobile refueling with hydrogen will be part of the planned test deployment. The benefit of gaining experience and engaging technology providers, regulators, and a real ship-docking site will be very valuable.
- Using the fuel cells in this application will help advance use in onshore power applications.
- The project clearly addresses a need.

Question 5: Proposed future work

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

- At this stage, it is very good that the project is also geared toward exploring the possibility of future host sites because test deployment needs to continue to accelerate user acceptance.
- There might be applications for the U.S. Navy for offshore power, or perhaps there are other research vessels or similar stakeholders that might need something like this.
- The future seems unclear. It would be good to know what the possible user demand for this technology is and how rules and regulations might impede its use.

Project strengths:

- This project requires understanding the host site's needs and a good deal of coordination. There is very good collaboration seen among partners, which resulted in timely upgrading to meet the host site's needs and the timely evaluation of potential showstoppers that could delay the deployment.
- The project's strengths include the team's flexibility to find the SIO after it was found that site requirements for Curtin Maritime setback regulations do not work. Using a 20-ft Container Express (CONEX) for these purposes is modular and a good fit.
- The project provides a solution to a specific need. The project addresses energy concerns both onboard a ship at sea and at dock.

Project weaknesses:

- This is an observation and not a weakness because the cost of hydrogen is not within the project scope: it would be good to develop a plan to secure lower-cost hydrogen supplies over a number of years, if this is possible at all.
- It would be good to show data statistics and/or a summary that highlights the effectiveness of the fuel cell, whether it has been running for one day or one week.
- The project was originally targeting reefer containers onboard ships. There are several questions, including whether there are different rules and regulations aboard ships that might interfere with technology adoption, how many reefer containers one of these units can power, what the lifespan of the unit is, whether there is an ideal type of ship that this unit might serve while at dock, and how scalable the technology is.

Recommendations for additions/deletions to project scope:

- It would be nice to know how many of these units might be needed to power reefers on a container ship, as well as what the ideal ship to be powered while at dock is. A better understanding of where the technology fits would help with understanding the potential range of application.
- Until results are available from this hoped-for host site, there is not really a need to modify the scope.

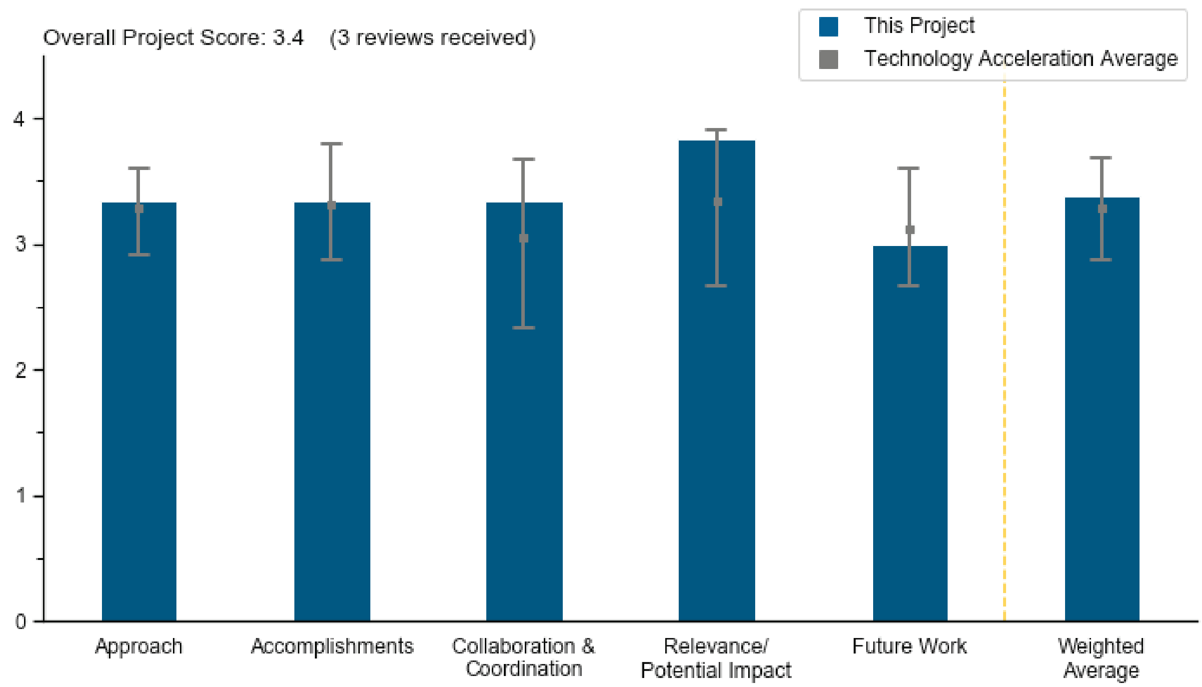
Project #TA-011: FedEx Express Hydrogen Fuel Cell Extended-Range Battery Electric Vehicles

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.

Project Scoring



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

Question 1: Approach to performing the work

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

- The approach was a green, renewable, and sustainable technology, but it is a bit hidden in the presentation (see chart 3).
- The approach was identified at a very high level. How the efforts are going to be accomplished and who is responsible for accomplishments is not obvious.
- The project objectives are clearly identified. The critical barriers may not have been adequately addressed. Non-fuel cell maintenance issues have had a significant impact, and planning for maintenance facilities for 20 vehicles appears to be a late consideration.

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 systematic demonstration of modification of delivery trucks, training of personnel, and testing of vehicle and power train requirements were achieved. The problems with the fuel cell system observed during testing and the impact on availability were addressed and resolved. The initial design issues with direct current (DC)-DC-convertor placement were resolved.
- All that was done was useful in meeting the goal of fleet experience with a fuel cell battery combination.
- The project is slipping its timelines, and there does not appear to be ample time to build and deploy the remaining 19 vehicles to meet the 2021 deadline.

Question 3: Collaboration and coordination

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

- The interaction with Plug Power was reported to be outstanding. The data release to the National Renewable Energy Laboratory was reported with no problems identified. There appears to be a problem within FedEx regarding the responsibility of using delivery trucks at longer distances from home base.
- There appears to be good coordination between partners, with the exception of the battery/electrical system provider.
- There appears to be little coordination between the plug and truck manufacturer with regard to the convertor.

Question 4: Relevance/potential impact

This project was rated **3.8** for 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 commercial demonstrations are critical, and the FedEx and Plug Power effort is outstanding.
- If the project team is able to address maintenance and reliability issues to support the build-out of the remaining 19 vehicles, there could be a great benefit to the DOE Hydrogen and Fuel Cells Program (the Program).
- The project includes real delivery routes driven by actual users.

Question 5: Proposed future work

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

- The proposed future work is fine, but there was no indication of how the project team would solve the critical issues.
- The presenter gave a shopping list of future work with no discussion of approach, potential difficulties, or means to resolve future issues.
- The maintenance issues seem to have put the future plans in jeopardy. Without the demonstration of the remaining vehicles, the project’s overall value and impact on the Program are greatly reduced.

Project strengths:

- Both Plug Power and FedEx are strong companies for this demonstration.
- It appears that the fuel cell system has performed well.
- The overall strength is the project management by an actual user and planned use in actual driving routes.

Project weaknesses:

- Maintenance issues with the non-fuel cell systems have had great impacts on the project and its future. It is uncertain whether this could have been avoided by better planning and failure mode and effects analysis (FMEA) activities.
- A project weakness is the high employee turnover rate.

Recommendations for additions/deletions to project scope:

- The project is well organized, and there is no obvious need for additions or deletions.
- Regardless of whether the project continues building the remaining 19 vehicles, it would be beneficial for the project team to thoroughly consider and evaluate the learnings from their activities. A report or other documentation from this project could be of great value for other projects in the future. For example, it may be beneficial for an FMEA to be performed, thus enabling a project team to be better positioned to deal with the failure of less reliable or long-lead-time parts.
- The positives and negatives should be identified. It would be helpful if FedEx could clearly mark the presentation figures in future presentations.

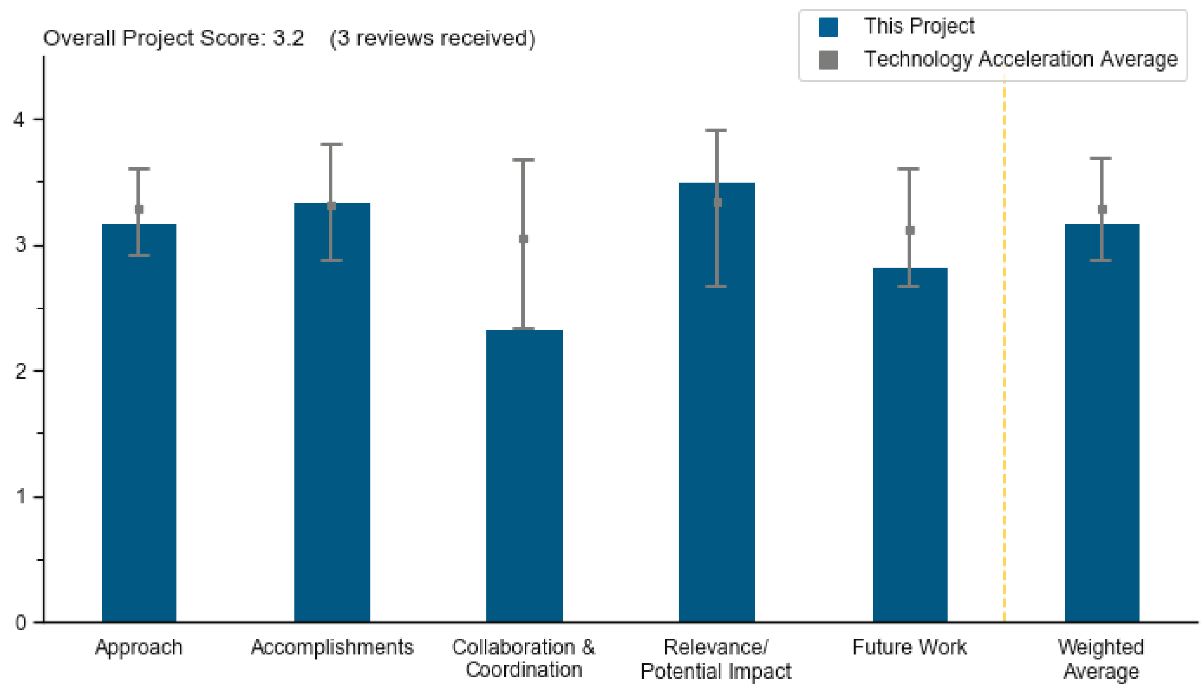
Project #TA-012: Northeast Demonstration and Deployment of FCRx200

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 analysis of 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.

Project Scoring



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

Question 1: Approach to performing the work

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

- The objectives and critical barriers appear to have been considered.
- The approach to work is good, except the project lacks a definition of the role of National Grid and does not make clear who would benefit from the extended range of battery vehicles.
- The principal investigator listed four factors for Approach/Scope that give specifications for components. There was no discussion on interfacing the fuel cell with the battery system, beyond a statement it will be done.

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 accomplishments appear consistent with project objectives and DOE goals.
- The project shows good progress toward goals, except that Phase II is in doubt because of the lack of a Phase I vehicle.
- There was not much discussion about accomplishments in the presentation or the handout. The team completed a safety plan. There are problems with Nissan changing the vehicle and the fact that Nissan does not plan to deploy the FCRx200 vehicle in North America. The Summary slide states that the integration of the fuel cell range extender and the storage and fueling interface were completed.

Question 3: Collaboration and coordination

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

- A good project team has been utilized.
- It is late to find out the vehicle will not be offered in the United States.
- Unfortunately, the collaboration with Nissan appears not to be going well: "No plan for [original equipment manufacturer] (OEM) to deploy vehicle in North America." US Hybrid reports Phase II of the project has a high risk, primarily because of the OEM's lack of support. Fueling infrastructure in the Northeast has been limited, and while this is not the responsibility of this project, the project depends on it. Limited fueling infrastructure could be the reason Nissan is no longer supportive.

Question 4: Relevance/potential impact

This project was rated **3.5** for 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 makes good innovative use of fuel cells, such as use as a vehicle heater.
- If the project team is able to complete Phase II, it could have a good impact on validating the technology for broader use.
- Demonstrations of fuel cell vehicles are critical to the technology's moving forward.

Question 5: Proposed future work

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

- The team did an excellent job of identifying future work needs, but how the future work will be executed is a problem.
- The proposed future work in the presentation identifies only work in 2019. Additional information should be provided on specific activities planned for the remainder of the project term (i.e., through 2022).
- There is no workaround for the lack of a Nissan vehicle.

Project strengths:

- The excellent use of fuel cell as range extender and heater is a project strength.
- US Hybrid is a strength; the company has a commercially available fuel cell system that has been demonstrated in the Nissan vehicle and versions of the fuel cell system operational in buses.
- This is a good project team, and learnings in early project activities are being applied.

Project weaknesses:

- The presenter stated that the safety plan will be provided to the Hydrogen Safety Panel (HSP) after the go/no-go decision (as stated, this was necessary to ensure that all players, including operators, are included). While it is good to have all project partners involved in safety planning, providing the plan to the HSP for review at such a late date (and considering there has been no other interaction with the HSP) could result in safety issues being identified too late to be easily or cost-effectively addressed.
- Nissan or another OEM is needed to complete this project. If a new OEM joins, that action will extend the project for at least one year.
- There are no plans for Phase II.

Recommendations for additions/deletions to project scope:

- The project needs an active OEM to move forward. DOE should assist US Hybrid in identifying an OEM to complete the effort.
- The project team should think about utilizing “used” Nissan vans for Phase II.

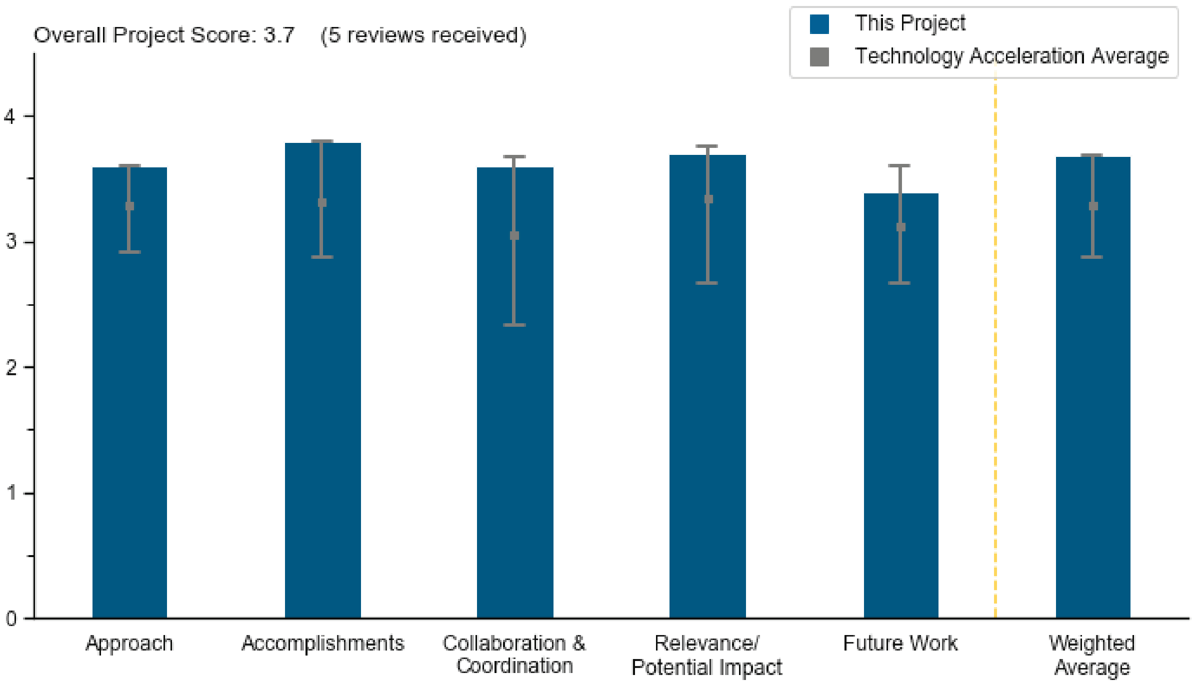
Project #TA-013: Fuel Cell Bus Evaluations

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/U.S. Department of Transportation 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.

Project Scoring



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

Question 1: Approach to performing the work

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

- The principal investigator (PI) has assembled an excellent cross-section of technologies and is sensitive to removing technology that is not relevant (e.g., prototype and/or demonstration units). The data are defensible and presented well and will help the industry identify the parts of the drive train that most need improvement (such as isolating the fuel cell power plant from the rest of the drive train). Others in the community (notably the California Hydrogen Business Council Heavy Duty Strategic Action Group) have proposed to perform such a study for the heavy-duty (HD) market, comparing fuel cell electric vehicle (FCEV) zero-emission vehicles (ZEVs) to standard technologies. In this way, this study’s value and relevance to the community is already being demonstrated. Many in the community seek comparative studies to use as educational material introducing hydrogen fuel cell technologies. This study provides that defensible, unbiased, well-thought-out, comprehensive data and analysis that are being sought. The approach for this work is very good, making the results defensible, credible, and important to the community. Overall, this is a nice project.

- The approach of gathering, processing, and reporting data from multiple demonstrations provides tremendous value. In this case, particularly in the areas of fuel cell power plant (FCPP) durability, maintenance hours and costs, and fuel cost, the project is turning out excellent value; and the long timeline allows for a significant body of data that gives good confidence for the progress needed to reach milestones.
- The approach is sound. The focus on refreshing the data is great, given that the technology is changing rapidly during the course of the study.
- The overall approach of the work is presented well. It is recommended that the wording on slide 4 be simplified to be clearer and more concise.
- The approach seems appropriate.

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.

- This project continues to provide valuable timely analysis tracking the performance of FCEVs and comparing them to each other and conventional technologies. The accomplishments and progress are in line with the growth and deployment of the FCEV technologies. Equally important is that this PI keeps the suite of technologies in the sample consistent with what is realistically expected to be deployed. This is nicely done.
- It is quite difficult for a project that has access to a wealth of data and has been going on for many years to continue to share useful results and prioritize key takeaways; this team continues to be successful at overcoming this challenge. The results of this work are routinely referenced in the field and help drive innovation for other non-light-duty fuel cell mobility applications. There are a few suggestions to further enhance the results. (1) The project should combine key data categories to generate insight into the total cost of ownership (TCO). Bringing together the upfront costs, fuel costs, and maintenance costs would be very useful when compared to other technologies. 2) If possible, the team should share additional insight regarding bus fueling (fueling and charging times, how to achieve lower-cost hydrogen, fueling infrastructure costs, etc.).
- The accomplishment of having durability exceed the ultimate target of 25,000 hours is impressive. In addition, the project has been able to adapt as the fleets have evolved to continue to provide data relevant to the current state of the technology. The project has also been able to move from demonstration mode to providing data relevant for early commercialization.
- Understanding real-world applications and barriers is essential to DOE objectives, as it allows for the right focus for several other investment directions.
- The accomplishments are very good and useful; however, to make the data more useful, the team should consider the following. (1) The overall FCEB cost per mile does not seem to be an accurate enough comparison to the baseline bus cost per mile, as indicated in the note found in the presentation that states, "Not all are equal comparisons." If possible, the team needs to improve this accuracy. (2) For the Stark Area Regional Transit Authority buses, the baseline is "[compressed natural gas]/diesel hybrid." Since those are really two different baselines, the baseline comparison should be split into two. (3) On the "Hydrogen Cost Data Summary, $/mi" slide, including the number of buses in the FCEB fleet and the baseline fleet would allow the reader to make a judgment on accuracy based on sample size.

Question 3: Collaboration and coordination

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

- This is a perfect assembling of entities for collaboration and coordination. This group of collaborators collectively represents operators and original equipment manufacturers, providing a good cross-section of entities encompassing the bus transit sector of the public transportation sector.
- The project effectively manages collaboration among four stakeholder groups representing public transit agencies and companies involved in building and integrating FCPPs, battery suppliers, bus service providers, and hydrogen fueling station operators.
- The quantity of data received demonstrates the project's good coordination with relevant stakeholders. The team is also encouraged to engage with key infrastructure stakeholders to better understand their perspective for fueling bus fleets (either at a dedicated depot or at retail stations). This may fall outside of the current scope, but fueling operations and costs are major aspects of bus fleet operations that could be better understood with more input from infrastructure companies.
- The following are suggestions for future collaboration and coordination: (1) The current participation is in California and Ohio, which is not a bad representation of two different climates; however, eventually it would be good to get more severe climates (e.g., cold and hot and humid). (2) It would be good to get feedback from the drivers that utilize the buses and the technicians that service them so that they can share the positives and negatives from their perspectives, versus those of the baseline buses.
- Collaboration with the studied fleets is critical to the project. It is not clear that other research organizations should be involved.

Question 4: Relevance/potential impact

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

- At the current stage of deployment of FCEVs (e.g., light-duty, material handling, HD, maritime, etc.), studies like this one are critically important for benchmarking the technology and highlighting the maturity and potential compared to conventional technologies. Much education is still needed with the public and with policymakers, among others, to demonstrate the value and potential for FCEV technologies to take their place in the ZEV sector. This study (and other like studies, which are to be encouraged) goes a long way toward providing defensible evidence on the performance of FCEVs, which can be used to educate those sectors of society that need to deploy, use, and make policy about them. This project is perfect for providing defensible arguments to the stakeholders. As such, the impact of this work is huge.
- The project has a high degree of relevance, not only in the areas of operational and cost metrics for the buses themselves but, perhaps more importantly, as an early source of operational and cost data for emerging medium-duty (MD) and HD applications that have central fueling.
- Understanding real-world applications and barriers is essential to DOE objectives, as it allows for the right focus for several other investment directions.
- This is a highly impactful project with minimal investment required. The project is well done.
- From the presentation, it was clear that some of the FCEB targets are already being met, which is fantastic news; however, it was not clear from the presentation what the baseline buses' comparative targets were for lifetime, availability, etc. Perhaps they are the same as those in the "ultimate target" column, but this was not clear.

Question 5: Proposed future work

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

- The proposed future work is a perfect natural growth of the existing work. This project was not scored a 4.0 because this exact approach and effort should be extended to other HD applications, such as Class 8 HD trucks (e.g., long-haul and drayage Class 8 vehicles, as well as smaller Class 6–7 vehicles), material

handling, airport handling, and portside applications. This is an extremely important activity and needs to extend beyond buses.
- The opportunity to add additional fleets will keep the data being reported by the project fresh and allow for trends to be seen as the technology and operation of FCEBs mature. It would be beneficial to see more emphasis and analysis on true "all-in" fuel costs and per-mile cost comparisons.
- Obviously, continuing the data collection is key, and the desire to expand the scope to include fuel cell truck projects is also appreciated. This will be of great interest in a rapidly growing market. It is also suggested that the team more deeply consider the fueling infrastructure component of the value chain, given the huge impact that it has on the TCO for commercial operations.
- Understanding the infrastructure costs, various scenarios, and how they scale is critical to identifying the barriers to adoption.
- The proposed future work looks good and appropriate. The focus, of course, needs to be on attaining a larger sample size and more data on baseline buses for comparison.

Project strengths:

- The project's strengths are (1) that it has already quantified the comparison between FCEBs and the baseline buses and (2) that it has shown that the fuel cell stack seems robust and that it is the balance of plant (BOP) and other propulsion-system reliability issues that need focus. On that note, perhaps there should be some funding programs to drive improvements in those areas.
- The project has a systematic approach to gathering data and a very thoughtful analysis of the data. The alignment of the cumulative costs of maintenance to the introduction date was very well done and very pertinent to the study's objective.
- This is a highly impactful and referenceable project that demonstrates the successes and remaining challenges for FCEBs. The value of this project is considerably higher than the limited allocation of DOE funds that is required.
- The project's strengths include its significant sample size and solid, long-term relationships with the project partners.
- This is a very important activity, well-conceived and well executed, with demonstrated value to the community.

Project weaknesses:

- It can be challenging to bring new ideas to reoccurring data collection projects and maintain focus on presenting the key results. This project is effective at sharing major updates, but there is still more that could be done to address key questions for industry and potential future operators. A stronger focus on overall TCO will have a greater impact beyond studying each element of cost separately.
- The activity needs to be extended to other emerging applications being pursued in the community, including those in Class 8 HD drayage, long-haul trucks, HD material handling, maritime (on- and off-ship), and airport ground support.
- The project's weakness include the following: (1) The comments saying that the fuel cost comparisons are not all equal makes it difficult to compare. (2) Furthermore, the comparison of the FCEB fuel costs to baseline buses should be improved. This should perhaps even be done in an appendix to the presentation for those who want to see the detail behind the comparison so that it is a thorough, apples-to-apples comparison. (3) For propulsion system issues, it would be good to itemize the ones that are required for the fuel cell system versus the ones that are due to the electric propulsion system to differentiate these two challenging areas. For example, it is not clear whether cooling system leaks are due to the cooling system for the fuel cell system or the electric drivetrain. If the leaks are tied to the fuel cell system, even though the fuel cell stack seems reliable, this means that its BOP is not reliable and needs to be improved. On the other hand, if the leaks are tied to the electric drivetrain that is commonly seen in a battery electric bus or hybrid bus, then it is a common reliability issue between these clean transportation propulsion technologies and is worth quantifying further. In the end, it still stacks up against the reliability of the FCEBs; however, it will help quantify how much work is required to improve the reliability of the fuel cell system and its BOP versus that of the other systems, such as the electric drivetrain, that are common with other propulsion technologies.

Recommendations for additions/deletions to project scope:

- It would be useful for the project team to do the following: (1) The team should better quantify durability and reliability and separate them into different bins, such as fuel cell and BOP versus the electric propulsion system, which can be considered a separate technology since battery electric and hybrid electric systems also use it. (2) The team should consider the emissions differences when using FCEBs versus the baseline technologies. (3) The team should determine the other technologies and challenges that must be addressed in order for FCEBs to be successful, as well as any advantages an FCEB would have over other technologies. For example, air conditioning on an FCEB or battery electric bus will have a significant electrical demand. It should therefore be determined whether this is an area that needs technical advancements to improve efficiencies or reliability, as well as whether an FCEB would have more range or reliability, since it is consuming hydrogen to create the energy to run the air conditioning system. This technology is versus a battery that must be plugged in to recharge and that uses a considerable amount of the electric bus battery's energy while in use.
- It would be beneficial to see additional detail related to fuel costs, including capital and operations and maintenance costs per kilogram and per mile for the FCEBs. These data will help in understanding the true comparison with competitive propulsion technologies and in understanding the commercial landscape for developing a fueling infrastructure for future MD and HD fleets.
- The project team should focus on showing total TCO from the data already collected today and expand data collection as needed to accomplish this. The team should also engage closely with infrastructure providers to capture their perspective and insights into the station side of the business.
- Understanding the infrastructure costs, various scenarios, and how they scale is critical to identifying the barriers to adoption.
- The project team should expand the scope to other emerging applications. This project should be kept funded.

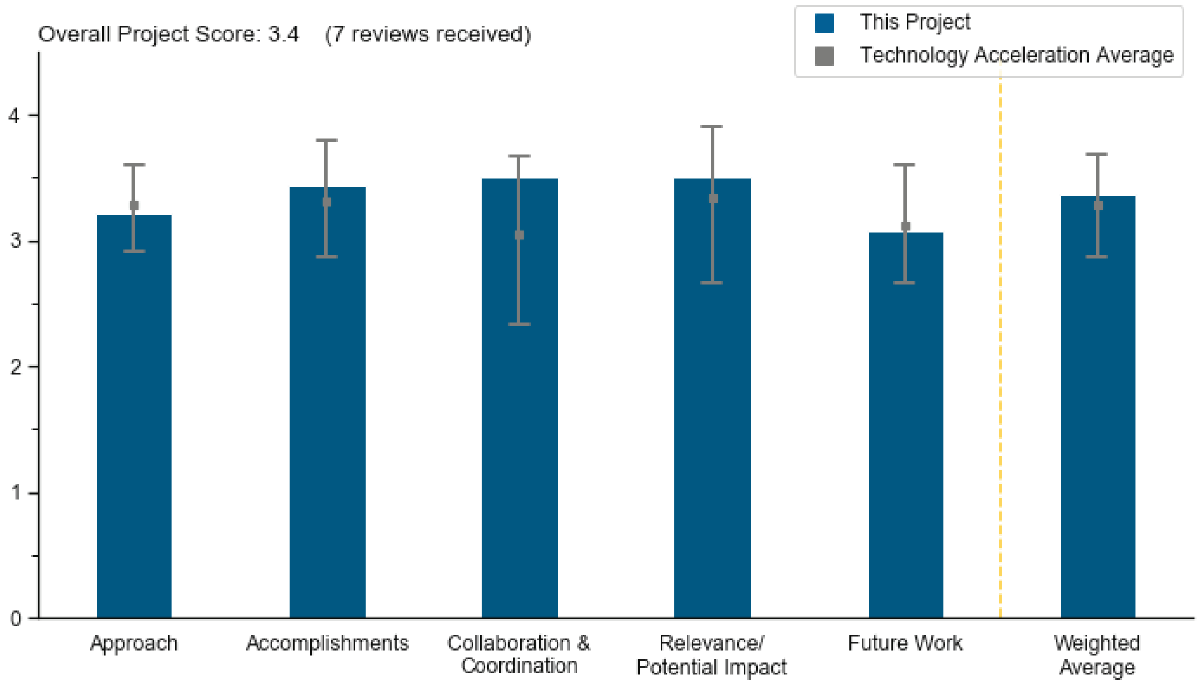
Project #TA-014: Hydrogen Station Data Collection and Analysis

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.

Project Scoring



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

Question 1: Approach to performing the work

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

- The overall approach is good, and it is good to see the project leverage the existing California Energy Commission (CEC) agreements to access data. In addition, the project tends to look continuously for new ways to analyze and synthesize the data it receives, which is a strong point. Finally, the new work on queuing is unique and directly addresses a data gap that has been an issue for governments supporting station development and needing to be well versed in operations. Since this aspect of the project has looked at only a couple of stations so far, it should be expanded so that those running the project can develop insights through more significant levels of supporting data. However, the tie to the CEC is too strong and is thus a weak point because the project has not identified a way to continue to receive data independently of CEC contracts. The project may need to find a way to garner support and participation from station operators on its own.
- Using actual California station data to evaluate performance is a very good approach to understanding and categorizing station reliability. This data is most likely the best set of aggregated data for doing this analysis. It is encouraging that the team focuses on the most utilized stations to identify reliability issues.

- The investigators have done a good job of accessing data from California stations and earlier infrastructure projects. The investigators have produced a wide variety of data products.
- The data collection methodology follows a comprehensive approach while data analysis explores a set of key performance indicators (KPIs) crucial for assessing the performance of the hydrogen refueling station (HRS). Queuing data and analysis is a novel element added to the analysis last year. It should be expanded to more stations based always on the availability of monitoring equipment. No information is provided on the template questionnaire used for collecting information as well as the frequency of updates.
- While the objectives are clearly identified, the project could be improved by better understanding who is using the data and how it is being used. If the lack of data is the high-level barrier, then the team should have some insight into why that data is needed.
- Drivers are notably absent from the evaluation. The approach should be extended to include their experience of stations. It might be difficult to organize such a study, but it could prove extremely valuable. In the end, the success of hydrogen fuel cell cars is dependent not just on consumer buy-in but on consumers' buying cars.
- The project is an ongoing effort, but the number of KPIs could be reduced.

Question 2: Accomplishments and progress

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

- The project collects a series of KPIs aligning with and serving DOE's main goals. The amount of hydrogen dispensed, availability, maintenance, and a number of other important parameters are covered. Further analysis is also provided to investigate the roots of downtimes and various interlinking indicators. As the source of origin for hydrogen is gaining importance, the identification of green hydrogen sources could be considered as part of the questionnaire. This and other similar analyses contribute to the technology and also program monitoring while comparing results with the Hydrogen and Fuel Cells Program targets. However, no information is provided on whether HRSs have fulfilled their targets and commitments.
- The project team's collecting data from station operators is excellent. The data presented and its analysis are extremely relevant. For example, it is nice to see, with the reduction in dollars-per-kilogram maintenance costs, that station design and operation are reaching a certain level of maturity. It was surprising to see the percentage of incidents related to the dispenser versus the compressor; it would be good for the project team to spend time analyzing this in more detail.
- The analyses that have been developed beyond the standard summary composite data products are outstanding. The queuing investigation detailed availability analysis and fueling behavior trend analysis are particularly insightful and useful right now.
- The accomplishments during this period were good and start to provide a good picture of the status of fueling technology in an early-stage market. This work should set the stage for further development needs, either through new project funding or leveraging existing work (i.e., hoses, nozzles, and technologies to help manage queuing).
- The data compiled is the best available set of real-world data describing infrastructure operations.
- While the project has shown a rapid growth of stations overcoming many commercial barriers, the fact that the contract for data collection has run out with one data provider renders the data set less representative of commercial use of hydrogen.
- The purpose of this effort is to use data for future innovations and research, but most of the data is based on existing operational equipment, which is several generations behind on current technology (and status of technology development). It is increasingly unclear how this data is valuable to facilitating future innovation and directing research efforts.
    - Regarding the queuing model, no benchmark has been identified for the project, so unless one was established (perhaps gasoline), this should be abandoned because it is a waste of taxpayer money.
    - The "missed fuel opportunity" is not needed. Station operators are aware of the impact of this on their revenues (even in a pre-commercial market).
    - The team should consider removing the Air Products $9.99/kg initiative that tried to see whether the market would respond to lower fuel costs. When this did not make a significant difference, Air

Products raised prices back up to previous levels. Removing this anomaly from the data provides a better reflection of fuel pricing (or digs into what actual margins or cost components are).

Question 3: Collaboration and coordination

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

- The project brings in a relevant suite of stakeholders. In addition, it is good that the project looks beyond just the station developers and the government funders. Including other public–private or similar organizations should help the project maintain relevance with the information needs of the broader industry and ensure that the developing U.S. hydrogen fueling market is one of the most well-informed global markets, with actual in-service data.
- The CEC made National Renewable Energy Laboratory (NREL) data collection a requirement for those HRS operators receiving California state funding and is paying NREL to collect data. Collaboration and coordination appear to be sufficiently broad.
- Collaborating with California and station providers is an excellent method.
- The project collaborates with a large and highly relevant group of California stakeholders: the representatives and leaders of the hydrogen/gas industry. The project did not explain why several station collaborators are no longer reporting data and whether they will be approached to continue for the next year.
- The investigators have worked well with the California infrastructure project. The investigators may need to be more proactive in working to ensure continuing data access where mandatory reporting has ceased.
- The project collaborates with the California Fuel Cell Partnership effectively, as well as with the individual refueling station operators to collect data. Nevertheless, international collaboration would be advisable through a comparative analysis for benchmarking and considering a number of publicly available KPIs. In addition, in cases where there is lack of data, more effort should be put on accessing or retrieving missing information for the sake of a robust analysis. Although already partially conducted (gasoline stations), the project team could attempt collaborating with conventional fuel refueling stations to compare similar KPIs.
- As stations in the Northeast are rolled out, it would be interesting to reach out to the operators of these new/future stations to perform the same type of data collection and compare with experiences in California.

Question 4: Relevance/potential impact

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

- Data collection and analysis is an essential element for providing key statistics and conveying messages about the performance of key applications. In this respect, this project, while focusing on HRS KPIs, reveals key results from the operation of the refueling stations. This, alongside a more inclusive overview and analysis on other applications, such as vehicles and stationary fuel cell systems, could provide the basis for a comparative assessment of the hydrogen and fuel cell applications against other technologies. Furthermore, an historical analysis of the available data will provide insights on the evolution of the technology and identify major achievements and weaknesses that necessitate further research.
- This project is highly relevant in measuring the key enabler to fuel cell vehicles: the hydrogen infrastructure. The results can be used by policy and industry decision makers to target commercial barriers and understand when they have been overcome. The team's ability to add new data sets during the course of the project has increased the potential impact of the data sets. The future addition of medium- and heavy-duty vehicle information will further strengthen the project.
- This is one of the most immediately relevant projects in the Fuel Cell Technologies Office's Technology Acceleration portfolio. The data capture is absolutely essential to supporting the ongoing work of publicly available analysis and transparency on the effectiveness of state investments.
- Real-world data is critical to both calibrate existing infrastructure performance models and to develop new models. The data is vital to inform potential investors in hydrogen fueling.
- The data presented is extremely valuable to designers and operators of stations.

- This work starts to shed light on the reliability issues station operators face and the key components affecting reliability and performance. Resolving the queuing issue would most likely involve a second dispenser and additional capital expenditures. This becomes problematic at an underloaded station that has high demand only at certain times of the day. The team should come up with recommendations as to potential solutions, other than a second dispenser.
- The purpose of this effort is to use data for future innovations and research, but most of the data is based on existing operational equipment (including HRSs integrated with technology five years old and older), which is several generations behind current technology. It is increasingly unclear how this data is valuable in facilitating future innovation and directing research efforts. For vehicle fueling data, this data may be most valuable for scenario modelers, as actual hydrogen infrastructure providers can request this information from fuel cell electric vehicle original equipment manufacturers.

Question 5: Proposed future work

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

- The project has a clear path forward to gather data from new California stations. The investigators should work with older stations so that the stations will continue to report data even though compulsory reporting is no longer in force.
- Getting ahead of identifying the needs for future stations is an intelligent next step for the project. While there was not much detail available regarding the potential new analyses in the coming year, past experience through the project does indicate that new and valuable insights will arise.
- The proposed future work includes plans to update data collection, which will also require securing/ extending contracts with data providers. Identifying needs for future stations increases the relevance of this work.
- The proposed future work should look at how the various hydrogen supply chains affect the following: station power consumption, losses from hydrogen source to nozzle, and compressor maintenance costs. The future work should also address how the various compressor and chiller designs affect costs and reliability.
- The project work could consider station design (layout, etc.) to try to understand whether it affects incidents like queuing behavior and overall consumer experience.
- The project provides a number of key bullet points in terms of future work. Although they are valid, no reference to lessons learned is mentioned, while linking them with concrete examples of future work. In addition, challenges encountered in the past, as well as ways to tackle them, should be considered as part of the future steps. A more detailed analysis would be useful and welcomed; nevertheless, more information is necessary to fully comprehend the next steps of this projects. Lastly, more ways to evaluate existing data should have been mentioned as part of future work.
- NREL should not engage in identifying needs for future stations.

Project strengths:

- The project's strengths are that it is addressing needs in the developing hydrogen fueling market that exist now and for which there are large knowledge gaps for industry and government stakeholders. This project is an essential part of "proving the concept" that hydrogen stations can be successful, can be operated reliably, and will be used if developed. In addition, while this project has an aspect of continuous data capture, project scientists also continue to seek new ways of capturing and analyzing the data, which is helpful for a growing industry that does not always anticipate its own information needs.
- The project exemplifies in the international context a detailed analysis on KPIs. All major parameters have been collected, analyzed, and visualized comprehensively. Detailed information is presented with monthly/ daily/hourly granularity, which is rarely available. The team undertaking the work is dedicated and committed, with extensive experience in the field.
- This project is developing highly relevant data sets on hydrogen dispensing, data that can guide work and investments by many California agencies, as well as developers. The addition of queuing and station availability has increased the project relevance. Analyzing both traditional and renewable hydrogen infrastructure can also be useful in guiding DOE programs and investments.

- The project summarizes issues and status of the fueling station network in California, highlighting early market status and challenges. The project also begins to set the stage for justifying new developments and focus areas and for ensuring hydrogen price points are eventually achieved.
- The project has assembled a comprehensive data set. The project has produced a broad and useful array of data products. The project will continue to add new data as new stations come on line in California.
- The project team is providing valuable data collected on a relatively large number of stations. It provides interesting information for industry and the public and deserves continued funding.
- The historical data track record of HRS development evolution is a project strength.

Project weaknesses:

- The project's biggest weakness is the tie to contracts that are outside the control of the project scientists or DOE. While leveraging CEC contracts has helped get a high level of early participation from station operators, it is becoming clear that the project will need to develop some alternative structure for ensuring that it continues to receive data beyond the life of the contracts. Moreover, if station deployment is truly successful and becomes more industry-led in the coming years, then there may not be state government contracts to leverage, even though there may still be a need for data and analysis. The project likely needs to develop a supplementary method for ensuring participation and data capture more long-term.
- Older California stations will no longer have to report data, but clear strategies to encourage stations to continue data reporting were not evident.
- The project needs to maintain the availability to collect data from all stations and continue to work with the most robust data sets possible.
- The project seems to cover many areas but does not drill down into any key areas. In addition, it would be good to see progress over time by picking the key issues affecting reliability or costs as the station network matures.
- The desire to collect more data without direction on what is most valuable to industry is a project weakness. Adding data collection points based on "collecting data for data collection's sake" is also a weakness.
- The absence of perspective from drivers is the main weakness, but it is not too late to collect such information through a survey and analyze the data.

Recommendations for additions/deletions to project scope:

- The project should support expanding the queuing analysis further for future work. The team should collaborate with state partners for two purposes: (1) to identify additional cost detail that could be useful in state efforts to understand the developing business case for hydrogen stations and (2) to develop a metric for effectiveness of state funding based on the methods used to choose stations to fund and the observed performance. The project should also incorporate analyses similar to the missed fueling opportunity analysis to identify insights not just for the observed data and the known locations, but for what the data could be saying about locations that have thus far been overlooked. This will likely require a tie-in to some geographic information system (GIS) analysis.
    - The project should also evaluate whether it currently collects or could easily collect data from fueling events that do not reach full state-of-charge. The evaluation of the data should focus on whether common causes of incomplete fills can be identified. This could help lead to insight on whether the fueling protocols need to be re-evaluated and/or re-tuned, as short fills may be caused by out-of-bounds operation that may not truly need to stop the filling process. In addition, it would be helpful to perform an analysis of drivers' reactions to short fills. It would be helpful to know (1) whether they attempt multiple fills and, if so, the number of fills; (2) whether it depends on the operating status of some particular pieces of equipment; (3) how often consecutive short fills occur; and (4) whether the reaction changes with the number of these happening.
- The measurement of green hydrogen as a fraction of the refueled hydrogen should be added in the questionnaire. Improvements in terms of monitoring performance data in real time are considered useful while enhancing the accuracy of the results and providing users with information on HRS availability. In addition, queueing data, if expanded to a considerable number of HRSs, could be used for further planning of new HRSs. Future work should include a plan for continuing data collection and ensuring the quality and

quantity once the number of HRSs increases to a few hundred. A comparison with bus and medium-/heavy-duty vehicle HRSs could perhaps enrich the existing analysis.

- The project scope should include identifying who is using the data sets and how final data sets will be used. This information will help ensure that future work is aligned and is most valuable to achieving industry improvements in hydrogen delivery and availability.
- The team should delete inclusion of the queuing model, “missed fuel opportunity” efforts, and the tracking of station types.
- The investigators should work to encourage and motivate stations no longer compelled to report data.
- The team should look at queueing as a separate topic.

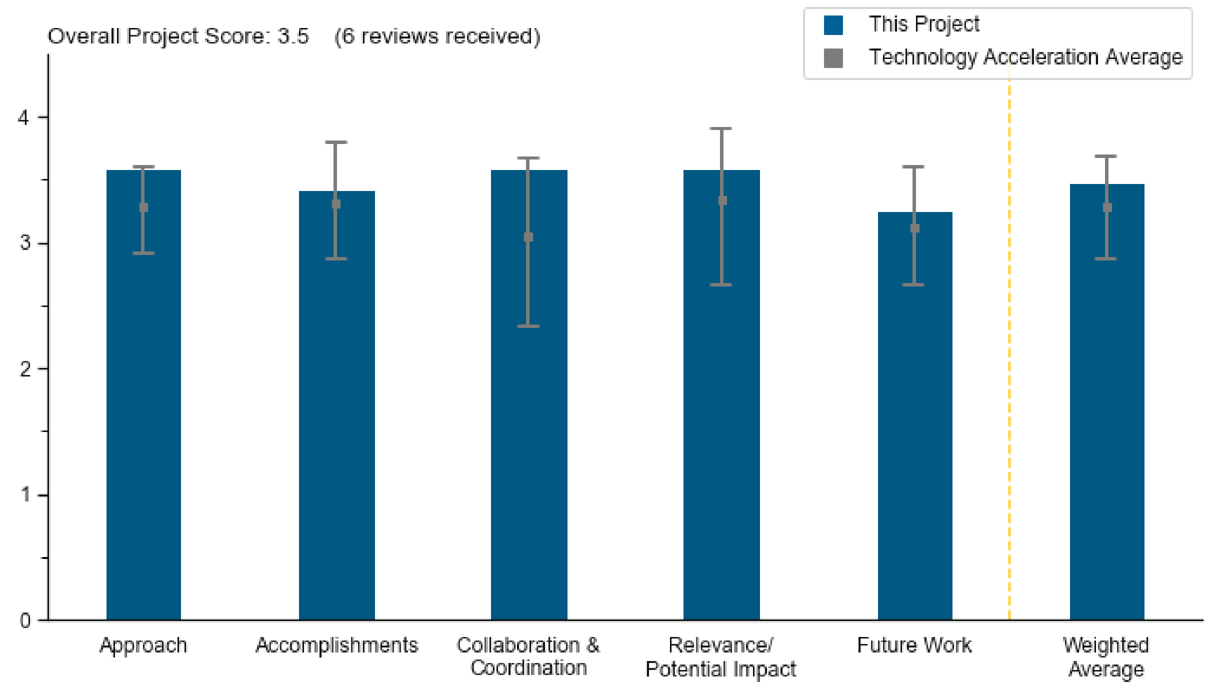
Project #TA-015: Dynamic Modeling and Validation of Electrolyzers in Real-Time Grid Simulation

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).

Project Scoring



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

Question 1: Approach to performing the work

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

- The team demonstrates a good approach to the problem of integrating electrolyzers into the grid. There is an appropriate level of effort to ensure satisfactory results, and the models estimate well the impact of renewables and electrolyzers supporting the grid. There is a good mix of hardware in the loop, modeling, and industry feedback.
- This work is timely, as it is necessary to address the integration of hydrogen systems and to design the electricity market to supply energy services to both hydrogen users and the grid. The migration to the Institute of Electrical and Electronics Engineers (IEEE) protocols for energy storage is another step in the process to get hydrogen accepted into the tool chest of distributed resources needed for electricity grids with high renewable energy penetration, an inevitable requirement given decarbonization and renewable energy costs.

- This project provides unique data and insights based on its approach. It will be good to see the work expand its runs and outputs to longer-term studies. While it is logical to look at single incidents initially, which seem to be the current project focus, it will also be interesting to see how the electrolyzer reacts to multiple consecutive demands or needs on the network. It would also be interesting to see how the front end controller and system might respond to events that would cause multiple possible demands on the electrolyzer and its output.
- The milestones and go/no-go gates for this multiyear project are well defined and align well with the project objectives and identified barriers.
- The combination of testing and modeling will provide a good basis for evaluating a wide range of implementation types.
- Controllers for mating the electrolysis systems with the grid and other renewable sources of power must be developed and sophisticated enough to handle the vagaries of the performance characteristics of the electrochemical process. Regarding the electrochemical system, the performance of such a device can vary widely based on environmental condition effects as well as operational variability, efficiency, and stability of the stack. It is a chemical plant. It is necessary to understand the impact of the variability, not just of the stack but of the entire electrolysis system, but it was not clear that the number of hours dedicated to such understanding would be sufficient to develop a robust controller system.

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 work modeling the impact of electrolysis on penetration of photovoltaics (PV) in microgrids is promising in terms of the electrolyzer matching solar–PV dynamics. The questions now move to the other side of the supply/demand equation, such as how much hydrogen can be used at this level of system integration. The following questions are unclear: what impact this has on hydrogen balances, distribution, and storage; how hydrogen can be used within the sub grids; what the degree of consistency with hydrogen demand models is; and most importantly, how much the hydrogen costs.
- There is good progress across milestones and go/no-go decision points. Two of the five milestones are expected to be complete by May, including the go/no-go pass decision. The project is proof that electrolyzers can make grids more robust and capable of increased renewable energy or more efficient operation of thermal power plants.
- The project is on track to meet milestones. It has demonstrated electrolyzer functionality to provide distribution grid support in a simulated, real-world environment of several utility grid configurations with varying levels of renewable penetration. To provide full value, the work needs to quantify the financial benefit of the services provided and net them against impacts on fuel production.
- Results to date show good performance and input into modeling tools.
- The accomplishments to date are good, though it was a bit difficult to discern what was completed in the last year compared to prior years of work.
- It is not obvious what electrolyzer was used, nor was the history of such an electrolyzer made clear. Different electrolyzers perform differently. The controller logic should be general enough that it can be modified to be useful with other electrolyzers currently available for testing. Ten hours of electrolysis testing and characterization is not enough to provide guidance for controller development. Furthermore, it would be important to include electrolyzer "hiccups" when evaluating performance characteristics, and then assess the effect on controller logic.

Question 3: Collaboration and coordination

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

- There is outstanding collaboration across multiple utilities for key market data input; good integration across NREL and INL, showing benefits and strengths of two laboratories working together; and deep integration of IEEE industry standards for interfacing with the grid. The university partners are an important part of the project and will enable a broader distribution of the efforts. The geographic range of Humboldt State University (in Northern California) to Florida provides a good range across the United States.

- This project has leveraged a wide range of expertise, with relevant academics, national laboratories, and energy and utility companies included in the work. In addition, it appears obvious that the project has responded to prior reviewer comments to bring in more of these types of collaborators.
- The project appears to be leveraging a well-coordinated team featuring national laboratories, utilities, universities, and regulators. This team is stronger than those of most peer projects.
- This is a good line-up of collaborators. Electric Power Research Institute (EPRI) was looking at storage and integration of hydrogen systems a couple of years ago (Matthew Pellow). Perhaps EPRI could contribute to collaboration. It would be good to know if there is an opportunity to get hydrogen on the agenda of California Independent System Operator resource planning.
- Having partnerships with grid power producers is a big step in getting buy-in and validation of the potential value of electrolyzers on the grid.
- Every group involved is well suited to contribute.

Question 4: Relevance/potential impact

This project was rated **3.6** for 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 relevance is clearly shown by the number of industry partners and results that show how electrolyzers can provide flexibility for both renewable energy and better operation of thermal power plants. This project will provide three clear benefits: (1) additional renewable energy, (2) lower-cost hydrogen production, and (3) better quality grid electricity to customers. The integration with universities is important for work force development and knowledge sharing.
- This project is highly relevant. This platform is a fundamental building block to developing a high-penetration clean energy hydrogen system. Having a physical system that demonstrates the concept and generates physical data is very helpful.
- Understanding how to manage and control the integration of an electrolysis system with renewables and the grid is a necessity. A successful outcome would provide numerous options for the utilities and the ability to meet the goals of the Hydrogen and Fuel Cells Program.
- Demonstrating and validating that there is significant value to the grid by using electrolyzers in load balancing is valuable, as grid management remains one of the biggest limitations in the growth of this industry. This project aims right at the center of this issue.
- The project begins to set the foundation for quantification of grid benefits of electrolyzers. The project will make an important contribution to understanding the viability of electrolyzers as grid resources connected at the distribution level.
- The project is looking to answer questions that are central to the H2@Scale effort and are currently relevant in areas attempting to expand their hydrogen-based programs.

Question 5: Proposed future work

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

- Future work with hardware in the loop and the clear example of the impact of 225 kW stacks on frequency and voltage regulation clearly demonstrate to grid operators that electrolyzers have value in providing better-quality electricity to customers. Saving fuel and reducing emissions from thermal power plants are important electrolyzer benefits, which may not be understood by those outside of a narrow set of people who have explored this or implemented the approach.
- These are good next steps. After a full scope of system integration is determined, it would be good to determine how results can be turned around to identify performance requirements as a list of specifications for electrolysis process, ramp rates, need for black start capabilities, operating range, capacity, etc. The next step will be to determine where in the electrical system (at what level) to connect to optimize the grid, hydrogen production, and hydrogen cost.

- The proposed future work provides a logical extension of the current project. Valuation of grid services is critical in understanding the ultimate potential impact of the work. The team could possibly extend analysis to transmission-level systems.
- Extension of the ongoing work as proposed is valuable.
- The proposed future work is good, though it is not entirely clear how the optimization module discussed will actually be a different study from another current H2@Scale cooperative research and development agreement project, which is also a collaboration between Pacific Gas & Electric (PG&E) and NREL.
- The industry needs to better understand electrolyzer performance characteristics. Decay rates and performance variability must be realistic and should be incorporated into the controller logic. It is recommended that these aspects be considered, if they are not already.

Project strengths:

- There is a good integration of partners. The project brings a clear quantitative benefit of electrolyzers that can be understood by multiple stakeholders. The renewable forecasting at higher penetrations shows how the grid can be built out and reach beyond early projections of 20% variable renewable penetrations to 30%, 50%, or higher. Deep quantitative analysis of grid nodes and the optimum placement of electrolyzers are strong aspects of this project. The optimization of electrolyzer set points to reduce the cost of hydrogen while meeting minimum utilization of the electrolyzers is a key question in the business case for electrolyzer-based hydrogen production.
- The project has created a platform for testing integration strategies to determine process requirements, design controllers, etc. to meet growing interest in hydrogen integration with renewable generators, fundamental building blocks for future clean energy systems.
- Project strengths include high-fidelity, hardware-in-the-loop simulation with supporting analytics, adaptation to early issues with controller design to develop a superior approach in collaboration with stakeholders, and establishment of quantitative impact on grid operations in actual utility system environments.
- Collaboration with grid generators is a project strength. This is a highly impactful topic needing data and modeling to demonstrate the potential and value to the grid.
- The project's strong point is the uniqueness of the approach, which is also going to provide high-value data to the industry and decision makers in stakeholder organizations.
- Team qualifications, collaborators, and grid knowledge are project strengths.

Project weaknesses:

- Being able to distribute this deep technical knowledge to utilities on the East Coast and outside those listed in the project would be an important aspect of leveraging the most value from this multimillion-dollar effort. A better demonstration of the value of grid services would be helpful.
- The team needs to work with additional innovative partners on grid integration. Perhaps the team could work more closely with independent power producers who hold expiring power purchase agreements or distressed system operators facing politically unpalatable curtailments.
- Electrolyzer operational characteristics are a project weakness. Nothing was presented regarding the evaluations and studies of the interaction of the grid and other renewable power generators with electrolyzers.
- Broader implications of the work are not possible to determine without understanding the value of the grid services studied.

Recommendations for additions/deletions to project scope:

- As an outcome, it would be good to see the opportunity for three groups to discuss next steps: (1) the project team, (2) the grid producers, and (3) the industry members who are likely to implement the electrolyzers. This project provides an opportunity for groups 2 and 3 to better plan deployment and capture the value of grid management. It is sometimes not obvious to members of group 3 how working with the grid producers is possible.
- The team should consider more detailed electrolysis performance characteristics, if this is not already being performed. Electrolyzer sizing (megawatts) should be determined to optimize efficiency and grid–electrolyzer dynamics. The controller must also take into account safety aspects of the "system." A failure mode and effects analysis and/or a generalized hazard and operability analysis review should be performed, and the results should be used to guide further development and refinement of the controller.
- The team should increase the scope to allow results to be implemented at a pilot or demonstration level with a utility. The team should determine the best venue for sharing this knowledge with policy makers, utilities that are moving from 20% to 30% penetration of renewables, and those regions with more than 50% renewable energy penetrations.
- The project should look at system response to strings of consecutive events—these could be strings of similar events under varying conditions—to see how the controller decides to react under similar signals in varying situations. In addition, the reaction of the controller to potentially conflicting signals should be evaluated to determine whether there is a risk of non-reaction or non-desirable and non-optimal reaction.
- It is unclear what electrolyzer requirements look like or what the implications are to storage and hydrogen uses in terms of hydrogen produced. Grid constraints are also unclear, particularly given the advent of battery electric vehicles.

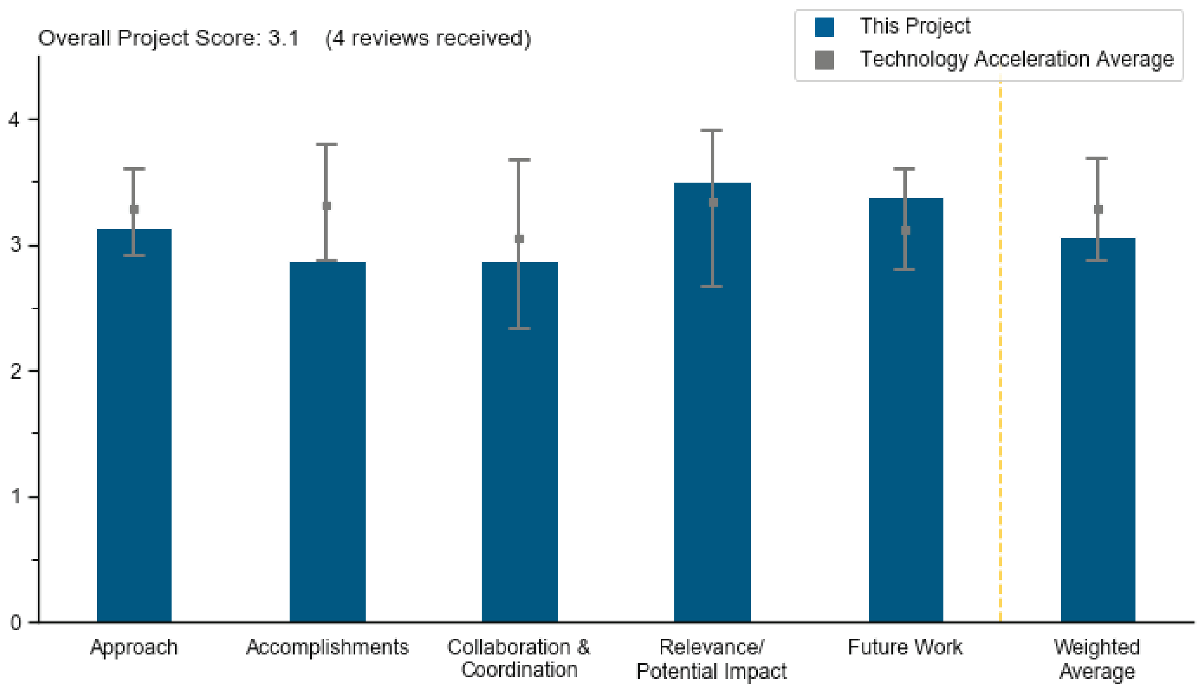
Project #TA-016: Fuel Cell Hybrid Electric Delivery Van

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

Project Scoring



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

Question 1: Approach to performing the work

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

- Building real-world hardware and getting real-world data, while at the same time educating operators and customers, is a very valuable approach at this time. In particular, the approach has brought forward specific design, test, and operation challenges (for example, DC-to-DC issues and fueling readiness) and prioritized work on getting those solved.
- The project demonstrates a sound approach to accomplishing tasks. The data collection and analysis of the performance of fuel cell trucks in this application should help the industry develop a fully commercial product. The timeline for the pilot demonstration is optimistic. The team should encourage maximum usage during the demonstration to help identify and correct issues before the Phase II trucks are built.
- The project scope is well aligned with DOE barriers. Phase II will be critical to understand "real life" behavior, gain experience and miles, and identify barriers.

- This project was initiated in 2014 and has encountered significant delays. The project could benefit from an experienced original equipment manufacturer (OEM) or integration company to better plan and work through the issues.

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.

- It is great to see the pilot truck finally completed and delivered for the demonstration period. The team has done an excellent job of mitigating early issues that caused delays. The team was also successful in acquiring funding to cover the whole project as planned. New funding includes moving to a refueling pressure of 700 bar to maximize truck range. This will help the truck design meet the needs of a broad range of users.
- The project shows good progress to date. Although the project is aimed at understanding the system, component issues could cloud the results.
- The DC–DC converter is a critical component in any fuel cell system. While this project should not be designing custom electronic equipment, it should have spent more time selecting the appropriate component. Progress has been slow and is at risk of becoming irrelevant compared to similar MD truck conversion projects. It is hard to determine whether goals have been met until real-world data have been collected.
- While it looks like Phase I deliverables have largely been met, it is not clear whether some of the delays due to problems (e.g., DC-to-DC) have resulted in delays from the original schedule and whether those delays might have changed the go/no-go date, thus affecting the issue of whether one year of demonstration can be completed before the funding opportunity sunsets.

Question 3: Collaboration and coordination

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

- The group of collaborators includes state, local, and federal governments, technology providers, integrators, and end users, in addition to the fuel supplier, so the full team encompasses real-world experience end-to-end through the supply chain. Real-world experience is a benefit despite some of the scheduling challenges, which may have arisen related to the coordination between the number of entities involved.
- The project has great collaboration with partners. One concern is with the OEM partners' ability and commitment to commercialize the truck. This will be important to ensure the project leads to an actual market product.
- The collaboration with the team entities seems to be good.
- There seem to be some major problems with the team in terms of successfully integrating a fuel cell system into the truck.

Question 4: Relevance/potential impact

This project was rated **3.5** for 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 continues to be well-aligned with DOE objectives. MD trucks are a large segment of the market, with the potential for high-volume production that would lead to lower costs for many components shared with other platforms. The growth of fuel cell trucks in the market could also help increase hydrogen station utilization and justify the need for more station coverage.
- With the increasing focus on MD and heavy-duty (HD) applications, this project looks very timely and relevant with its look at the "last mile" delivery fleet model. It would be good to see more emphasis on the fueling infrastructure/process since that is really a key driver/enabler of commercial viability for commercial fleet applications.

- Relevance with DOE objectives is in alignment, highlighting issues with fuel cell conversion of existing delivery vans.
- Lack of vehicle systems experience in real-world applications is an important barrier that this project addresses head-on.

Question 5: Proposed future work

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

- The proposed future work (Phase II of the project) is on target for achieving project objectives.
- The proposed work is reasonable. The short timeframe for the demonstration and go/no-go decision could be the biggest challenge for the team.
- There is a need for all problems to have root cause solutions and appropriate validation before the project proceeds to the go/no-go point. While this may cause some headaches managing the project, especially with calendar constraints on funding, it is critical in bringing the demonstration from a one-vehicle demonstration up to the planned fifteen-vehicle "pilot" fleet, which is a critical next step to commercialization.
- It is unclear whether the conversion to 700 bar tanks is a good idea, given all the other problems encountered.

Project strengths:

- One strength for the project is that the team included user input in designing the truck. This helps ensure the truck meets user needs. In addition, the economic assessment is important to help other potential users to understand the technology and costs for better planning. The larger fleet of trucks in Phase II will be important to prove out the design for this application.
- The project structure (demonstration, validation, go/no-go, then pilot fleet) is a strength. The principal investigator has had to deal with a lot of evolution of the project to keep it on track, so the flexible project management is also a strength.
- This project is well aligned with DOE objectives. There is a sound approach for the prototype in Phase I and deployment in service and data collection in Phase II.
- This is directly aligned with DOE goals to get fuel cell systems on the highway.

Project weaknesses:

- The tight timeframe for the go/no-go decision point does not leave much wiggle room for mitigating issues. The technology partners need to take an active role during the demonstration to identify design flaws and engineer corrections before building the Phase II trucks.
- The relative lack of product experience and business stability of the partner companies has been a challenge, which has resulted in both schedule and technical issues for the project.
- This is a small team, and several immature components threaten to cloud the system performance and its evaluation.
- It has taken too long to integrate the fuel cell system, and at the go/no go decision point, the team should consider whether it is worthwhile to continue deployment of this particular system.

Recommendations for additions/deletions to project scope:

- For Phase II, very precise data related to refueling/infrastructure should be maintained and communicated. Since this project is demonstrating the type of MD/HD commercial fleet that is getting a lot of attention now as a fuel cell market, there is going to be much scrutiny of fueling costs, any issues/concerns that arise, and operational convenience. It would especially interesting to see a "total cost of fueling" analysis, with the price per kilogram and, more importantly, the cost per mile including capital and operations and maintenance components, so that the team can provide some real data on total cost of ownership for this type of fleet. Shell has good station cost information based on information the company has shown publicly, so the project team should encourage Shell to participate fully in this part of the analysis and reporting.

- The project is developing a significant knowledge base of lessons learned that are valuable to the community at large and can push the state of the art in terms of fuel cell electric vehicle integration. The project is encouraged to disseminate these lessons learned beyond their publication in the final report.
- The project could benefit from an independent analysis regarding the fuel cell technology proposed compared to the state of the art.
- The project should ensure active participation of technology partners during the pilot demonstration phase.

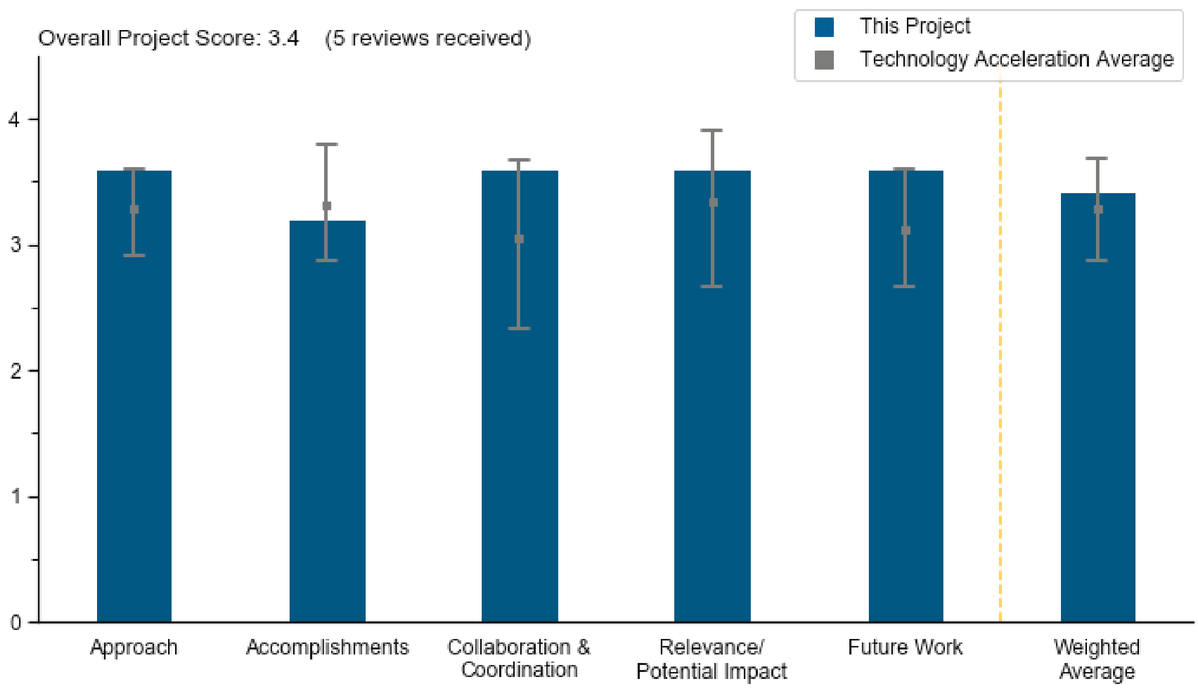
Project #TA-017: Innovative Advanced Hydrogen Mobile Fueler

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.

Project Scoring



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

Question 1: Approach to performing the work

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

- This project appears to directly address three key Fuel Cell Technologies Office (FCTO) barriers. Once deployed, the mobile fueler will be able to provide real-world operational data to NREL. A special DOT permit allowing transport at 95 MPa has been issued for the system, which reduces the cost and improves logistics of transportable hydrogen storage. The demonstration phase will help local authorities familiarize themselves with codes, standards, advantages, and concerns around hydrogen fueling infrastructure. This was clearly laid out in the presentation.
- This project has an excellent approach to addressing the lack of hydrogen infrastructure. Self-contained design makes it easier to site with a smaller footprint. U.S. Department of Transportation (DOT) approval for transporting high-pressure tanks is important for industry.
- The team has designed and is currently building a mobile hydrogen fueler. The approach is strong, and the mobile fueler will deliver hydrogen in a fully code-compliant manner—the same as a stationary fueling

station. Having the unit fully self-contained is valuable, but it would have been preferable to have a fuel cell or other green power source rather than a diesel generator.
- The project approach appears to result in technology progress for mobile and stationary hydrogen fueling stations (HFSs) (and in this instance, a liquid nitrogen [LN_2]-based cooling system, compact Welcon-like heat exchanger/chiller, and 95 MPa DOT-permitted storage tanks).
- This project is aggressive in that 3–5 fills in the first hour, and 20–40 per day, is a challenge for stationary systems, let alone a mobile one. However, the team assembled to take on this challenge is extremely capable. While the project has experienced some difficulties, the overall approach and the team's handling of the setbacks has been appropriate, if not good. Several of the novel approaches are particularly impressive, e.g., using LN_2 to increase efficiency and decrease the real estate and weight requirements. It is also clear that this project is on track in construction of the fueler, even with difficulty in hardware delivery and other supplier issues.

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 design phase appears to be complete, and construction has begun. The schedule was delayed for DOT certification, which is reasonable because those types of approvals always take longer than expected. Completion of the DOT certification process is a major accomplishment and a really valuable step in improving hydrogen transport options. Construction has begun, and the team reports that 50% of the components have been procured. It is a concern that the system might not be ready for field testing by mid-2019 since the testing portion is supposed to last 18 months. It is good that the team plans to deploy at a facility already permitted for use as a hydrogen station, as that should reduce the permitting time for the new system(s). It is a little concerning that site selection is not complete yet. There will likely be unexpected hurdles in getting the system landed at a location for testing (e.g., local permitting issues, especially for the diesel generator, challenges in getting shore power identified and supplied to the system, etc.).
- The team has made good progress with the project. It is great to see DOT approval for high-pressure tanks on the road. The fact that other clients were waiting for this approval shows this was beneficial for the industry.
- Currently analyzing frame and fire protection design for 95 MPa storage tanks is an accomplishment, and lessons learned could transfer to truck-mounted systems (or from truck-mounted systems to this system). It may be good to attempt to use the definition for station capacity used in California (either from previous California HFS grant funding opportunities [GFO] or to be assessed with a new NREL/California formula).
- It seems this project has overcome the scheduling and cost overrun difficulties of the past and is back on track for a successful completion.
- The project has already seen cost overruns and schedule delays. The new project controls now in place will, one hopes, get the project back on track. Acquiring the special DOT permit is an excellent accomplishment that can have an impact on the community, in addition to benefiting this project specifically. The sooner the fueler can be deployed, the sooner it can collect data and support the expansion of (and the current) hydrogen fueling networks. The reporting should include performance data of the LN_2 precooling system. With the target of three sites in 18 months, the fueler needs to be completed, sites need to be selected, and it needs to be deployed as soon as possible.

Question 3: Collaboration and coordination

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

- The collaborators and coordination for this project are very appropriate for achieving the desired outcome. The team includes a very well-established industrial partner capable of executing and continues the deployment of this system. Partnering with NREL in data analysis is appropriate, and working closely with those states needing this for deployment (California and Northeast states) is spot-on.

- The partnership coordination seemed really good, especially given the input from Air Liquide during the Annual Merit Review (AMR) presentation. The research team has clearly benefited from Air Liquide's technical expertise. It is concerning that the site selection process is not yet complete, but presumably Air Liquide is working diligently to identify the sites and will support the effort to get the system deployed quickly and into testing.
- This is a well-balanced team of contributors to accomplish project goals. The addition of a site partner will be important for demonstrating the system and assessing customer acceptance.
- The team is strong, with the right background to build and deploy the mobile fueler.
- This is a strong team, and coordination appears to be good.

Question 4: Relevance/potential impact

This project was rated **3.6** for 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 very relevant and timely. California is predicting that, with the projected growth of HFSs compared to that of vehicle demand (just light-duty fuel cell electric vehicles [FCEVs]), demand will outpace growth in the next couple of years. Equally important is that places like California and the Northeast have worked hard to ensure that coverage is appropriate; HFS reliability remains an issue. In early stages of build-out, a solution to reliability is redundancy; this mobile refueler addresses this very critical issue. This project is very relevant, and its impact in early deployment is huge.
- This project aligns well with DOE goals and addresses barriers of hydrogen supply. This project could help build out fueling infrastructure, which can facilitate early adoption of hydrogen vehicles. This also allows easier introduction of hydrogen fueling to areas that are not yet familiar with FCEVs.
- The mobile fueler enables the establishment of new markets and support of current markets for hydrogen vehicles. If the LN_2 cooling system is effective, it could be deployed at other stations or provide technological pieces for liquid hydrogen cooling systems for liquid hydrogen stations.
- DOE should consider funding 10 additional units to bring manufacturing experience for this type of system from technology readiness level (TRL) 1–3 to TRL 5–8.
- The project appears to clearly address at least three key FCTO barriers and will provide some valuable information to advance hydrogen fueling knowledge. It is not totally clear what direct benefit this fueling system will have on the industry. It is unclear whether this system is designed to provide temporary fueling capabilities while a permanent station is being built, or to test out demand in certain locations before investing in a permanent station, or to provide redundancy for permanent stations. It is also unclear whether any of these scenarios are key issues within the HFS space right now. It would be valuable to get a sense for how this fueler will be deployed in the real world and at scale.

Question 5: Proposed future work

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

- This is a well-laid-out plan to complete the project. Economic analysis will yield important data for the industry. The team plans to use the system past the scheduled demonstration period, which is a bonus. It would be useful to see the data submitted for this longer period to add to the analysis for the industry.
- The proposed future work is in line with what one would expect for the construction and completion of a prototype piece of hardware. The project has overcome some difficulties and is on track to complete the unit as proposed in this project.
- Preventing any more schedule slips is crucial to achieving all project goals. There are bound to be issues that need to be worked out after the initial (and potentially subsequent) deployments. The team needs to keep sufficient time in the schedule to work out these bugs. The proposed schedule and work plan will enable meeting the key objectives outlined in the project.
- The project should build, build, build (and test/verify that things work as designed).
- The schedule on slide 15 of the AMR presentation shows site selection completed by the end of the second quarter of 2019, which is only two months away. It is a concern that even when site selection is completed,

it could take several months to deploy and commission the system. That is going to squeeze the schedule if the contract calls for 18 months of testing. Beyond the project, it would be helpful to get a better sense for how Air Liquide will use the system. It is unclear whether the system is for research and development testing of various components or whether it will be field-deployed to support construction of permanent fueling stations. It is also unclear whether this system has a practical real-world application for industry.

Project strengths:

- The fully code-compliant H70 mobile fueler is demonstrating new technology (a LN_2 cooling system) and the path to DOT approval of new technology (transport of 95 MPa H_2). This innovative mobile fueler can provide support of the current fueling network and expansion into new markets. The flexibility of running fully contained, with hydrogen storage and power onboard, or with external hydrogen storage and "shore" power enables operation in a wide range of environments.
- DOT approval for transportation of high-pressure hydrogen is a significant strength. Compact design should facilitate installation and address customer concerns over the footprint.
- The project team appears very capable of completing the design, construction, and operation of the system. The project was well scoped, with achievable goals and a clear deliverable: an operational mobile fueling station.
- This strong, capable team has already demonstrated the will and ability to rally collective resources to ensure a successful completion.
- Project strengths include a 70 MPa mobile fueling solution meeting SAE J2601 T40 with same capacity as early stationary retail HFSs, DOT permit/approval for 95 MPa, inclusion of a compact heat exchanger/ chiller, and testing of the system in the field.

Project weaknesses:

- Earlier concerns from previous AMRs have been addressed with the progress presented this year.
- This appears to be a one-off mobile fueling solution. Running a generator on regular low-sulfur diesel using renewable diesel (not biodiesel) where possible instead would improve the selling point in emission-sensitive areas where 480 V 3-phase is not available.
- The schedule delays associated with the DOT certification are going to put stress on the testing phase, and a good deal of value is to come from that phase.
- Gathering performance and efficiency data, education, and expansion of the fueling network are key objectives, making the schedule delays problematic.

Recommendations for additions/deletions to project scope:

- If possible, the project duration should be extended to accommodate a full 18 months of testing (if delays have reduced that testing phase). It would be helpful to include a case study or scenario that clearly lays out the value of this system once the project is completed. For example, if this is backup for a permanent fueling station, the team should show the cost of deploying the mobile fueler and how that generated benefit for the permanent fueling station if there was an unplanned outage for a certain period of time. The team should make it clear to the fueling industry that this system can provide real value.
- Publishing as much information as possible about the high-pressure DOT permitting process will enable others to follow a similar path for other tanks. Reporting performance metrics (and design information) on the LN_2 cooling system could lead to technological breakthroughs for hydrogen cooling.
- The team should emphasize that AHMF has 480 V 3-phase plug-in capability in all presentations. The team should define station capacity using either the new draft California Air Resources Board/California Energy Commission (CEC) definition or a previously used CEC definition (pick any previous round of requests for proposals/GFO funding, as long as it is clear which definition was used).
- DOE should keep this project funded to its completion. Succession funding to evaluate and test in the field with hydrogen station equipment or device performance should be considered.
- It would be helpful to see the system updated to address medium-duty vehicles. The team should continue to supply data for long-term analysis.

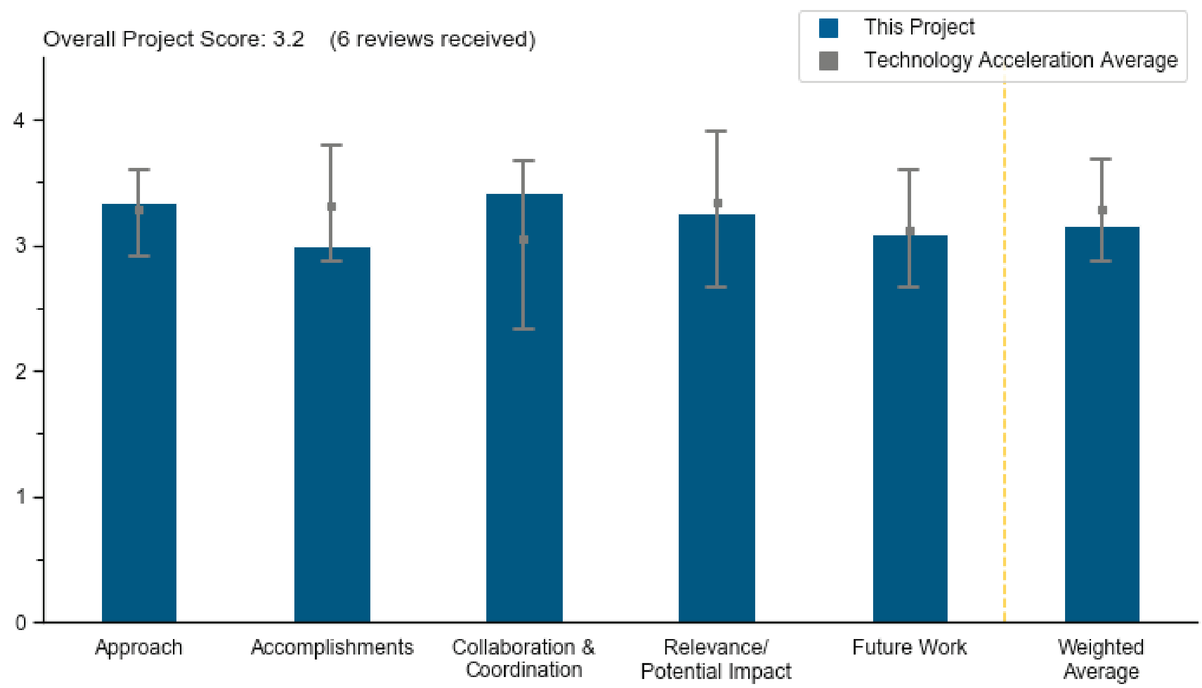
Project #TA-018: High-Temperature Electrolysis Test Stand

James O'Brien, 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) operate the system with co-located digital real-time simulators for dynamic performance evaluation and hardware-in-the-loop simulations.

Project Scoring



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

Question 1: Approach to performing the work

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

- This is an excellent approach to providing initial understanding of HTE on a large scale. To have a full portfolio of realistic hydrogen sources, it is very important to have the ability to test realistic operating parameters for HTE with foreseeable high-temperature sources of heat and electricity, and on a reasonable scale.
- The project has a clear rationale and approach to performing both intermediate-scale and large-scale HTE.
- The approach is well formulated. However, the objectives discuss goals for integrating the HTE system with both renewable and nuclear energy resources. Presumably, these will each provide different challenges of electrical and thermal energy flows for the HTE system to address or to which the system will be exposed. The approach does plan to report on HTE performance in response to such changes, but the

project has not yet clearly defined how these will be tied back to separate scenarios of integration with renewable energy sources, nuclear energy sources, or both. It would be very helpful to see the work presented in context of these conditions, rather than reporting on the HTE as if it were responding in a standalone state.

- The approach is good with regard to the test station design and build. The development of an over-instrumented test stand is necessary to generate the information from the electrolysis unit and its interactions with subsystems and the heat source. It is not clear that the station was built with an element of flexibility so as to modify its engineering and subsystems, as test results may require in the future. It is not clear why the OxEon Energy, LLC (OxEon) stack was chosen over a larger, more established industrial and industry-engineered supplier's stack. This is not a stack design initiative. The OxEon stack was built for NASA and is typically not a general purpose industrial gas production design. The project should rely on generic stack degradation data, not just data from a single stack design or supplier. The testing plan should be based on data. No such data were seen in the Annual Merit Review presentation (not even data from the 2000-hour, 5 kW tests that were referenced). Dealing with a proprietary stack design is informative but limiting.
- The project seems to be working well to establish HTE testing capabilities. The relevance of working on oxygen-producing units (i.e., solid oxide electrolysis [SOE] and the Mars Oxygen ISRU Experiment [MOXIE]) is not clear. There should be clearer tie-ins to hydrogen production and plans for redesigning or repurposing these units to optimize hydrogen production rather than oxygen.
- The project objectives were not clear from the presentation. The overall scope of the project is understood, but there is a need for clear metrics (e.g., cost targets, efficiency targets, output pressure targets, etc.) and clarity in terms of superlatives for how this system is differentiated (for example, perhaps it is the highest-temperature electrolysis system or the most efficient high-temperature system). The concept of an HTE system has tremendous value, but it is unclear how this project is differentiated. The team needs to clarify what the value proposition is. This is crucial for a successful project.

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.

- Much good development work on the test system has been completed, and it is encouraging that the team seemed to find a good solution for procuring the HTE stack. However, it is unclear how the project is to meet milestone 2 (listed as on track), given that this seems to include final production and delivery of the 25 kW electrolysis stack, integration with the test system, validation of the installation, and several test cycles.
- Completion of the 25 kW facility will allow for critical integrated testing of realistic HTE configurations. The team should consider the value of heat exchanger designs and materials to realistically match the anticipated heat exchangers for high-temperature reactors, such as high-pressure helium to steam heat exchanger. Since the facility exists, extending the realism to the heat exchanger connection anticipated in a reactor may be of value. The accomplishments in developing the solid oxide electrolyzer cell (SOEC) stack at the 5 kW level are very promising.
- The investigators have set up the equipment on schedule. The accomplishments are more activity-based than results-based. There should be targets for device performance as well as just for getting the device to work.
- The significant accomplishments and progress of this project are related to the construction and installation of the test cells.
- The project is relatively new. There appears to be satisfactory or good progress to date versus the project scope.
- The results of the test station build seem appropriate; however, the performance of the station was not addressed. If it is not running well, the team needs to determine whether the problem is the station or the stack. Also, it was not reported if a failure mode and effects analysis (FMEA) and/or hazard and operability (HAZOP) review(s) were carried out to assess the station's engineering design logic, safety, and functionality. This process is standard in industrial engineering programs and leads to a better understanding of the entire process. No instrumentation was seen in the piping and instrumentation diagram

(P&ID), nor were what variables and responses will be monitored and varied in future operational tests with the stack. Stack performance will be difficult to understand if the OxEon stack is considered proprietary. Therefore, the cause of any degradation rate will not assessable. The 5 kW stack should be tested 24–7 so its operating characteristics can be assessed.

Question 3: Collaboration and coordination

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

- The project is employing an excellent mix of partners, including the industrial collaborators. This is also an excellent collaboration between the DOE Office of Energy Efficiency and Renewable Energy and the DOE Office of Nuclear Energy. Idaho National Laboratory has a rich history in high-temperature ceramic electrolysis and fuel cells. The principals at OxEon also bring a rich history in developing solid oxide fuel cell (SOFC) and SOEC systems. FuelCell Energy, Inc., has a good deal of high-temperature commercial fuel cell system design experience. Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL) are excellent national laboratory partners for this type of project.
- The presenter showed good interactions with partners and is taking a helpful and supportive role in spurring enterprise outside of the laboratory as part of the overall project effort (several small businesses were mentioned).
- The project has appropriate collaboration with NREL, PNNL, SNL, and industry (OxEon, formerly Ceramatec, Inc.).
- The project has assembled a group of collaborators in national laboratories and in the HTE industry.
- The collaborations with industry seem appropriate. However, it does seem like this project is quite separated from other energy system experts across other national laboratories, such as NREL. It would seem appropriate to implement more collaboration with these laboratories, especially to bring context to the testing results.
- The collaboration level is appropriate. It is not clear how much collaboration is taking place with SNL on the work reported in TA-015. This may be a redundancy.

Question 4: Relevance/potential impact

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

- HTE has long been anticipated as a potential key element in large-scale market-based hydrogen supply. From high-temperature nuclear reactors, the expected production of hydrogen may be closer using HTE than from thermochemical conversion. Early-stage testing anticipated by the HTE will provide the key initial datasets for integrating HTE systems in realistic configurations.
- HTE is an important technology that should be part of the overall technology portfolio. The thermodynamics of electrolysis improve dramatically with temperature. There are many sources of waste heat (beyond nuclear power plants), so there is a great opportunity for this project to have impact beyond its current scope (for example, in steel mills that also can use hydrogen on site). Nuclear plants can also utilize other sources of revenue for their excess generated power.
- The relevance is important, as is the potential impact. Studies and related efforts such as these are necessary for ascertaining knowledge and learning if this concept is ever to be used.
- The scope of HTE has changed significantly in the past decade, changing from very large-scale hydrogen production to the current smaller-scale, intermittent production that is the topic of this work.
- The project goals overall seem to be aligned well with DOE Fuel Cell Technologies Office goals; however, it does seem to be too early to fully and accurately assess the potential impact. In addition, with current popular and political opinions surrounding nuclear energy, this project's results may not have a chance at full utility in the real world. On the other hand, if the project results find significant benefits and can communicate those benefits well, the project could provide a very useful resource for helping to better inform future decisions around nuclear energy resources.

- The project has activity-based goals and targets rather than clear performance-based goals. For maximum relevance, it needs clear goals tied to hydrogen production targets.

Question 5: Proposed future work

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

- All of the proposed future work for fiscal year (FY) 2019 and FY 2019–2020 looks very promising and is completely appropriate for the activities at this stage. One thing that might prove to be a critical issue is the need to keep degradation below 0.5%/khr. It could be valuable to evaluate any degradation rate early to identify that as a challenge. It is unclear what is meant by establishing a large-scale test capability in FY 2019–2020.
- Most of the elements and initiatives in the proposed future work are consistent with the objectives. It is not clear how the 25 kW stack will be tested and proven out, and the long-term degradation data collection obtained, in a single test rig. It seems like most of the effort is about the stack rather than determination of the interactions and resultant effects of key operational variables of the HTE on performance. The future work should also include subsystem effects.
- The proposed work is well in line with what must be completed for the overall project goals. The only concern is that it may be a highly challenging and ambitious schedule to complete all the 25 kW testing and procure, integrate, and validate a 250 kW installation.
- The project should implement performance-based goals. The relevance of MOXIE and SOE technologies for hydrogen production should be clearly established and described.
- The overall project scope is fine. No go/no-go decision points were seen, which is worrying.
- Establishing key metrics is important to track project progress. It is not clear where the value of ~0.5% degradation over 1,000 hours originated. Metrics for other electrolysis projects have 1% over 1,000 hours. The thermal energy delivery system (TEDS) heat transfer system should be evaluated at scale. The “old” goal of the nuclear hydrogen initiative was the idea of using He-cooled steam from a very-high-temperature reactor at elevated temperature with trace contaminants (potentially tritium). The team needs to clarify what the current heat transfer materials and mechanisms are, as well as whether they will also operate on an intermittent basis and how they will perform.

Project strengths:

- The project has a solid team of collaborators and partners. The current state of the SOEC technology and the opportunity to test it on a large scale in this project’s facility should be very valuable to the DOE Hydrogen and Fuel Cells Program and nuclear program.
- The overall project strength is its potential to provide new insights on nuclear energy resources that could spur a redirection of current trends for this resource. The project also has a well-structured approach that will provide real operational data, potentially providing highly convincing information for decision makers.
- This is an applied project that aims to demonstrate intermediate-to-large-scale HTE with commercial materials (i.e., SOEC stacks). The work has resulted in impressive facilities and promising results.
- The project’s strengths include its significant national laboratory resources (i.e., engineering and equipment). The project is building on knowledge of SOFC technology and related systems design and controls.
- The use of SOXE is an important testing platform, and this work is important.
- The project has established DOE expertise in the implementation and operation of HTE equipment.

Project weaknesses:

- The project represents a significant and unique integration of complex components into a high-temperature thermoelectrochemical system. The potential for unexpected technical challenges may be higher than with other complex systems. There does not seem to be a plan to deal effectively with such unexpected challenges.

- The project weakness is clearly the relatively low availability of HTE units. It seems that if the project partner is delayed or somehow unable to fulfill development for this project, then the overall project's accomplishments could be at risk. It is likely wise to continue searching for a second procurement source, just in case the primary source has any issues.
- Too much emphasis has been put on an unproven stack technology (which was developed for non-industrial, small-scale application). As it is presented, this is a test stand development effort. The test stand does not seem to be flexible with regard to testing and proving out related subsystems. No mention was heard of an FMEA or HAZOP review to guide system development. The team needs to better understand the variability in heat sources using the test stand and then understand the impact on stack performance and efficiency.
- The "intermittent" nature of the proposed electrolysis systems is questionable. This is asking a good deal of existing or known materials systems including seals, electrolytes, electrodes, etc. Perhaps an economic analysis could be pursued using a fraction of the electricity produced in a quasi-steady-state matter coupled with hydrogen storage, instead of multiple on/off cycles.
- Clear metrics, go/no-go decision points, and overall project management seem to be lacking. The team must have clear "objectives" to measure success.
- The project goals are not tied to specific targets.

Recommendations for additions/deletions to project scope:

- It is recommended that the team add context to the analyses so that they demonstrate the potential real-world impacts to policy- and decision-makers. Sample tests of system performance should be tied back to representative events in the typical, occasional, out-of-bounds, and problematic operations of the other energy resources into which the HTE is integrated. Evaluations should then be made not just of the HTE's performance and ability to absorb and meet these demands but also of the effect it would have on the remaining energy resources' operations.
- The researchers should perform an FMEA and a HAZOP analysis as a guide for making a better test station. They should also obtain a stack from a second source and test and compare the results; perform an analysis whereby the hydrogen compressors in the cycle are replaced with an electrochemical hydrogen compressor; perhaps run the economics; operate the stack and system on the test stand so that pressure is generated and assess the test stand's ability to evaluate the effects of pressure; and reference the P&ID, as the gas does not seem to be thoroughly dried to industry standards (-50°C dew points) in this current generation of the test stand. The overall losses in the entire system should be assessed to provide performance and efficiency metrics so as to guide development of HTE systems in the future. The team should also check with the TA-015 team regarding front-end controller development efforts.
- It may be worthwhile to consider evaluating different heat exchanger configurations that employ anticipated renewable or nuclear thermal inputs.
- The project should establish performance-based goals tied to hydrogen production cost targets.
- Overall program management would be important. This should be more than just a proof-of-concept project.

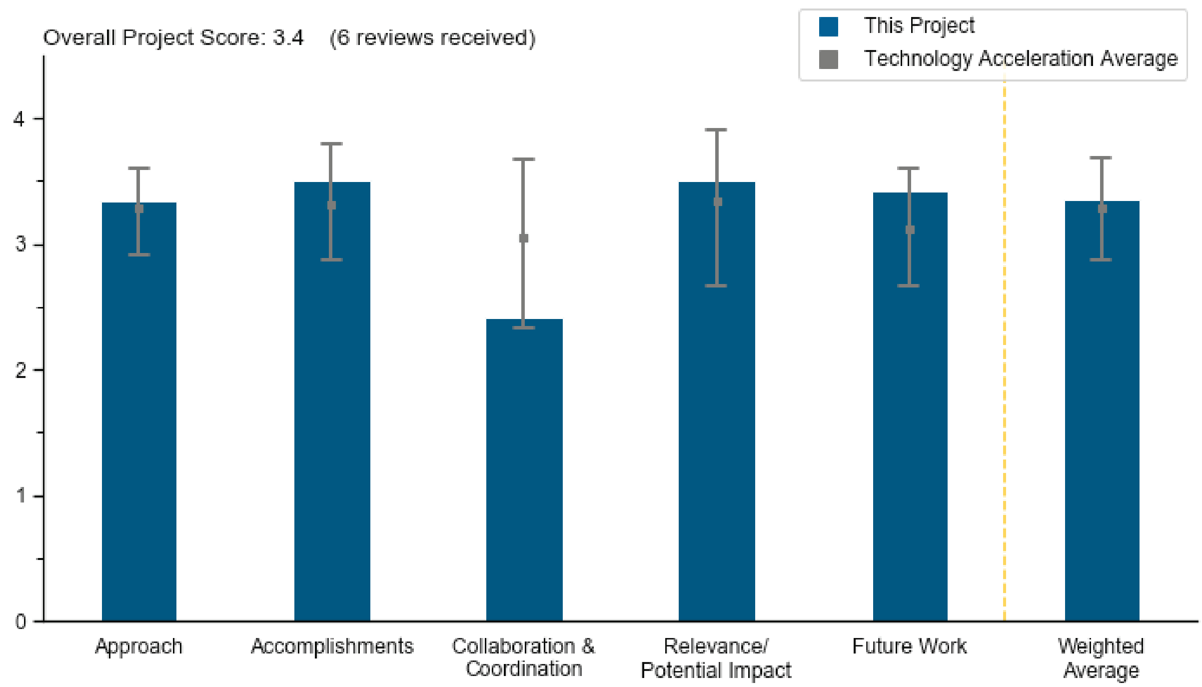
Project #TA-019: Modular Solid Oxide Electrolyzer Cell System for Efficient Hydrogen Production at High Current Density

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 significantly reduced cost of electricity use for electrolysis; (2) enhance SOEC stack endurance by reducing the 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.

Project Scoring



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

Question 1: Approach to performing the work

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

- This project's technical accomplishments are impressive and represent the potential for a step change in hydrogen production and power integration methods for the industry. The scaling-up process and test methodology are consistent with the technology readiness level of the development and size of the project.
- The approaches are excellent and logical.
- The approach is very comprehensive.
- The approach is very well thought out and explained. The only suggestion is that the economic analysis be completed at a large scale, perhaps 50 tonnes per day or more. Solid oxide electrolysis (SOE) is probably not as suitable for distributed production sites (of 1.5 tonnes per day).

- The approach seems reasonable for the steady-state electrolysis operation. It is unclear if this is a practical, real-world scenario; the possible electricity source was not discussed. Renewables are intermittent, so it may be nuclear, or it may be just grid-powered. It would be good to see the technoeconomic analysis (TEA) for this type of operation.
- The project is close to the end and has quite a bit of funding left. The researchers said they plan to buy equipment. Usually, it is best to buy equipment at the beginning of the project and use it throughout the project. Given that the project is scheduled to end September 30, 2019, and that an equipment procurement can often take several months, it is not clear how the equipment purchases will benefit the project.

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.

- Year after year, the team continues to show good progress and report results of improvements in stack and cell performance, as well as degradation.
- The project has made excellent progress toward the overall project objectives.
- The project is meeting and exceeding targets and milestones; this is very good.
- The project has good accomplishments and progress, especially in studying degradation over long times. At 50%, the steam utilization seems quite low. The team has a creative modular design.
- The project has demonstrated multiple years of operation at high currents. The cells and stacks seem very sensitive to uncontrolled disruptions in operations. The team needs to build better test stands, perhaps with backup power, to minimize the disruptions. The researchers tried to repeat the work, but the repeat of the cell had a higher degradation rate than the best-performing. The post-test analysis was very interesting. Cr migration and Ni depletion are challenges that have been solved in solid oxide fuel cell (SOFC) operation, so the team may be able to take some strategies from SOFCs and apply them to the project technology.
- The performance metrics were met for the electrolysis stack. However, demonstrating a complete and scaled-up system has not yet been done and will consume most of the project funds.

Question 3: Collaboration and coordination

This project was rated **2.4** for its engagement with and coordination of project partners and interaction with other entities.

- The amount of collaboration for this project is sufficient.
- Collaboration with other organizations and national laboratories is highly recommended.
- Collaboration remains the biggest weakness in this project. Without independent verification of the process or the results from a collaborative team, this project suffers from a credibility gap. Projects are always stronger when there is a diverse team working with the results and verifying outcomes. It would be particularly helpful to have a third-party TEA to validate the economic projections.
- There does not seem to be much collaboration. There does seem to be some coordination within FuelCell Energy, Inc. (FCE) with Versa Power Systems, Inc. (Versa) (which is owned by FCE) and some loose coordination with National Energy Technology Laboratory (NETL).
- There seems little collaboration up until this point. Perhaps NETL will participate in the TEA, but this was not mentioned.
- There is very little collaboration. Only two other collaborators are listed on the project, and one of them, Versa, is a subsidiary of FCE. NETL is referenced but, as stated, contributes only indirectly.

Question 4: Relevance/potential impact

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

- If this project is successful, it could represent a breakthrough in the approach to energy and fuels, leading to a scalable platform with flexible applications, as is needed in this industry.
- Bringing down the cost of hydrogen at the nozzle is key to the success of the technology, so this has significant relevance and potential impact.
- Hydrogen is a core problem to be solved. This project addresses the efficient production of hydrogen with an SOEC system and provides a benchmark.
- The project aligns well with the DOE Hydrogen and Fuel Cells Program.
- The work directly contributes to DOE's solid oxide targets and goals.
- This project is highly relevant to H2@Scale. It has the potential to produce low-cost hydrogen. The scale-up and demonstration are needed for H2@Scale. Given the limited time left on the project, unless a no-cost extension is granted, the demonstration will be of minimal impact.

Question 5: Proposed future work

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

- This project seems to be very well managed and focused.
- Completing the demonstration and the performance testing will be the critical deliverables for this project, and the team is on a good pathway for completion. It remains to be seen if the schedule will permit sufficient testing before the project closeout.
- The future work is the demonstration. The demonstration is very important, but it is not clear whether enough time remains on the project for the demonstration to gain useful information.
- The proposed future work is appropriate; however, a more detailed description of the proposed approaches (e.g., pressurized operation) may be needed.
- Building a scaled-up complete system and running a demonstration will be most interesting. The question remains whether the stack can scale beyond current proportions. The proposed megawatt installations with numerous small stacks seem problematic. A larger stack would help simplify the proposed future large-scale installation.
- It is great to do cost analysis, and fine to do it for small production sites, but it seems the trend is to use SOE for large-scale production. As such, a cost analysis should be completed for large-scale hydrogen production as well.

Project strengths:

- This project is a novel technology that has the potential to significantly reduce the dollar-per-kilogram cost of hydrogen and can be offered in a modular format, therefore also being relatively cost-effective from the manufacturing perspective (as pointed out by the presenter).
- The technology development is excellent. This is a comprehensive project and technology development pathway.
- The project has done excellent work in stack development and degradation. FCE has many technical experts and is well suited for completing laboratory testing of their materials.
- The project was well funded. The durability tests were very important. FCE did a good job sharing the failure modes, such as the chrome and nickel migration.
- Demonstrating long-term steady-state SOEC data is very helpful and provides a benchmark performance metric for further research or modeling.
- The project's main strength is in the approaches and technical direction.

Project weaknesses:

- This project has no major weaknesses; however, additional coordination with other organizations and national laboratories is recommended.
- The project did not leave enough time for the demonstration unit. There is quite a bit of funding and not much time left. The demonstration should have started in the middle of the project (in year 2) so there would be sufficient time for the demonstration to occur. There is a good deal of valuable information that can be gained from the demonstration.
- The project should discuss scale-up for very large production volumes and include TEA for large production sites. There was no real collaboration with non-FCE entities.
- The lack of collaboration on the project has the potential to weaken the credibility of the results and projections. At a minimum, a third-party TEA is strongly encouraged.
- It is perhaps an oversight not to include some controlled thermal cycling and, instead, to base it only on steady-state operation.
- The lack of transient response data is a weakness, along with the absence of an economic justification or TEA.

Recommendations for additions/deletions to project scope:

- It is recommended that the team continue to build out the full standalone system; the results are highly anticipated. Possible additions could include stack scale-up and the TEA to make the economic case for the technology.
- Further real-world validation (which can include power outages, thermal excursions, etc.) is recommended to show robustness.
- It is a concern that the testing of the demonstration will be tight in the schedule. The results of this testing are critical, and an extended test period should be considered as a possible project extension.
- The team should apply for a no-cost extension.
- TEA for a large-scale production system is recommended.

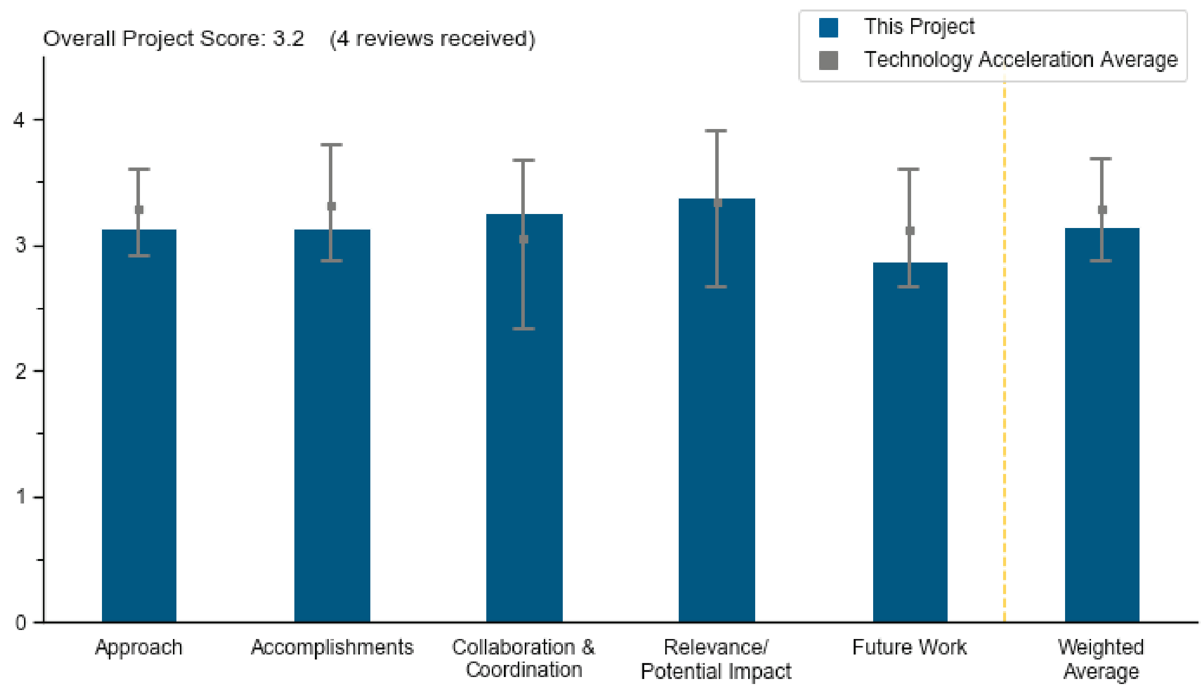
Project #TA-020: Optimal Stationary Fuel Cell Integration and Control (Energy Dispatch Controller)

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.

Project Scoring



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

Question 1: Approach to performing the work

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

- This is a good approach to the challenge of building control and grid integration. The team has a very quantitative explanation and comprehensive set of variables for all the control levers available for optimization, including constraints for the building occupant’s comfort.
- The approach to this project is well aligned with U.S. Department of Energy (DOE) targets and the overall goals of the DOE Hydrogen and Fuels Cell Program (the Program).
- The approach appears sound. Focusing on inputs that are readily available and commonly produced by installed equipment ensures the model will be practically applied in real-world scenarios. The researchers mentioned “comfortable temperature bounds” in the presentation, which is an important consideration. This model will only be as effective as it is comfortable for users. Tenants will not care about economic dispatch modeling if they are sweating in their cubicles. It would be good to know whether those comfort bounds

have been defined, either by this group or previously. Progressive development can be seen in this project; the team focused on the model for single-zone building, then expanded to multi-zone. The researchers may have advanced too quickly. Ancillary services are "nice to have," but given that those markets are not well developed in the building space, it might not make sense to make them a core component of the objective. Capacity charges are probably the highest-value component of the electricity bill to pursue. It would also be beneficial to know whether the modeling effort includes rooftop solar. It would be valuable if building owners could try different scenarios with different components and then optimize for capital cost, energy cost, emissions, internal rate of return, etc. There is also some value in "islanding" a building during grid outages. Fuel cells could complement solar storage, especially in areas with low solar incidence for extended periods (days or weeks).
- This project seems to be driven by modeling building energy balances for the Grid Modernization Initiative (GMI). The project needs to generate some results from the model that indicate how it relates to hydrogen technology, fuel cell performance, etc. Developing a base case using natural gas combined heat and power may be useful in validating the model and assessing the "hydrogen advantage," if there is one.

Question 2: Accomplishments and progress

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

- The project team has made nice progress, with the inclusion of multizone buildings to ensure comfort across a broad range of layouts and people. This will dramatically extend of the usefulness of the modeling and optimization results. The communication with Volttron and the open-source project is an important demonstration.
- The team has accomplished the expressed purpose of the project: a useable evaluation tool that enables the integration of stationary fuel cells into a building's energy efficiency design. The methods and tools developed by this project will certainly enable building designers and planners to consider stationary fuel cells in ways not previously considered.
- The results presented were concerning. The predicted values versus actual values did not appear to match well. Perhaps there is a metric that can be used to quantify modeling success, like the R^2 value. No results were presented for the single-zone buildings. It may be that the prediction was better for those simpler scenarios. It seems like a good practice to optimize the model on single-zone buildings before taking on a more complex problem. The researchers stated that modeling proved harder than anticipated; however, the key goal for this work has to be developing a good model. Everything else is dependent upon that core objective. It may make sense to abandon some of the later goals (e.g., hardware integration, ancillary services value) in order to focus remaining resources on improving the model. There was no discussion of economics, which has to be the key target for optimization. At the end of the day, building owners want to see the economic benefit to enhancing control of building systems. The value of this type of modeling comes out in the scenarios. From an industry perspective, what is wanted is a model that can reduce energy bills or building emissions by X% using this advanced control logic. The researchers should focus on reaching the point where some key scenarios can be modeled and the economic or environmental benefits can be clearly demonstrated.
- Alas, software tools take hours to develop but only seconds to use. It is hoped that the project will generate results and sensitivity analysis to see what insight these models give.

Question 3: Collaboration and coordination

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

- Collaborating and sharing information with Washington State University, as well as interfacing with Volttron and the open-source community, are important highlights of the National Renewable Energy Laboratory's efforts toward collaboration, including efforts with Pacific Northwest National Laboratory. A wide range of expertise is needed to incorporate weather forecasting, in addition to building climate optimization. Including the OpenADR Alliance provides additional benefits by opening the door to

ancillary services. Including the University of Colorado Boulder is important for workforce development, as well as for enabling a broader distribution of the project and knowledge that has been gained.
- While the project is primarily an academic exercise, the project team has established enough critical links to private industry to enable a robust feedback loop. This has enabled the project to select reasonable examples and consider real-world applications not previously considered, addressing key gaps from the previous year's reviews.
- This is actually a big problem to solve. It looks like the partnerships are diverse enough to cover the various disciplines required to advance the work, and partners appear to be contributing value to the project.
- Until the project team has results that show something of interest to facility managers and engineers, it will be difficult to find collaborative connections, except among fellow modelers. There may be some intrinsic advantages to hydrogen systems that would capture interest, such as how fuel storage can be located in-structure, etc., which could segue to a compelling reason for hydrogen. This is what was found with backup power systems in Hong Kong: hydrogen storage was easier to site and approve than equivalent diesel fuel systems—in the event of a fire, the hydrogen storage would vent.

Question 4: Relevance/potential impact

This project was rated **3.4** for 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 research is absolutely critical to advancing fuel cell deployment in buildings. This kind of modeling is the first step in identifying potential deployments and building the business case for fuel cell integration. This will be a really valuable tool for researchers, project developers, and building owners. This is why it is so important to focus on the quality of the model and its ability to optimize for economics and emissions reduction.
- Buildings are a major energy consumer, and this project will enable future zero-energy buildings through extreme optimization and renewable energy optimization. The open-source nature of the tools will also enable as widespread an update as possible, without the barriers of proprietary high capital cost implementations, which may be more difficult to implement in less affluent areas of the United States or abroad.
- This project will have positive impacts on the design and use of stationary fuel cells as it reduces the barriers to designers and developers when considering fuel cell technology.
- The project does not seem to be directly relevant to goals of the Program. Thinking of building management systems as part of a larger energy system may support both clean energy systems and the core objectives of clean fuels for transportation and decarbonization. There could interesting synergies both on the system design and on the financing, using long-term property mortgage financing. That being said, hydrogen systems do not scale well to smaller sizes, and the source of the hydrogen is unclear.

Question 5: Proposed future work

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

- Keeping everything open-source is really valuable to advancing this work after the project is complete. Modifying the model for a web-based interface will also help more people use and refine it. It might be valuable for the presentation to cite other examples of open-source software that have been adapted for commercial use. It may have been that Linux was adapted to commercial software used for industrial control software, under the open-source model. Something along those lines would assuage any critics who may be concerned that industry will not want to develop something that is open-source. Hardware testing is not as important at this point. The early value will be for making the business case for optimizing operation. Integrating with actual hardware makes sense only once that business case has been verified. Future work should include using the model to look at scenarios for real building case studies. The team should be showing that the model is effective and then using it to propose optimized dispatch and calculate economic and environmental benefit.
- It is a good to see that the software will be integrated with a web interface to enable more user adoption. The hardware-in-the-loop (HIL) implementation and co-simulation should bring the project more

credibility and give future adopters a better idea of the limitations and opportunities of implementing this energy management solution. Future publications of analysis and lessons learned will be vital for ensuring a lasting value beyond the limited scale of the project.
- A stronger emphasis should be placed on communication. Publication and dissemination should be the main focus. Further research and HIL implementation are less critical to the project's impact than communication.
- The proposed future work is okay, but there is a concern that the project may run out of time before value is derived from the work.

Project strengths:

- The project addresses a key barrier to the use of stationary fuel cells in building energy systems. By creating a robust and accurate tool with relevant examples, the team has generated a work product that has the potential for significantly impacts on the market. This tool provides building designers and developers the information necessary to select stationary fuel cells, information to which they certainly did not have easy access in the past.
- The project's strengths include its open-source nature, the peer review with the sheer number of partners, and the focus on technology transfer that will ensure that the knowledge can be implemented outside the national laboratories with colleges and various other partners. The hotel case study is an excellent choice.
- The team and its partners represent a broad skillset and the experience to cover the many facets required for a modeling effort like this. This work is highly relevant and, if successful, will be very valuable to the fuel cell market.
- Software tools have been developed in the context of the GMI program, addressing identified barriers.

Project weaknesses:

- This project needs to increase the effort to communicate the results, thus ensuring the potential to accelerate private building developers' use of stationary fuel cell technology.
- There is a lack of progress and measurable results. More scenarios and an analysis of how well the model matches to the real world need to be seen. The project is running out of time, and it is concerning that resources are being used for hardware testing and ancillary services when they could be better spent improving the model.
- The project's weaknesses include bridging from research and development to opportunities for actual commercial or open-source implementation.
- At this point in the project's development, it is not clear how relevant hydrogen systems are. The team is running out of time, and it is not certain that the results will get to market.

Recommendations for additions/deletions to project scope:

- The project team should brainstorm with architects, building designers, and developers of other applications that could benefit from power from fuel cells and see what the models have to show. There may be input that could inspire the use of hydrogen fuel cells. For example, there may be applications such as data centers that could benefit from using low-voltage, direct current (DC) power, where energy could be delivered through a gas network, or applications in which fuel cells could convert hydrogen to DC power at point of use, with some heat recovery. New solid-state light sources could benefit from low-voltage DC power that could be produced by fuel cells at the point of use, etc. It will be interesting to see how Japan will use hydrogen to power the 6,000-unit Olympic Village for the 2020 Tokyo games.
- The project team should increase efforts to distribute the knowledge (e.g., through publications, analysis, and case studies) and ensure that open-source software with documentation is available in a single project portal page that does not disappear at the end of funding. The team should try to quantify the savings from implementing the software for different building types in order to encourage adoption.
- The project should remove HIL testing and the work on ancillary services. The project team should also show at least one case study (a real-world building or a DOE prototype building) in which the model showed the value of integrating a fuel cell.

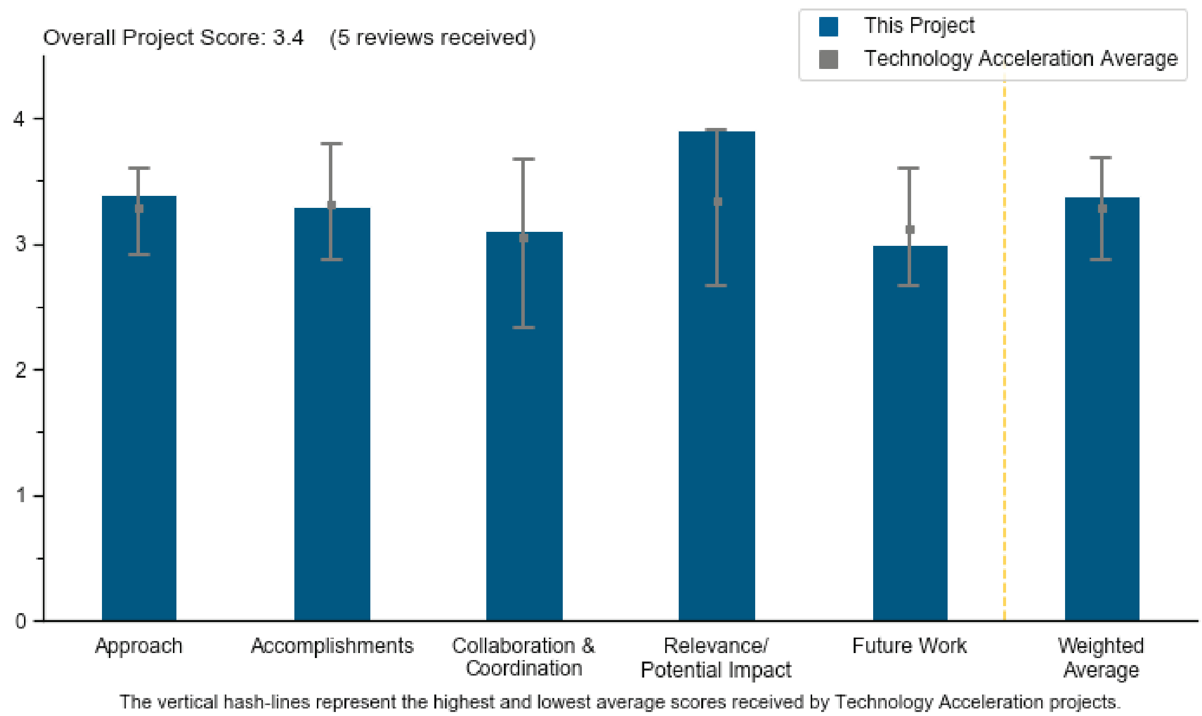
Project #TA-021: Integrated Systems Modeling of the Interactions between Stationary Hydrogen, Vehicle, and Grid Resources

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 (FCEVs) 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.

Project Scoring



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 relevant efforts.

- The project provides a good economic evaluation with a focus on California, where the biggest challenges will be experienced with excess renewable energy. The model includes historical prices for a realistic framework for evaluating the benefits of hydrogen production from electrolyzers. Optimization is occurring between the grid and hydrogen, with detailed inputs from the Scenario Evaluation, Regionalization, and Analysis (SERA) model on the use of FCEVs and the demand for hydrogen. By using PLEXOS simulation software, the project team will have a full picture of existing electricity demand. This is a comprehensive approach that should provide a realistic set of results.
- The project approach is well aligned with both the project objectives and the Hydrogen and Fuel Cells Program objectives. The project is also well described and effectively communicated. It is clear that the

researchers understand the detailed subject and have worked hard to resolve the most relevant information to make it easily understandable for a larger audience. It is this final, critical step of "distillation" and communication that separates satisfactory projects from excellent projects.

- As illustrated on slide 3, the conceptual overview is straightforward and readily understandable. The barriers addressed by the project, as shown on slide 2, are not specifically included among the barriers listed in the Technology Validation (now Technology Acceleration [TA]) or Systems Analysis (SA) sections of the Fuel Cells Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan. The project approach is to develop a hydrogen–vehicle-to-grid integration model that utilizes and integrates work done on multiple models; this approach is logical and efficient as a means of achieving the challenging objectives of this project. As described in slides 6–10, the approach is comprehensive and thorough, and it incorporates real-world data. The approach has outstanding potential to achieve the project objectives cited on slide 3. However, the primary focus of project activity seems to have been on developing a more extensive modeling capability. Evaluated as a TA project, the approach is "good." Evaluated as an SA project, the grade would be at least "excellent."
- This work is very good. However, there are some components that should be considered to make it more robust in future work, such as the daily volatility of gas prices and the availability of electricity rates in the regulatory framework.
- It is good that the work is building on other modeling work that already exists and is integrating those models to explore this area. There are some scenarios that will, one hopes, be produced in the wrapping-up portion of this project going forward; their summarized results and output are highly anticipated.

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 cost comparisons for multiple hydrogen infrastructure scenarios, as reported on slide 13, are impressive. The accomplishments cited on slides 13–15 are a testimonial to the potential benefits associated with an improved, more extensive, integrated modeling capability. The potential will be realized, however, only to the extent that the integrated model will be used to inform decisions by stakeholders, including vehicle manufacturers, hydrogen producers, electric utilities, and regulatory agencies. The project team has responded well to prior comments from reviewers and input from stakeholders (as seen on slide 16).
- This project makes a solid contribution to both the Hydrogen Production R&D subprogram work, in terms of understanding the economics of production and distribution, and to the H2@Scale framework by developing specific scenarios for the availability of hydrogen and electric power.
- This work supports the rollout of FCEVs and supports understanding of the infrastructure and value that could be derived from that infrastructure.
- The accomplishments of this project are significant in that the analysis has a significant impact on the stakeholders. It is well explained but could be more concise. The results beg the question of practicality. Onsite electrolysis has been implemented at hydrogen refueling stations in California, elsewhere in the United States (at DOE facilities), and globally. It may be that the researchers were not granted access to the data from those installations, or they may have simply not asked industry partners for data. Many might consider onsite electrolysis in California as bringing about some significant practical barriers, with respect to negotiating rates and relevant scale for the grid operator. While the results show a great advantage to onsite electrolysis, perhaps there is something in the implementation that is worth investigating.
- Good progress has been made on four of the five stated questions, and progress has been made toward the project's goals by studying the following: (1) the benefits of central versus distributed hydrogen production; (2) the potential level of renewable energy integration with hydrogen production; (3) the economic impact of hydrogen on the grid through PLEXOS; and (4) the impact of the accelerated hydrogen demand from medium-duty (MD) and heavy-duty (HD) hydrogen trucks. The last portion of the project through September 2019 will likely cover higher penetrations of wind and solar. The team has made a credible effort toward integrating multiple complex modeling systems, including SERA, PLEXOS, and renewable profiles. Unfortunately, there are a few items that could be improved. It is unrealistic to expect shipping delivery organizations to use hydrogen if MD and HD vehicles are not evaluated. This would be especially relevant if hydrogen cost targets are met, i.e., lower-cost hydrogen could be used for transport.

As liquid is stated as the preferred delivery method for most stations being built now, it seems the model is missing a key distribution option.

Question 3: Collaboration and coordination

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

- It is very good for the project to build on models from the National Renewable Energy Laboratory (NREL) and others and to collaborate with data coming out of California.
- There is good integration with multiple laboratories and some input from an industry think tank. It would be helpful to collaborate with some industrial gas companies or station providers to give more realistic input on future station developments.
- Within the project, the collaboration among team members from Lawrence Berkeley National Laboratory, NREL, Idaho National Laboratory, and Emerging Futures, LLC, seems appropriate and effective. There are concerns regarding insufficient coordination with teams working on other hydrogen-related modeling activities, e.g., H2@Scale. During the question-and-answer portion of the presentation, a question was asked about the intersection of this project and H2@Scale activities. The response indicated there is awareness and some communication but that coordination across projects is limited by time availability and is not a high priority. The issue of whether there is overlap and duplication among modeling projects being funded by FCTO should be addressed.
- The project's collaboration was primarily referred to in terms of utilizing the models from NREL and others (SERA, V2G-SIM, PLEXOS, etc.). Otherwise, there was not much reference to specific discussion or coordination with the partners. The presenter acknowledged this in terms of time limitations for getting the work done. It seems like there are some additional opportunities here for more peer interaction and likely related refinement or improvement of the results.
- This project appears to suffer from a lack of non-academic stakeholders. The conclusions reached regarding onsite electrolysis generation ignore significant barriers to the practical implementation of such a solution. Industry stakeholders are needed to validate the conclusions and provide critical feedback to conclusions reached through economic theory. A workshop, or similar discussion of the project among stakeholders, would greatly benefit this project.

Question 4: Relevance/potential impact

This project was rated **3.9** for 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 output of this project is very highly relevant to H2@Scale; one of the greatest benefits of using hydrogen as an energy carrier is making renewable energy available at times other than when it is being produced. Therefore, this work is going to inform the economics of which applications make economic sense, as well as where and at what scale.
- This work will be very valuable for utilities and others evaluating the infrastructure needs.
- The effort gives high-level input for the direction of hydrogen and the potential for renewable integration. The work can be considered as a general pointer for integration and for how hydrogen can be used to benefit the grid. The project may be taking on too much, but there is good progress to date.
- The potential benefits to stakeholders are summarized on slide 5. This summary underscores the project's relevance. In response to a question asked after the session, Dr. Greenblatt stated that an independent transmission system operator engaged the project team to provide information for its analysis and decision-making. Stakeholders' use of results provides a tangible indication of relevance.
- This project has significant potential impact, particularly in California, where the largest commercial hydrogen energy market exists. Unfortunately, the analysis is incomplete and belies a false conclusion for policymakers, which industry partners will now need to dedicate time and effort toward correcting. This type of work is counterproductive to the overall goal of sound policy and progress toward cleaner air and lower carbon intensity. Industrial partners are needed in this project to provide sufficient insight into the practical aspects of the developed theory. With this critical insight, the clear barriers to market evolution

can be determined and demonstrated. Through such collaboration, strong, dynamic, and market-based solutions can form virtuous cycles that encourage positive behavior. For example, the researchers should consider the Low Carbon Fuel Standard hydrogen capacity credit program recently instituted at the request of industry. Similar policies could further incentivize the acceleration of grid-scale electrolysis, with all the benefits cited in this work.

Question 5: Proposed future work

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

- The last part of the work will be the most valuable. Finding the tipping point for increased renewables should only make hydrogen more attractive. The energy markets are enormously complex, and considering the stock of hydrogen, the spark spread between natural gas and electricity, and the impact of out-of-state liquid, there is still much to be done.
- The work that is to be done during the remainder of the current project (through September 2019) is described well on slide 19. The analyses will appropriately utilize the modeling results accomplished by the project. Including the results synthesis and dissemination in the remaining work this fiscal year (FY) is a plus. There was only a single line describing work that could be done with funding beyond FY 2019; this is not sufficient to make a case for additional resources. The grade for this element would be higher if there were more specificity about follow-on work beyond FY 2019, how that work would address barriers and benefit stakeholders, and how the work would complement other FCTO-funded activities.
- At this point, it appears that the future work consists primarily of summarizing and reporting the results. It will be valuable for the principal investigator to do some sensitivity scenarios related to the price of renewable power, as it is possible that the increased demand for stranded renewable power will result in the price’s rising. It was also proposed that it would be helpful to have an understanding of the model’s sensitivity to the interplay of electricity prices and natural gas prices.
- The proposed technical direction for the project is well aligned with the project objectives. The proposed future work should include the feedback from other stakeholders.

Project strengths:

- The project team has extensive experience with the development and application of the multiple models that have been integrated. The modeling and analytical capabilities within the national laboratories are superb. With sufficient stakeholder collaboration, analyses resulting from the integrated models have the potential to be valuable inputs for organizations with an interest in fuel cell and hydrogen technologies.
- The project does a good job of integrating and building on other models that describe the “building blocks” of the overall ecosystem. The project also does a very good job of addressing a very important element of implementing H2@Scale and renewably producing hydrogen for fuel.
- The project has good modeling if the narrow scope and artificial framework is acknowledged. More aspects and market dynamics will need to be covered to get the most use out of this project. There is nice integration of SERA and PLEXOS, which are very complex but allow for good linking of diverse markets.
- This is very good work.

Project weaknesses:

- At least so far (and this may resolve with the final work on the project), there has been no reference to the economics of hydrogen production. It needs to be shown if there are modeled scenarios that will produce hydrogen at or near the DOE target cost for hydrogen fuel. This is the key value of this project; there is a need to identify the many scenarios where work can be stopped, as well as the few scenarios that need focus, based on economics.
- This project has strong technical strength yet lacks critical feedback from industry and policy stakeholders that would guide the practical application of the results of the analysis.
- The project needs to (1) receive more industry input from those building hydrogen stations, (2) improve the integration of other energy streams, from renewable natural gas to liquid delivery, and (3) consider hydrogen as transportation fuel for tube trailers (or liquid, if included in a future effort).

- There seems to be insufficient collaboration or joint planning with other hydrogen-related modeling and analytical activity, much of which is being conducted by the same national laboratories associated with this project. Work such as what has been accomplished by this project should be well coordinated with other systems analysis activities funded and supported by the FCTO, including H2@Scale. There is no clearly articulated link between this project and the barriers cited in FCTO plans. Nevertheless, the project does support the FCTO's goals and objectives. There could be more outreach about the project and its results to stakeholders with financial and regulatory interests in hydrogen and fuel cells.

Recommendations for additions/deletions to project scope:

- It would be very helpful for the project team to include some sensitivity studies of the impact of varying electricity prices and the capital expense of varying electrolyzer usage to narrow down the scenarios that should be pursued.
- If follow-on work to this project is funded by the FCTO, it should be planned in conjunction with and folded into activities under the H2@Scale umbrella.
- The project team should perhaps include liquid hydrogen and the impact of out-of-state biogas in future efforts.

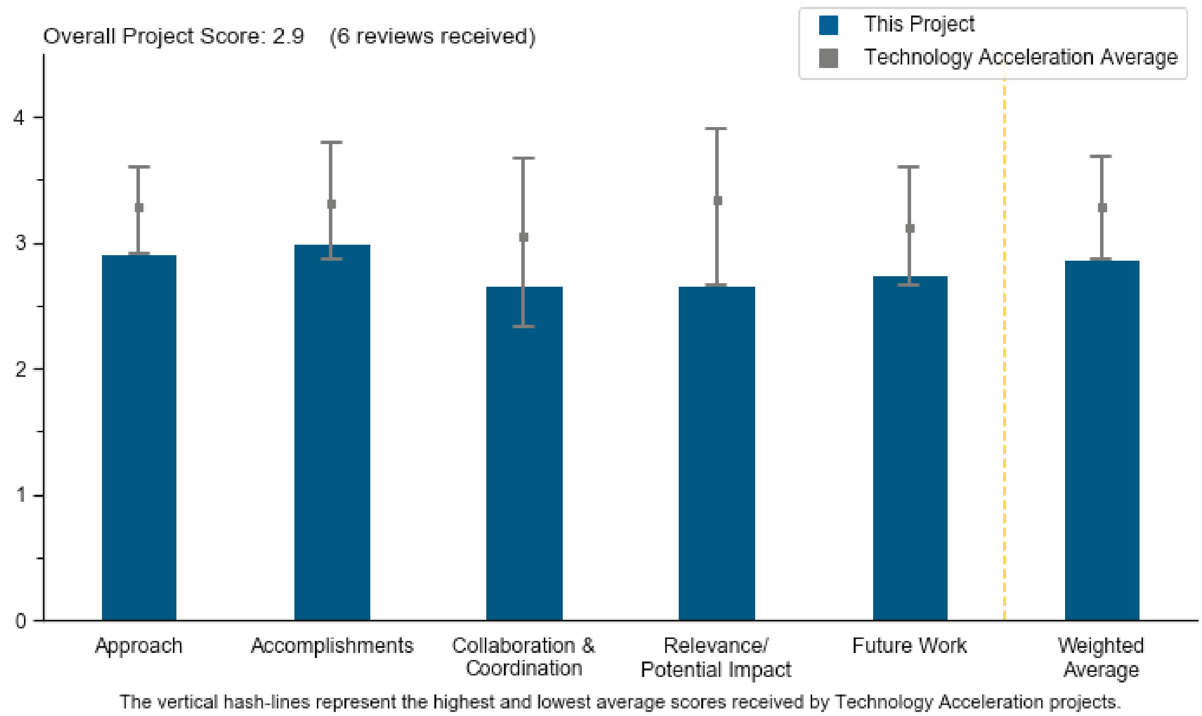
Project #TA-022: H2@Scale: Experimental Characterization of Durability of Advanced Electrolyzer Concepts in Dynamic Loading

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 and electrode development and (2) evaluating the influence of low loading, intermittency, and system controls on durability.

Project Scoring



Question 1: Approach to performing the work

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

- The approach is essentially determining the conditions under which electrolyzer operation will affect system durability, lifetime, and performance. From a materials perspective, this is an appropriate position, but it would be good to see the project better bridge to the electrolyzer design. The team should consider whether there is an acceptability criterion or a design criterion that could be developed to determine acceptable performance under these conditions. The team should determine how much degradation is acceptable and how a system can be designed or operated to minimize this.
- The research is following a logical path in an area highly relevant to the integration of hydrogen renewable power systems.
- This project should be able to contribute to cost reduction over the service life of electrolysis from numerous intermittent energy sources by extending the service lives. The project does provide useful input to future electrolyzer designs for challenging operating environments. It is very relevant to the success of

such applications. However, while the repetitive trial-and-effect method does a good job improving understanding the results of various catalysts, cell materials, morphologies, etc. in the presence of specifically varying inputs and loads, it does not address the underlying physical chemistry. Getting to the fundamental mechanisms of change within the cell and its materials would serve a wider purpose for future electrolyzer designs needed in intermittent and variable renewable power sources. The cycling tests show that degradation increases with the total number of cycles and cycle frequency, which is not unexpected, but the wave shape effects (flat, square, and triangle) show differences that lead to the need to understand the fundamental kinetic mechanisms for the degradation. The team should determine whether there are time-resolved effects (dE/dT, dI/dT, etc.) that need to be understood. If more fundamental studies were possible, they could more effectively lead to loss mitigation strategies for more universal electrolyzer design criteria. Such efforts do not fit within a $650,000 budget, however.

- The project uses catalysts with much lower loadings than real catalysts and subjects these model catalysts to severe operating conditions to obtain deactivation in a short time. Accelerated catalyst aging is useful to obtain deactivation data in a reasonable time, but accelerated aging sometimes involves deactivation mechanisms that have little or no relation to mechanisms present in the aging of catalysts under real conditions. To understand whether the deactivation mechanisms are the same, the investigators should make greater use of advanced characterization techniques on real and model catalysts deactivated under standard and accelerated conditions.
- It was not until slide 13 that it became apparent that this presentation was on polymer electrolyte membranes (PEMs). The approach is basic: fabrication, testing, and post-mortem. The cycle is missing "revised design." The approach appears to be to test PEM cells with iridium- or rutile-doped electrolyte (several grades of deionized water) for various load profiles and then to evaluate the structure of the catalyst layer.
- The approach to this work seems a bit rudimentary, given the maturity of the industry. It is not clear why there are not more industry partners or why the approach does not include a validation with field experience. The barriers are industry barriers based on feedback from field experience and industrial issues. This experimental approach seems to miss this critical connection.

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 project has effectively built upon previous years' work with much-needed data and analysis on the materials performance. This will provide a good basis for the next steps.
- The accomplishments and progress to date lead toward a number of design inputs for electrolysis in highly variable environments. The testing to relate various electrochemical element component choices to sensitivity to operating environments should be very useful.
- The project has established some useful test methodologies that can be used to evaluate potential mechanisms for performance loss, as demonstrated by the interesting findings regarding the fabrication of membrane electrode assemblies (MEAs).
- The experiments have been carried out carefully, and the mechanisms of deactivation have been identified. Given the fact that the deactivation mechanisms have been identified, the project needs more focus on techniques for extending catalyst lifetime.
- Half-cell and single-cell testing with iridium- and rutile-doped electrolytes promotes catalyst degradation. The increases in Nafion™ content appear to accelerate the degradation.
- The work presented seems to be a repeat of junior-level chemical engineering coursework from the early 2000s. The low loading and effects of square wave on Nafion membrane single cells are well known. Additionally, the effect of fabrication techniques seems specific to the work conducted at NREL, with no correlation as to how production of a single cell with low catalyst loading has any relationship to the cells of a multi-megawatt stack produced commercially. It is hard to understand how the researchers were unable to use the $650,000 provided to develop a project with greater impact. Perhaps this is unfair criticism, but the information provided does not demonstrate any substantial contribution to DOE goals. If this criticism is inaccurate, perhaps the investigator should better explain how the accomplishments will be used by

industry for commercialization, or if this is a standard approach for other researchers in evaluating single cells. This is a guess, as it is not explicitly stated by the presentation.

Question 3: Collaboration and coordination

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

- The collaboration between NREL and LANL was effective in accomplishing the different efforts of the project.
- Given the performance of commercial catalysts, the project should seek industry collaboration in continuing the work under a new mandate. In the meantime, the project should continue its strategy of publishing and presenting findings.
- It is probably time to bring in more electrolyzer design teams from industry to evaluate how these data and this performance information can better inform their operations and system designs.
- It would have been nice to include a PEM electrolyzer manufacturer, such as Proton OnSite.
- Although the investigators have worked with one other national laboratory, there is no indication that they have collaborated with or sought input from manufacturers of commercial solid oxide fuel cells (SOFCs). These interactions are vital if the project is to yield results that are useful in the real world.
- This project involves two national laboratories operating in a silo, independent of the industry; this has resulted in research for the sake of research. It is unclear whether anyone besides the project participants will see this information other than at the Annual Merit Review.

Question 4: Relevance/potential impact

This project was rated **2.7** for 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 topical area of electrolyzers' service-life sensitivity to dynamic operating environments is critical to the long-term success of electrolysis from intermittent sources, such as renewables. This project addresses some of the underlying service-life issues.
- Electrolyzer reliability and durability remain key issues in the long-term reduction of hydrogen production costs.
- Performance degradation is an important issue and highly relevant to the industry's achieving targeted cell-stack lifetimes and life-cycle costs.
- If hydrogen is to be used as an energy storage buffer (e.g., fuel cells or flow batteries), power-load following of the grid is required. Electrolyzers do not like load following. Simple loads were tried (e.g., square wave and triangular wave), and they accelerated the decay. Higher potentials were also an issue, as would be expected from catalysts operating above reversible hydrogen electrode (RHE). The team should try limiting the local oxygen potential to less than 1.0 V above RHE. This could be done with a dummy load.
- Although the project focuses on catalyst deactivation, the investigators have no evidence for what role catalyst deactivation plays in the cost of SOFCs. Without a quantification of the impact of catalyst deactivation on the capital and operating costs of SOFCs, it is impossible to gauge the importance of this work. The project seeks to identify the causes of catalyst deactivation, but it has not produced strategies for maximizing catalyst life.
- This project has significant potential but fails to leverage necessary partners and develop a project with relevance. Lowering the cost of electrolysis through technology improvement is a key factor in the transition to lower-carbon hydrogen production technologies. Electrolysis performance, particularly the better use and durability of catalysts, is a critical area of research. The researchers unfortunately squandered that opportunity with research that is devoid of industry interaction. This is despite seemingly well-positioned capabilities for the production of single cells and a project idea for low loading and high potential, which is seemingly meant to accelerate end-of-life failures or design vulnerabilities (though this is not clear, as it is not explicitly stated). The researchers manage to provide only a research-for-research's-

sake result that has benefit for neither industry stakeholders nor research peers. NREL has done DOE a disservice in the execution of this project.

Question 5: Proposed future work

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

- The work will continue to use testing methods to identify sources of performance degradation, which is good. The team should publish results and get feedback. Continuation of this work should be supported by industry.
- The proposed current-based testing could be helpful in identifying more fundamental mechanisms of performance degradation in a dynamic environment.
- The project investigators should work with commercial fuel cell producers to quantify the potential benefits of the project. The team should work to verify the assumption that the deactivation of low-loading catalysts under accelerated aging conditions is the same as the deactivation of real catalysts under normal operating conditions.
- It is suggested that, prior to full-sized cells, the team should first master local voltage control of a single cell. The team should avoid conditions of mixed potentials on the anode, a condition that may result in excessive local cathode potentials.
- The proposed future work does not address the key issues with this project and does not allow the results to achieve some useful purpose. During the review, the presenter was asked simply, "What is success?" The project team should return to this question, as neither the presenter nor the presentation clearly answered this basic question. It is not the DOE Hydrogen and Fuel Cells Program's (the Program's) management goals or a lack of clear DOE targets, it is not a lack of interest from the industry, it is not a lack of technical understanding by the reviewers, it is not a lack of funds, nor is it a lack of skill or resources. It is the research team and the DOE Program manager who are complicit in not achieving a better result. There is time yet to achieve a positive result, and the team should move quickly to change direction to find a means to define and achieve success.

Project strengths:

- The project makes good use of electrochemical characterization to model the deactivation of model catalysts under accelerated aging conditions.
- Tools have been developed that should be helpful in improving the performance of electrocatalysts in electrolyzers.
- The project partners made significant progress in their planned research, given a somewhat limited budget.
- There is detailed materials analysis of degradation modes.
- The topic of electrolyzer performance is the best part of this project.
- The project's strengths include the team's diligence and energy.

Project weaknesses:

- There is no technoeconomic analysis to validate the assumption that extending catalyst life will have a significant impact on the cost of hydrogen. The project also has a weakness in its assumption that the deactivation of low-loading model catalysts under accelerated aging conditions is related to the deactivation of real catalysts under normal operating conditions. There is little or no activity in the project for improving catalyst lifetime.
- The lack of depth of study into more fundamental details of the electrolyzer degradation process in a dynamic loading environment may make it difficult to understand degradation and failure modes of electrolyzers in a way that could lead to successful design changes.
- The results need to be tied in and made relevant to electrolyzer design and operations from a systems-level perspective.
- The project needs to engage industry in order to continue the work; the researchers should get feedback on the relevance of the test methods, etc.

- This project has many previously outlined weaknesses.
- The project's weaknesses include communication skills.

Recommendations for additions/deletions to project scope:

- The scope of the project is accurate; the project should apply itself to achieving its potential through communication and relevance rather than through further efforts in new technical results.
- With industry support, this project should seek continuation.
- The project should add technoeconomic analysis to quantify the impact of catalyst deactivation and set targets for improvement in catalyst lifetime. The team should also carry out work to compare the deactivation of model catalysts under accelerated aging to the deactivation of real catalysts. The team should also work with commercial SOFC manufacturers to make sure that the work is relevant.
- The team needs to collaborate with industry suppliers to understand any problems in electrolyzer performance that may be caused by variable operating environments. The team should extend the project into more fundamental analysis of basic physical, materials science, and chemical processes in electrolyzers related to intermittent and variable supplies and loads. If at all possible, the project should consider alkaline systems as well.
- The team should look at the effect of local voltage control.

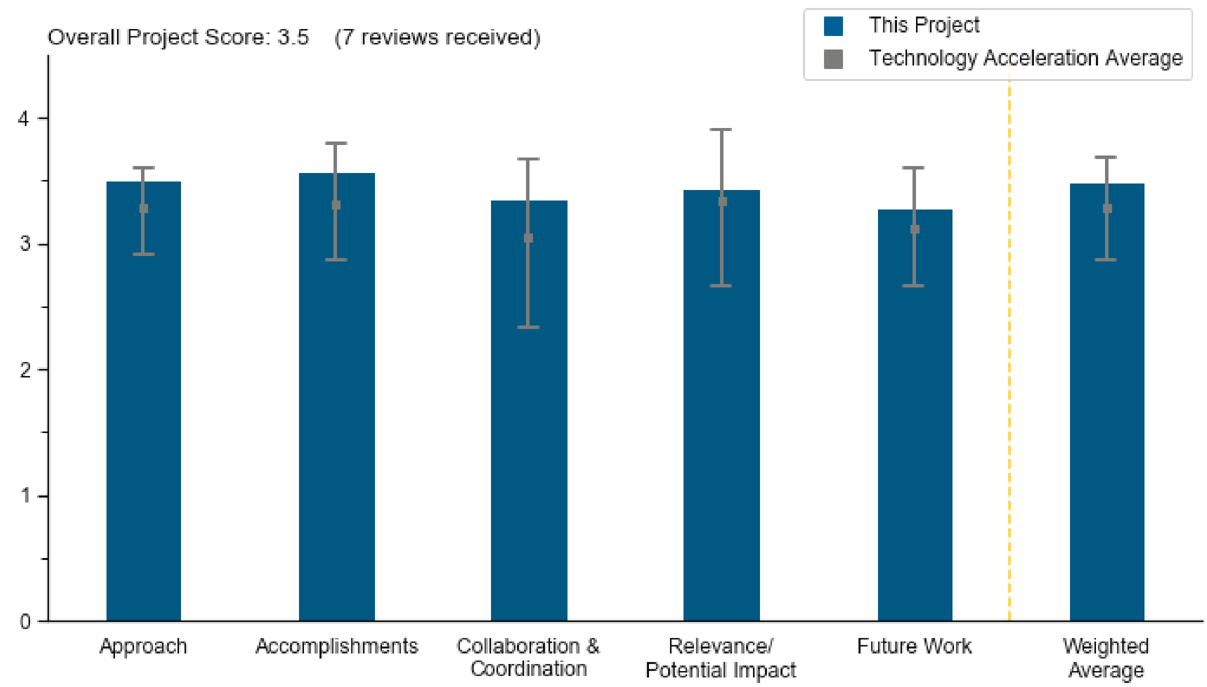
Project #TA-023: Hydrogen Stations for Urban Sites

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 (SNL)–National Renewable Energy Laboratory (NREL) 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.

Project Scoring



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

Question 1: Approach to performing the work

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

- The project has clearly identified three Fuel Cell Technologies Office (FCTO) barriers to address and is positioned to address all three appropriately. The FCTO has targeted a 40% reduction in station size by 2022, relative to 2016. It sounds like this was initially a technical target, i.e., whether fueling station equipment can be reduced in size to reduce the overall footprint. A key takeaway from this update appears to be that this is not a technical question but primarily a regulatory question. That is, the work has identified the main drivers of station footprint, and they appear to be fire codes. This analysis, however, is scientifically rigorous and fact-based, which will make it valuable in addressing the regulatory hurdles to reducing station footprint.
- The approach is very clearly defined; the project identifies three critical barriers that guide the focus of the station design. The project also considers the objectives and input of the FCTO, as well as those of the

commercial and policy stakeholders involved in the H2USA initiative. Codes and standards are also integral to the scope of the work.
- The approach for this project is very well aligned with its objectives and the Hydrogen and Fuel Cells Program's (the Program's) goals.
- The project has a well-organized approach to reducing station footprint. The station delivery size appears small for commercial application. Presumably this would be a prototype station.
- The approach uses reasonable assumptions and established industry specifications for the delivery methods and technologies used in the layouts.
- The project appears to cover most of the aspects of hydrogen refueling stations (HRSs), from a modeling perspective.
- The approach is excellent and appropriate for the project work.

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's accomplishments appropriately represent the key questions industry faces when siting stations in compliance with existing fire codes. The work highlights some of the key aspects beyond simply the equipment and takes into account the various challenges faced in real scenarios. The work accomplishes a scientific method for evaluating sites and options in order to highlight the interaction of equipment technology and site layout with the efficacy of hydrogen in the gasoline forecourt.
- The project demonstrates that a comprehensive set of key accomplishments has been achieved. The base case and critical components for station footprint have been established for gas and liquid delivery as well as on-site electrolysis. Codes and permitting issues have been identified for each of these as well. Economic analyses are included. The comparison with a real-world station further strengthens the project.
- The project's accomplishments include its well-organized analysis of station types with explanations of the strengths and weaknesses of gaseous, liquid, and electrolysis cases. The team has clearly identified that the size of the delivery trucks for gaseous and liquid hydrogen is important. The team has also evaluated alternative designs for reducing footprint, identified a co-location case with a convenience store as a real case, and analyzed gas stations to get a comparison base. However, it is not clear if the daily delivery of gasoline fuel is the same as the daily delivery case for hydrogen that was studied here.
- The project appears to provide useful information for station development and future development direction with regard to footprint planning and development.
- The team shows good progress toward evaluating a range of station types.
- This project has made excellent progress to achieve its objectives.
- The researchers have made good progress on developing their base cases and examining some key alternatives to potentially reduce station footprint. The summary table of lot sizes for all cases is an effective way of sharing the data and showing the key results from the study. The summary table of setback distance that could be reduced was also an efficient way of communicating that information. It is recommended that the team provide some additional description of how setback distance can be reduced, i.e., through special measures, but also perhaps some justification for challenging the setback distances with data. The base case is for a 600 kg/day station. California typically looks for stations with a size of 1,000 kg/day, especially if public money is provided. The authors should consider commenting on how much impact station capacity has on the overall footprint and, specifically, how increasing capacity to 1,000 kg/day would affect the study results, at least qualitatively. It would also be interesting to know if there is another way to quantify lot size that takes into account the area and features of the length of the sides. It may be that most station lots are relatively square, so area is sufficient. But if there are oddly shaped lots (like a really long, skinny lot), additional parameters would be required to really understand how the station layout could be optimized for minimum footprint.

Question 3: Collaboration and coordination

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

- The project has sufficiently discussed and vetted information with various stakeholders to ensure that the information is science-based, generically applied, and useful.
- Fifteen stakeholders are identified in this collaborative project with Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL). There is a strong effort to get the hydrogen community involved.
- Effective and excellent coordination has been demonstrated.
- The collaboration and coordination are good.
- While there is only one other formal project partner, several collaborators are named as informing the project. The project should further illustrate the type of information that is shared between the broader set of collaborators and what additional information could strengthen the project.
- A better approach to this project might be to partner with a site owner or a city planner to look at specific sites for implementation and optimization. In the field, there are huge variables from site to site that are well beyond the simplified layouts used in this study.
- There are a number of collaboration partners listed, but the presentation did not give the sense that many of them had contributed more than equipment data. Fueling station developers and operators should be more involved, especially in considering an atypical station layout, such as underground or rooftop. Questions remain, such as whether those designs are exclusively economic decisions. It is unclear whether developers and operators provided any input on concerns about operations and maintenance, permitting, or aesthetics; whether they have much experience in reducing setback distances; or how they feel about the shorter delivery truck concept. California Air Resources Board's California Hydrogen Infrastructure Tool could be useful for identifying existing gasoline stations that would represent high potential for hydrogen fueling. Those stations could be selected for further analysis of co-locating hydrogen fueling and of what setback reductions or other advanced concepts would be required to successfully integrate hydrogen fueling.

Question 4: Relevance/potential impact

This project was rated **3.4** for 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 reduction of station footprint is a critical barrier to commercial fuel cell vehicle deployment, and this project is very relevant. The potential impact of the project is made stronger both by including theoretical designs and by integrating real-world barriers and issues into the analysis. The project's focus on California and the Northeast is also very much aligned with the original equipment manufacturers' plans for vehicles.
- There is significant potential impact for this work, especially as it concerns focusing future research and development efforts. If appropriate, the authors should explicitly state that the key to station footprint reduction is not primarily a fuel cell technology problem but a regulatory problem (e.g., setbacks) or logistics problem (e.g., delivery truck size). Additionally, creating a framework to screen existing gas stations would be very beneficial in developing new hydrogen fueling options and focusing state money (at least in California) on the most cost-effective locations for station development.
- This is an important project that anticipates the design of a hydrogen station in a commercial environment. The project has the potential to place the safety, codes and standards (SCS) and permitting for the future deployment of hydrogen stations on a firm basis.
- This information has a strong impact, not necessarily on the industry participants, who likely already know the challenges, but rather on the overall community. This work helps establish a consistent and defensible dialogue around site challenges and equipment options to allow policymakers and industry participants to engage in productive dialogue. This is a key aspect of the Program's goals.
- The project aligns well with the Program.
- The project has clear potential impact; however, the focus is not on the co-location of hydrogen with other fuels (such as gasoline), while that is what industry is currently pursuing because of zoning and aligning with providing a gasoline fueling experience. Something that should also be kept in mind with all DOE and

H2FIRST reports is that when final reports are finally published, the observations are far behind the status of technology, and this is typically not clarified in reports.

- This project is difficult to strongly support. Most of the work on this project is already being done in the field by the station installation teams and project teams, and the site-to-site variability of elements such as layout, facility hookups, look and feel, and site owner acceptance is a huge issue that cannot be addressed in this study. This type of project may be best left up to the industry players.

Question 5: Proposed future work

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

- The project has accomplished a good deal, and the team is on a good trajectory to complete the key goals for the study. The proposal to incorporate alternative means into SCS is a logical follow-on to this work, given that reducing setback distance appears to be the key pathway to footprint reduction. Exploring underground storage safety codes seems less valuable, given that so few stations will likely find it economical to deploy underground storage.
- Because the project is near completion, the proposed work focuses on finalizing the studies and designs and preparing the final report. The future work proposed under new contracts appropriately concentrates on SCS to further address that barrier.
- It is excellent to see direct liquid burial included in the work proposed for the last few months of this project.
- The proposed future work is appropriate.
- The proposed future work is to complete the project and issue a report; this would be outstanding, like the rest of the project. Unfortunately, real fueling stations supply 200 to 300 vehicles per day, and this approach would address only 30 to 60 vehicles per day. The future work should consider stations with commercial delivery capability.
- The project will end, but the proposed future work could use more evaluation and better detail to ensure that it will be relevant. Validation of alternative means and methods is a very difficult approach and might be stepping over the line between academic work and industry advocacy. Additionally, underground storage may be interesting, but perhaps there are some other areas, with respect to safety consequence and frequency reduction, that might elicit more beneficial results.

Project strengths:

- The team is following a logical and rigorous process for working through this problem. They have developed good results that clearly identify the best levers to pull to reduce station footprint. The real-world case studies are a great way of communicating the impacts to the audience.
- The project is very focused on key barriers and objectives and very much aligns with industry needs for further vehicle commercialization. The end results will inform technical work as well as policy and codes and standards.
- The project's strengths include its effort to assess what factors play a role in reducing footprint based on codes and standards, as well as alternative methods to meet the same intent.
- The project fits a need within the industry's best practices, helping to identify barriers and placing those barriers in easily understood terms.
- The strong team made up of SNL and NREL has made this project successful.
- The project has good conceptual topics and a good use of industry standards for systems and layouts.
- The project's main strength is in the approaches that have been used to conduct the work.

Project weaknesses:

- It would be good to use the station capacity definition that is used in California for state-funded HRS projects. The team also needs to further analyze earthquake-proof overpass-grade-located station equipment. Additionally, by the time the final report is available, it may confuse new industry stakeholders, as it contains good lessons that have been learned but not what the current status is for HRS development.
- The team could benefit from coordinating more closely with HRS developers, and even gasoline station developers or owners, to understand the other barriers to deploying new stations, as well as any tips or tricks for reducing setbacks or the footprint required for delivery trucks. A question from the audience involved using the street or adjacent empty property for the delivery trucks, thereby reducing the required footprint. The project team should find out if this is a common practice in the petroleum fueling space. It would be interesting to get some input from those already in urban refueling.
- Formally including additional partners, or at least clearly defining how collaborators are being engaged and providing information, would further strengthen the project.
- The project team might be considering some opportunities too mundane to address, instead hoping for more challenging evaluations (e.g., underground storage), while the mundane solutions, and particularly some depth of rigorous scientific support, could have a greater impact.
- The project weaknesses include its relevance to real-site challenges. A given site almost always has many more constraints with regard to layout, site owner acceptance, etc. than are discussed in this project. A general study of “typical” sites is not particularly useful for these highly constrained sites.
- The project does not address the delivery quantities of a commercial fueling station.

Recommendations for additions/deletions to project scope:

- The project scope is well considered and needs no additions or deletions.
- It is recommended that the project add a sensitivity analysis to consider the impact of increasing the station capacity from 600 kg/day to 1,000 kg/day. The team should identify the reducible setback distances and explicitly state the method by which each could be reduced (e.g., special exemption, adding firewalls, etc.). The team should also identify a case study that clearly shows how to reduce setbacks and the impact it has on a real-world station location.
- It is worth investigating how significantly the project outcomes would change if the project included larger-capacity stations (such as the limits indicated in National Fire Protection Agency). This relates to the comment about calculations seen on slide 9. For the final report, the team should acknowledge the capacity points at which things would change significantly.
- The project should continue to highlight synergies with other FCTO projects (and state projects, where applicable) on station development and codes and standards.
- It is suggested that the project team work with a station installation team to do evaluate an actual site to see the kinds of challenges and constraints that can be faced.
- This project does not address commercial-size fueling stations. A follow-up project should be initiated that addresses commercial fueling station requirements, and this project should include an existing fuel delivery company such as, for example, Exxon.
- There are no recommendation for additions/deletions to project scope.

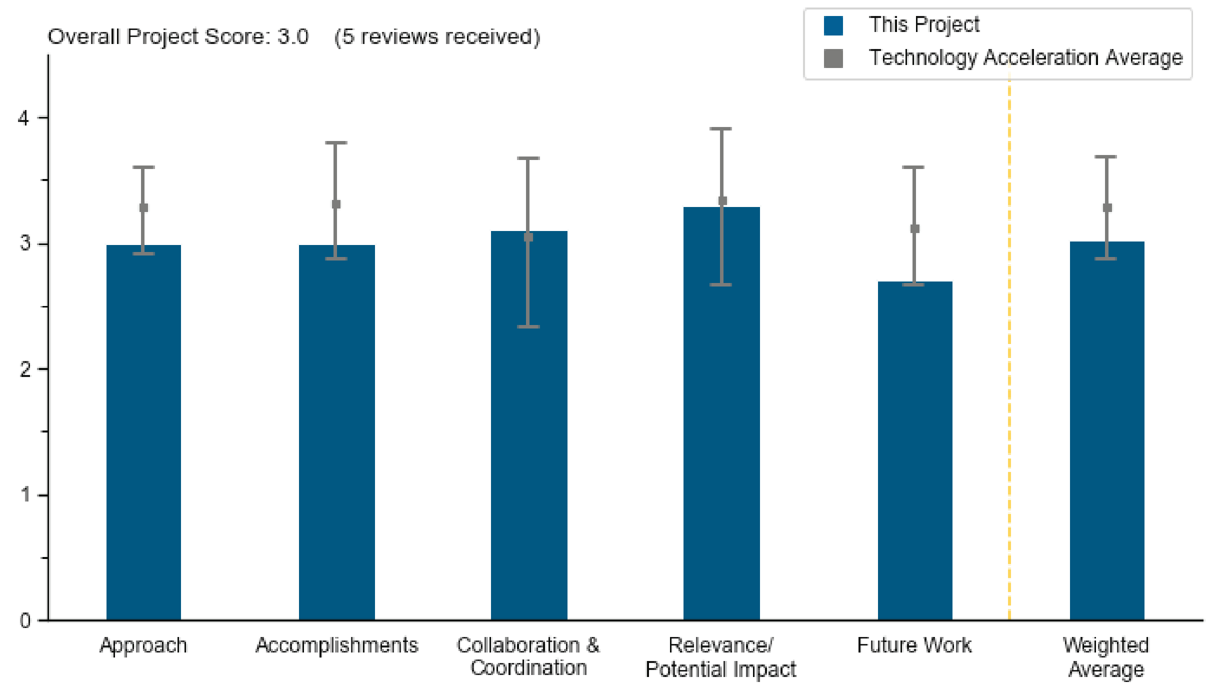
Project #TA-024: Analysis of Fuel Cells for Trucks

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 (DOE) by creating a design solution that will meet or exceed the baseline performance and cargo capacity of a conventional vehicle.

Project Scoring



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

Question 1: Approach to performing the work

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

- The project has a sound approach; using a common platform helps identify differences in requirements for the platforms supporting each technology. Investigating the cooling problem is highly relevant to the deployment of fuel cells in Class 8 trucks.
- The approach is well thought out and comprehensive; this is a good use of a workshop to obtain industry input.
- There seems to be a disconnect between the barriers cited on slide 2 and the project objectives stated on slides 3 and 9. The barriers, as described in the Technology Validation section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan, refer to the need for vehicle operational data that can be related to established targets. Thus, there is an implication that the project focus is on comparing "real-world" performance between fuel cell electric trucks (FCETs) and conventional diesel-powered trucks. However, the first objective (as seen on slide 3) is the development of models that enable comparison of potential FCET energy and cost performance with those of current and future diesel trucks. The second objective is to quantify FCET cooling requirements (as seen on slide 9);

here, the approach is to develop models that enable improved understanding of the thermal behavior associated with the options for FCET cooling systems. While the project's objectives and approach do not directly address the stated barriers, they are consistent with a project that can provide useful information on the potential for FCETs to compete with conventional trucks. The approach utilizes and builds on the significant vehicle modeling capability established at ANL. The team understands the importance of linking the work on this project with related activities and capabilities; other projects intersecting with and contributing to this one are noted on slide 4. This is a plus.

- The approach is set up well, and a deeper understanding of the current draft of targets for FCETs is very valuable. However, there may be more effective ways to accomplish this goal. There are a few key points to be made: (1) The intent behind including a detailed study of cooling requirements is not well understood. This may be a useful exercise, but it was not apparent how this relates to setting targets. (2) The definition for "best in class" seems to be based more on how a truck is operated rather than the technology itself (simulated as lower cargo and lower speed). For added clarity, it is suggested that going forward, the project team should benchmark to one standard diesel truck that follows DOE targets. This will capture lightweighting and other efficiency improvements while reducing the complexity of the study (i.e., showing just baseline diesel as opposed to two different diesel baselines). (3) Finally, the project team should show the current draft targets being used as a baseline.
- The approach of using Autonomie as a simulation engine is sound. However, there are a number of competing parameters that define a "good" or "best" FCET, e.g., battery size versus fuel cell size, motor power versus torque. These require detailed trade-offs, which then require intimate domain knowledge. A formal optimization wrapper would significantly improve the approach, with expert inputs on how to limit the optimization parameters for meaningful results.

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 work clearly identifies the challenges facing fuel cell technology in Class 8 applications.
- The accomplishments seem reasonable; there is nothing unexpected or unusual.
- Progress has certainly been made to vet the draft truck targets, and it is highly anticipated that the continued work will set accurate and useful targets to drive innovation. Based on the data presented, there are a number of recommendations that could improve the presentation of future work. (1) It is recommended that the project remove "best in class"; the value of this metric is somewhat unknown, and it is not modeled in an apples-to-apples comparison with the other simulations. It would also help greatly reduce the complexity of the results and focus on key points. (2) The team should use graphs that show analysis and comparison; the current graphs appear to plot the targets of each in a separate graph. To improve clarity, it is suggested that the fuel cell and diesel graphs be combined for the relevant metrics (both technical and cost-related). (3) The project needs sensitivity analysis of key targets. The key intent of this work is to inform the draft targets and help set them appropriately. It is suggested that the project team run a few scenarios of the key targets to better understand whether the current draft targets are appropriate or need to be adjusted. (4) More insight needs to be provided; considerable analysis and data have been presented, but it was difficult to assess the accuracy and impact of the targets. The team should share some insight on these key takeaways. (5) More discussion on how the cooling analysis affects targets should also be provided.
- For the first objective (which is to support medium-duty [MD] and heavy-duty [HD] target-setting), the preliminary results summarized in the technical accomplishments (as seen on slides 7 and 8) seem encouraging for FCETs. It is concerning, however, that the results are determined by the assumptions documented in slide 6, specifically that the targets are expected to be achieved in 2030 and 2050. It would be helpful to provide the results of sensitivity analyses for ranges of technology performance and cost. However, the project's limited funding constrains the team's ability to analyze the multiple cases reflected by this comment. Regarding the second objective (which is to quantify FCET cooling system requirements), the accomplishments are impressive for a project with relatively limited funding and short duration. It seems that exercising ANL's Autonomie model for this work takes advantage of the results provided by other FCTO-funded projects that address fuel cell systems for HD trucks. The results from this

project should be beneficial in determining where to apply available resources for future FCET research and development (R&D).

- It seems that the FCET model has been optimized heuristically. A formal optimization wrapper would likely change the configuration and would likely provide more significant benefits that can change the ranking versus other power plants. Without that certainty in the FCET configuration, the basis for the value predictions is weak.

Question 3: Collaboration and coordination

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

- Coordination and collaboration with industry is always a good thing; the sharing of papers with SAE International is also great. Assuming that there is good communication between project members, leveraging the assumptions and work from existing projects is excellent collaboration.
- The project's collaborations to conduct analysis and receive feedback from industry are very good. Additional outreach is encouraged if more input is needed when the team is amending targets.
- Collaboration and coordination are difficult to evaluate when specifically limited to and in the context of this project. The graphic on slide 15 indicates that this project is being done solely by an ANL team. Based on the presentation and Dr. Vijayagopal's response to a question, the organizations cited on the right side of the slide provided input in forums related to multiple ANL modeling activities. For example, work on this project has drawn from the results of a workshop that is mentioned; the same workshop has provided information used by multiple other projects. The same "collaboration and coordination" slide was used in ANL's presentation on project SA-044. It is fine to use the views of the organizations shown on the slide as input for the planning and implementation of multiple ANL projects; however, it would be helpful to clarify that coordination with all these stakeholders did not occur in the context of this project alone. SA-169, managed by the National Renewable Energy Laboratory (NREL), is another project that seems to intersect with TA-024. Its approach, which uses FASTSim as a primary modeling tool, also calculates cost of ownership for MD and HD vehicles.
- Hopefully, the investigators will have the opportunity to get data from ongoing demonstrations in the California Ports project. The team could coordinate with Ballard Power Systems, Inc., or involve the Toyota Motor Company and Kenworth Truck Company team. The team should also consider the buses at the SunLine Transit Agency that operate in the summer months.
- There is significant effort in the same area at NREL and Oak Ridge National Laboratory. These are partnership opportunities that would significantly increase the quality and impact of the work. At a minimum, such a collaboration would allow for the cross-validation of the results but hopefully would allow for a significant increase in quality of the results. Collaboration is a missed opportunity in this project.

Question 4: Relevance/potential impact

This project was rated **3.3** for 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 highly relevant application for hydrogen and fuel cells, given the ability for trucks to scale up in terms of infrastructure, the significant impact they have on emissions, the prospect of future restrictions on the use of diesel, etc., and the value of the energy service provided by trucking. This project should be supported.
- The impact and relevance for setting and analyzing FCET targets is of great importance to stakeholders. The project team is encouraged to obtain any final feedback before swiftly moving to publish the targets in order to drive the industry forward.
- MD and HD trucks are potentially important applications for fuel cell power. This potential is a legitimate topic for FCTO interest and activity. A project with this one's limited scope and duration, however, has limited ability to help achieve the FCTO's technology and cost targets. Regarding objective 1 (as seen on slide 3), it would be preferable for the team to apply the available funding to the development and testing of

fuel cell technologies for trucks rather than analyses of 2030 and 2050 results premised on the achievement of FCTO targets. Regarding objective 2 (as seen on slide 9), R&D on options for achieving cooling system requirements for FCETs seems reasonable. It would be helpful for the presentation to include the underlying rationale that led to the selection of the cooling system as a focus for this project.
- The project has excellent alignment. However, some of the approach's flaws can inject misleading conclusions that are questionable at a minimum. It is counterintuitive to put forward the view that FCETs are better suited for urban or MD applications, rather than long-haul (even if the long-haul diesel power plant is close to optimal).
- There are many areas in HD FCETs that need development and work. The cooling loads will certainly be an important consideration for the operation of an FCET, but it does not seem to be a high priority at this time, as there are so many other technical topics that need to be solved.

Question 5: Proposed future work

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

- There is not much time left in this project, but the work on developing a cooling system to fit the technology will be highly useful. If there is a follow-on project, it would also be good to consider liquid hydrogen. Liquid hydrogen would have a number of benefits, including extending range, dealing with cooling issues, and reducing fuel dwell times. Liquid hydrogen is also compatible with distributing hydrogen in a hydrogen infrastructure at large scale, as well as with public and large-fleet refueling.
- The key is the long-term goal of "making thermal characteristics an integral part of the vehicle-sizing algorithm for all powertrains."
- More support is needed in developing the targets. The proposed details of this work are somewhat vague, but the work scope is important. It will be interesting to hear more about how the scope of cooling requirements is directly related to target-setting.
- Slide 16 provides a general indication about continuing similar modeling work upon completion of the current project. Evidently, no proposal for related work has been submitted to the FCTO. Continuation of the modeling work associated with the "target development process" should have lower priority for FCTO funding than R&D on truck-related fuel cell technologies. The R&D of cooling system technologies for FCETs is appropriate. However, exercising the Autonomie model as part of that activity at this time is questionable and is an issue that the FCTO should address.
- The proposed future work needs deeper consideration. It is strongly recommended that the project team with NREL and consider an optimization wrapper.

Project strengths:

- The topic of FCETs is growing rapidly, and the development of accurate targets will help guide the academic community, the setting of policy, and industry. The team is encouraged to continue the great work in support of this topic.
- This is a highly relevant topic for scaling up hydrogen infrastructure and decarbonizing the delivery services of goods. FCETs may leapfrog fuel cell electric vehicles in terms of fuel demand and overall proposed value.
- This project has the right focus. Running an industry workshop provided a great start, and the approach is generally sound. The analysis of cooling capacity versus battery size is convincing and pertinent to the objectives.
- The project's strengths include its industry input and collaboration; the team should make sure these continue, as well as the project's long-term goal.
- The project team at ANL has significant vehicle modeling expertise, which has been developed and refined over many years. Its models and related analyses are highly regarded and widely used.

Project weaknesses:

- This project is evidently linked with other related analytical activity. However, as a stand-alone effort with limited scope and funding, its presentation does not convey confidence that it is an important element of an integrated plan for the advancement of FCET technology, or an element that provides critical analysis related to that technology. It is not clear that organizations cited on the collaboration and coordination slide have made comments or recommendations specifically related to this project. There is a conclusion that the performance and cost of FCETs will be competitive with conventional diesel-powered trucks; this conclusion seems to have resulted from the assumption that FCTO targets will be achieved. While that has some benefit, it would be much more valuable for modeling and analysis to identify areas with a high potential for adversely affecting the ability to achieve long-term targets and that could provide a rationale for the application of future R&D resources. There is a disconnect between the barriers cited on slide 2 and the project objectives stated on slides 3 and 9.

- An optimization wrapper is needed, coupled with expert supervision of the optimization process, in order to avoid unrealistic corner cases. There is a gap that needs to be filled in the project's collaboration outside of ANL, especially with NREL and other DOE/Vehicle Technologies Office projects.
- The project's weaknesses include the lack of data from Class 8 trucks for testing models. The project scope is unduly restricted, and the team needs to look at the feasibility of liquid hydrogen as onboard fuel for long-haul applications.
- The project's approach for analyzing the draft truck targets could be improved to be more impactful and efficient. It is expected that the targets could be published rather quickly if a few improvements were made.
- This work could possibly be done at a later date, after more critical technical challenges have been overcome.

Recommendations for additions/deletions to project scope:

- The team should add liquid hydrogen and liquefied natural gas to the list of comparables. The team needs to be cognizant of the impact of diesel emission restrictions in the long term. It looks like diesel will be banned in some jurisdictions.
- If modeling and analytical work, such as that accomplished by this project, is continued, it should not be as a separate, "standalone," independent activity with limited funding. The work should be incorporated into a comprehensive and well-integrated modeling and analytical project, designed to support FCET R&D.
- This project should perhaps be made a subset of a larger, more comprehensive HD modeling and testing project.
- The cooling system simulation is interesting, but the justification for how it fits within the target-setting scope needs to be made clearer. Perhaps these resources could be better used to focus more on the targets themselves. It is recommended that more effective analysis be done within the current scope.
- An optimization wrapper is needed, coupled with expert supervision of the optimization process to avoid unrealistic corner cases. There is a gap that needs to be filled in the project's collaboration outside of ANL, especially with the NREL and other DOE/VTO projects.

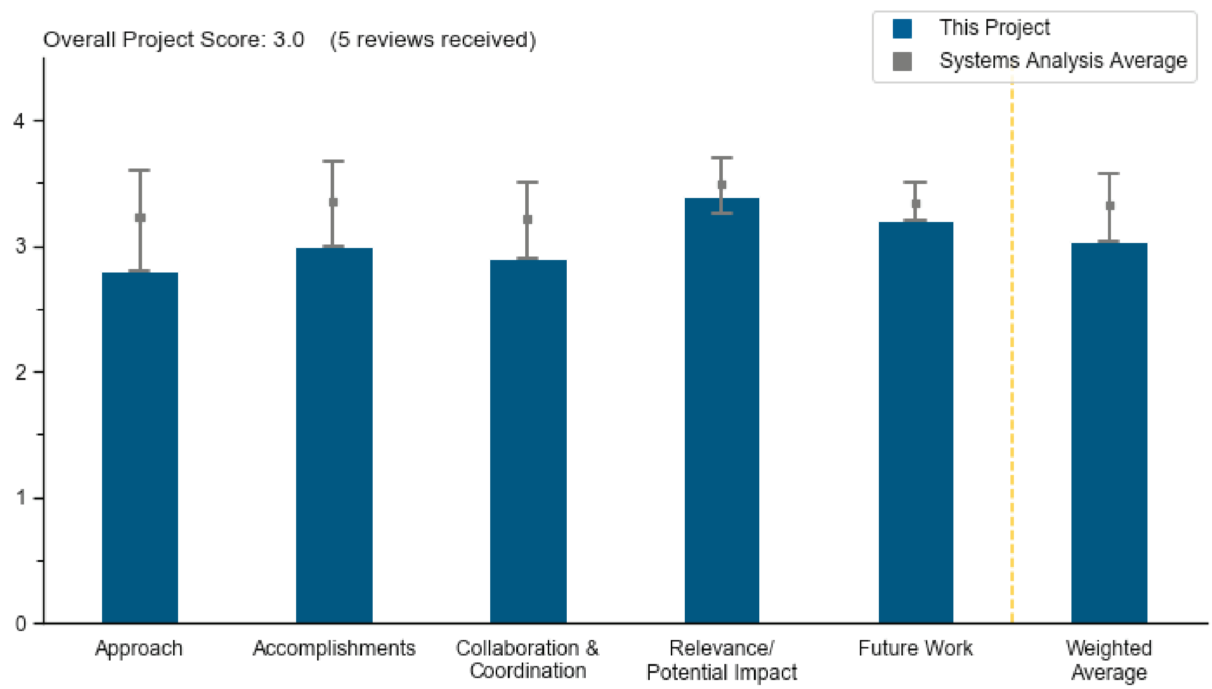
Project #SA-044: Cost–Benefit Analysis of Technology Improvement in Medium- and Heavy-Duty Fuel Cell Vehicles

Aymeric Rousseau, Argonne National Laboratory

Brief Summary of Project

This project aims to quantify the impact of fuel cell system improvements on energy consumption and economic viability of fuel cell electric vehicles (FCEVs). The project will (1) analyze fuel cell stack, hydrogen storage, and fuel cell system improvements in terms of their impacts on the cost of driving FCEVs and (2) evaluate whether current fuel cell and storage technology targets are sufficient to make FCEVs viable.

Project Scoring



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

Question 1: Approach to performing the work

This project was rated **2.8** for identifying and addressing barriers, project design, feasibility, and integration with other relevant efforts.

- This project has a solid, transparent approach to evaluate the DOE targets and is coordinated with a number of other projects across Argonne National Laboratory (ANL). The project leverages the Autonomie model, which has been used for similar evaluations in previous studies. The business-as-usual improvements are not clearly defined in the slides, but the concept very informatively demonstrates the impact of achieving the DOE targets. The project approach is described with ample clarity and focus. There are a few suggestions to improve the value of the results: (1) The project should include more insight for earlier years (e.g., 2020) rather than just focusing on 2030 and 2050. It is good to understand the near-term challenges and development pathway. (2) The comparison to diesel as the main baseline certainly makes sense, but there could be a stronger focus on FCEV comparisons to battery electric vehicles (BEVs) to highlight the applications in which fuel cells have a superior advantage, assuming a zero-emissions vehicle (ZEV) solution is required.

- The project approach is straightforward and well described. The use of existing modeling (Autonomie, systems analysis cost models, etc.) represents good leverage on past work and others' work.
- The model background and development is opaque. It was difficult to understand the value of the analysis. Many of the slides had acronyms spelled out on a single slide, far removed from the core results. The presentation of the results had too small of an axis, making it extremely difficult to differentiate the technologies and value of the effort.
- It is unclear whether the project approach is related to the barriers identified. The approach provides a process of analytical analysis and modeling when the barriers are related to a lack of performance and reliability data and a lack of real-world operational data.

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 description of objections in question-and-answer format is succinct and instructive. Consideration of multiple vehicle powertrains and vocations is useful and adds substantially to the project. The project work substantially aids in answering questions stated in the objectives and in furthering DOE goals.
- The results presented are very insightful and clearly demonstrate clear advantages for fuel cell electric trucks (FCETs). The project is encouraged to expand the results to include years prior to 2020 so that the audience can clearly understand the near-term challenges over the next decade. Understanding these challenges will help drive innovation. There are a few additional suggestions to maximize the value of the work:
    - The project should broaden the description of total cost of ownership (TCO) to include targets for fueling and maintenance costs, expanding beyond just the capital expenses of the trucks.
    - The research team could create a deeper dive, similar to slide 12, comparing only the ZEV technology choices (FCETs and BEVs), as diesel may not be the proper baseline in certain future markets that require a ZEV solution.
    - The principal investigator should clarify whether fueling time has been included and valued in some way. If fueling time is included and valued, it should be shown in this analysis separately, or if this analysis has not been conducted (related to overall TCO), it should be included.
- The accomplishments and progress provided establish the value of the DOE targets in areas of performance relative to truck performance.
- For starting in fiscal year 2019, this project has many results and provides meaningful conclusions. The plots could be presented in a more informative way to clarify the cost components that drive the purchase price over time. One could then see which DOE targets make the largest impact on vehicle price and may be the most important to attain.
- While some work was done to compare drivetrains, minimum information or assumptions were shared, which makes it difficult to evaluate progress and accomplishments.

Question 3: Collaboration and coordination

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

- This project collaborates mainly within ANL. However, the project team seems to have a diverse background in this medium-duty (MD) and heavy-duty (HD) vehicle modeling and is leveraging the Autonomie model and other projects that have a wider collaboration team that extends across DOE and various original equipment manufacturers (OEMs) and technology manufacturers.
- The collaborative nature of this project has been very good to date, considering the limited data available. However, deeper consideration of utilizing automotive fuel cell technology for MD and HD vehicles is encouraged. Based on the comments received to date, the bulk of the feedback received seems to come from Ballard Power Systems (Ballard). This serves as a good baseline, but Ballard will not be able to achieve the cost reductions compared to automotive stack technology due to high-volume production. OEMs such as Hyundai Motor Company, General Motors, and Toyota Motor Corporation are already

announcing and demonstrating the use of automotive stacks in MD and HD vehicles, which could significantly reduce the cost of the powertrain. Obviously, the durability is currently unproven, but the project team is urged to consider this when setting targets and reach out to additional stakeholders for additional feedback.
- There is good use and coordination of output from other models. Vetting of results with collaborators is not stated.
- It is unclear how the collaborators listed provided relevant information to address the barriers or the accomplishments, as the model results presented relate only to the DOE targets and "business as usual." It is inferred rather than explicit that the data contributed by the collaborators were used to establish the "business-as-usual" case. The investigators do not sufficiently establish the validity of the real-world data, if such were used in this "business-as-usual" case.
- Additional partners could have been included regarding conventional trucks and HD parts suppliers. This would provide more confidence in the effort in which some assumptions were missing.

Question 4: Relevance/potential impact

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

- MD and HD fuel cell applications are very relevant with the current market dynamics and recognition that other ZEV technologies may not be capable of meeting the commercial vehicle application needs. This project does a nice job of identifying how reaching DOE targets improve the competitiveness of FCETs in commercial applications.
- The impact and relevance of analyzing the potential of MD and HD FCETs cannot be understated. Vetting and adapting the targets is a worthwhile exercise, and the work to date is encouraging.
- The project has the potential to provide key insights in the further development and refinement of the DOE goals. The accomplishments provided suggest that achievement of the DOE targets will, in some cases, provide only muted benefits, while in other cases such achievement will provide substantial benefits. Such insight allows DOE to further evaluate the key performance indicators selected for project goals. As such, the project potential is substantial to the overall DOE Hydrogen and Fuel Cells Program (the Program).
- Studies of MD and HD fuel cell trucks are lacking. This project is relevant and is beneficial to both DOE and the technical/policy community.
- With the level of modeling and lack of transparency in the assumptions, it is difficult to judge the project impact. Perhaps with a different presentation approach, there would be better external uptake and motivation for technology investments or regulatory adjustment.

Question 5: Proposed future work

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

- The future work contemplates very relevant questions. The impacts of the proposed evaluations could have impacts similar to the accomplishments demonstrated in this work.
- The suggested expansion of TCO is excellent.
- Future work is clearly defined and described.
- The TCO work should be helpful in comparing the existing technology evaluations. More input on markets and impacts of drastically increasing emissions requirements will need to be taken into account. The most value would be in providing a transparent list of assumptions and clearly explaining how the final model iterations across technologies are clearly described, which would give credibility to the presented results.
- It will be very interesting to see which market analysis aspects of this project are highlighted in future work.

Project strengths:

- This project is very relevant. It is important for DOE to understand how to best set the technology performance and cost targets to improve FCEV adoption for commercial applications.
- The relevance of the project is greatly important, and the impressive modeling tools used for this study are robust. The capabilities of these tools continue to grow and expand.
- In-depth modeling is leveraging expertise from multiple programs. A wide range of results were presented comparing business as usual versus meeting DOE technical targets. Many elements, such as sizing and power, are of interest to industry; cost of components is also of interest to industry.
- The project has a clearly defined methodology. Results are succinctly and logically conveyed. The project examines a high number of cases (vehicles and powertrains) and compares them on numerous relevant parameters.
- The work has good potential for significant impact on the DOE Program. The analysis methods have strong precedence and are well substantiated with scientific methodology.

Project weaknesses:

- The analysis itself is sound. Resources could be more optimized with a stronger focus on key takeaways. With a bit more direction and focus, the impact of this project can be increased.
- The presentation of the results lacks a clear demonstration of the conclusions from the analysis. The graphs are difficult to decipher and provide a confusing display of the results. The presentation should explain the results in a more clear and succinct manner. The effect of the results is lost in the overwhelming amount of detail provided by the presenter.
- There is a lack of transparency of assumptions used for input. There is a lack of clarity in data presented and comparisons across technology options. The presentation was limited as to considerations of component sizing, power requirements, and ultimately how the different technologies, truck chassis, and components differ across scenarios.
- The cost projections for the hydrogen storage system in slide 8 seem too high. A listing of additional vehicle/analysis assumptions should be included in the backup slides.
- This project’s main weakness is the use of DOE targets without any evaluation of the specific targets that are most important to achieve for commercial vehicle applications.

Recommendations for additions/deletions to project scope:

- This project is well defined to evaluate FCET targets, and additional scope is already being evaluated by other projects within the DOE portfolio.
- Suggested additions include (1) pre-2030 targets (e.g., 2020, 2025, etc.), (2) a strong focus on total TCO comparison, (3) specific FCEV vs. BEV comparisons (not just a focus on the diesel baseline), and (4) more discussion on the value of fueling time (as part of TCO).
- The project team could better present the assumptions and results. There should be a clear comparison of TCO, including infrastructure assumptions and how that affects business operations for each of the vehicle classes. The most important aspect would be to benchmark assumptions compared to the state of the art, and to understand fully the future of advanced diesel engine development, when major markets are suggesting eliminating diesel in the coming decade or two.
- The project could consider a historical evaluation of the light-duty vehicle market and the data developed for the current deployment of light-duty vehicles.
- A TCO analysis (including fuel cost) should be conducted.

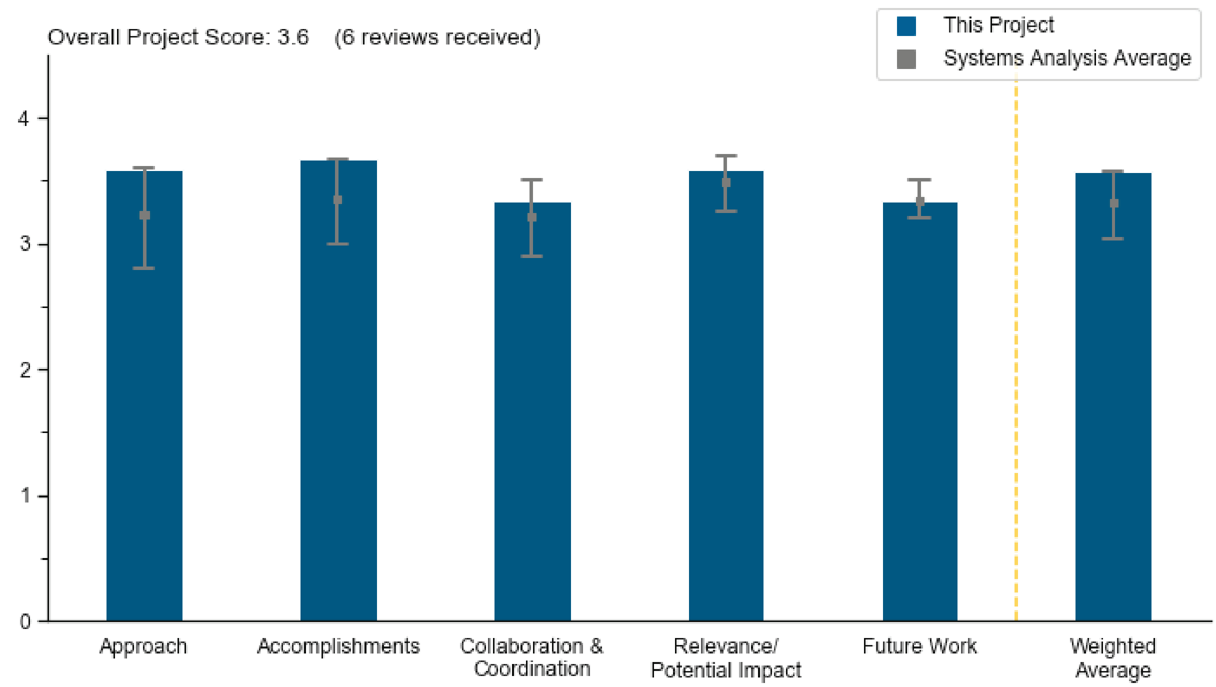
Project #SA-169: Market Segmentation Analysis of Medium- and Heavy-Duty Trucks with a Fuel Cell Emphasis

Chad Hunter, National Renewable Energy Laboratory

Brief Summary of Project

This project provides stakeholders a broad assessment of medium-duty (MD) and heavy-duty (HD) fuel cell vehicle market opportunities and helps guide future U.S. Department of Energy investments in the area. As part of this effort, systems analysis models that assess cost and market barriers to fuel cell vehicle adoption will be enhanced and expanded. The tools and models used in analysis include the Future Automotive Systems Technology Simulator (FASTSim) for vehicle optimization to obtain vehicle cost, fuel economy, and weight; and the Scenario Evaluation, Regionalization, and Analysis (SERA) model for stock modeling and modeling of direct costs, opportunity costs, and other value streams. The SERA model will be used to calculate total cost of ownership (TCO) for each vehicle class and vocation by region.

Project Scoring



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

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 relevant efforts.

- This project has an exceptional scope that leverages a vast wealth of tools and knowledge. The key focus on what matters most to stakeholders is apparent and explained very clearly: TCO. The project team is applauded for having a clear objective and minds open to feedback to ensure the greatest impact of this work.
- The use of existing models (SERA, FASTSim) is a strength. This kind of integrated analysis requires numerous assumptions. Therefore, the use of established values and existing analysis tools is a solid approach.

- This is a good approach that mixes modeling and real-world reports, including out-year targets that are peer reviewed by stakeholders and invested industry players.
- The project effectively uses a wide variety of analysis tools to assess fuel cell electric vehicle opportunities in the truck market.
- This project approach is well aligned with the objectives and with the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program targets.
- The approach is logical and addresses the need for information to compare alternative fuel choices in different market segments. As with all these types of comparisons, the results are highly dependent on what input parameters are chosen for the different technologies. The source of the values chosen for the individual technologies is not clear, in particular the 61% number for fuel cell peak efficiency on slide 6. The text suggests that the values are from DOE targets, but the peak fuel cell system efficiency shown for 2020 and the ultimate efficiency match neither DOE Fuel Cell Technologies Office (FCTO) targets for fuel cell system peak efficiency nor results from recent commercial vehicles. Testing on the Toyota Mirai at Argonne National Laboratory has shown a peak fuel cell system efficiency of 63.7% (with a fuel cell stack efficiency of 66%). The target fuel cell system efficiency for 2020 is 65%, with an ultimate of 70% in the 2016 FCTO Multi-Year Research, Development, and Demonstration Plan. At a minimum, the targets should all be set to the value for the Toyota Mirai, and it is suggested that the 2020 and ultimate targets be set at 65% (for the medium estimate).

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.

- These results are immediately useful to all interested stakeholders who have been craving an in-depth third-party analysis of TCO across many key powertrain types for a number of MD and HD vocations. The project team's consideration of all key factors is apparent and shows the team's willingness to solicit and act on feedback. The inclusion of cargo and dwell-time considerations is rarely seen in other analysis projects, and it is commendable. The analysis makes the value for fuel cells very clear, and the future results are much anticipated.
- The project's accomplishments are numerous. The team has considered multiple vehicle classes, multiple powertrains, and with low, medium, and high variation of key parameters. There is a nice compendium of scenarios. It is a good idea to benchmark against existing vehicles (e.g., from Nikola Motor Company [Nikola] and Hyundai Motor Company) and different drive-cycle analysis programs (e.g., Autonomie). The breakdown of the manufacturer's suggested retail price for each powertrain is nicely displayed.
- There is excellent quantitative discussion of TCO, including a broad spectrum of costs across other technologies. The uncertainties are critical with this level of first estimates for out-year technologies. The assumptions are clear and realistic. This was a very good presentation. There is a clear path to diesel parity.
- The investigators have established TCOs for a wide variety of vehicle technologies and operational variations. Sensitivity analysis points out the areas where research should focus to enable specific technologies. A preliminary example of an online version of the tool is already available.
- This project showed significant progress from last year, with positive response to feedback and input.
- The project has made good progress to date, providing preliminary analyses for long-haul trucks in 2018 and for Class 4 parcel delivery for 2019. The results have been benchmarked with fuel economy data from the industry and are in good agreement for the short-haul case. In the case of long haul, the FASTSim results for fuel economy are consistent with those from Autonomie but are substantially lower than the reported fuel economy of the Nikola One. The results showing the large payload opportunity costs for electric vehicles for both long-haul and short-haul Class 8 trucks and large dwell costs for Class 4 Parcel delivery are important. It is not clear how dwell-time costs are calculated in the TCO model or what is included in those costs. For example, it is not clear whether it is just the hourly charge for the time of charging and refueling, whether the time considered is strictly the refueling and recharging time, or whether additional time is built in to account for times when the recharging or refueling equipment is occupied by a different vehicle charging or refueling, etc. There is much uncertainty, and the error bars for the preliminary TCO for Class 8 short haul are large enough that the TCO of one fits within the error bars for

all vehicles for all scenarios. It is not clear why the uncertainty is so large in some cases or what can be done to decrease this uncertainty. Maybe the project should narrow the market segments more.

Question 3: Collaboration and coordination

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

- This is a good mix of stakeholders and interested parties. Robert Bosch LLC and Toyota Motor Corporation are major players in the emerging fuel cell truck space. Cummins knows a lot about the challenges of gaseous fuels, and the Center for Transportation and the Environment has run many projects.
- The project has drawn from numerous sources of data, which suggests a good degree of collaboration (of assumptions, if not verbal communication). A broad set of external peer reviewers was consulted to provide feedback to the team.
- The project team's desire for collaboration and feedback is apparent, and the stakeholder list is relevant and broad. It is recommended that the team do some additional outreach to the infrastructure providers to gain more insight into a large portion of the TCO: the fuel and infrastructure costs. Obtaining this feedback and including an associated infrastructure cost as part of the TCO is a natural expansion of this great work.
- The project appears to be reaching out to the community and collaborating. The list of external reviewers included was appropriate. An expanded list of fleet users in the collaborators and reviewers could be beneficial.
- The project utilizes a sufficient number of partners to ensure the credibility of the results and their relevance to the market.
- The investigators have vetted the model with industrial partners.

Question 4: Relevance/potential impact

This project was rated **3.6** for 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 impressive and will have great positive impact. The project team is strongly, strongly encouraged to publish a version of this model that any stakeholder can use. The value of this tool—to assist all interested stakeholders in better understanding the sensitivities, comparisons, and value of developing, investing, and operating alternative powertrain equipment— cannot be understated. This wealth of knowledge will ultimately lead to more demonstrations of the proper technology for each application (and fuel cell electric trucks are a strong candidate).
- The project will provide transparency to the relatively closed-off industry of fuel cell trucks. This will provide financial investment and some long-term certainty for large-scale hydrogen production, which can further reduce TCO.
- This project does a good job in demonstrating the impact of DOE targets on the overall market. The project provides a fair assessment while identifying the unique attributes of fuel cell trucks that contribute to the TCO.
- This type of analysis is vital to guiding future research efforts and to informing investors. Sensitivity analysis allows stakeholders to identify critical variables.
- Until recently, studies on fuel cell trucks had been lacking. This fills a substantial need.
- The project is relevant and useful for DOE and others to determine what the opportunities are for fuel cells in the HD/MD vehicle market. The large uncertainties and error bars limit the usefulness of the models.

Question 5: Proposed future work

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

- The future work toward buses and drayage will be important as California moves to 100% zero-emission buses in 2035, and transit infrastructure plans are due in 2020. The sooner this work is shared, the better. Drayage trucks are an important space in which to leverage existing capital costs, as there are 25,000 fuel cell forklifts already installed.
- This project will end in 2019; however, the potential future work proposed for a new project is interesting. Perhaps the team would consider a region-based assessment and align with H2@Scale analysis efforts to help establish some of the regional aspects.
- The project is almost complete, and the proposed future work is appropriate for completing the project.
- The researchers have laid out a clear plan for completing the project.
- The project did not receive a 4 for this metric simply because of the slight hesitation to publish a full TCO model. If the project team does this, the industry will be forever grateful.
- Making the SERA model available online is appreciated. The remaining classes of powertrains that are to be modeled are not clear.

Project strengths:

- These are all good things to see here: impactful relevance, the leveraging of DOE capabilities, a focus on useful results, and the desire to share a published model for everyone to use. The project team should carry on; the developments going forward are highly anticipated.
- The project provides a very good assessment of the truck market and helps industry participants prepare for the likely market segments. This work also demonstrates the need for more aggressive targets in TCO to make any alternative to diesel competitive (without incentives).
- This project's effort is extremely quantitative and transparent in its various assumptions. The comparison to other fuels and technologies allows for a clear comparison. Many aspects have been considered, and the work is very thoughtful.
- The project's strengths include its good use of excellent modeling tools, its good collaboration with industrial entities, and its clear reporting of ownership costs for technologies and operational variables.
- This is a well-described and clearly executed project. Drawing upon the vehicle and other assumptions from other models and leveraging existing models are great strengths.
- The project's strengths include its ability to compare results across vehicle platforms.

Project weaknesses:

- The project's weaknesses include its slight hesitation to publish the final TCO model. The project team should not think about it any longer and should just do it. The project team is also encouraged to reach out to stakeholders so that they can share their thoughts on the value of this project. It seems likely that all of them will strongly encourage the team to find a path forward to publishing and will be willing to help in any way they can.
- The project would benefit from real-world performance data, but this cannot be helped until more real-world data is available.
- The target fuel cell costs for trucks appear to be based on the cost targets for light-duty vehicles. This is not realistic. Using more realistic targets will increase the cost of fuel cell trucks even further above the cost of diesel trucks. The battery cost of $145/kW seems too low. This may mistakenly be the cell cost, when it should be the battery pack cost.
- The project results are reasonably well presented but are still a bit complicated. There is still room for improvement in communication. The team seems not to have reached its full potential for communicating the results.
- It would be nice if parts of this work could be open-source, or if a user tool could be provided for organizations that are considering expanding or implementing hydrogen infrastructure and equipment for the first time.

- There are large uncertainties for many of the TCO parameters. The project team is not using more realistic models for how trucks are bought, used, and resold in a secondary market.

Recommendations for additions/deletions to project scope:

- A few natural progressions would be (1) to include more of the infrastructure piece of the puzzle (i.e., fuel cost, infrastructure cost, scalability of different fuels, etc.); (2) to continue to include more vehicle types and vocations; and (3) to publish the model and continue improving it based on stakeholder feedback.
- The project team should work closely with Nikola and others to obtain data. The team should also examine economics as a function of volume- and weight-limited operations. The weight-limited case includes 30% volume-limited operation. The full range of operations should be examined, from 0% weight-limited to 100% weight-limited.
- The development of an online tool is a good focus; however, the team should also consider a simple reference with key data and suggestions for future researchers and industry strategists, with references for trustworthy data.
- It would be good if, where possible, some aspects of the model could be released for external use, as well as inputs of individual assumptions or expected cost targets.
- For fleet vehicles, taking a closer look at the cost of infrastructure based on fleet size could be beneficial.

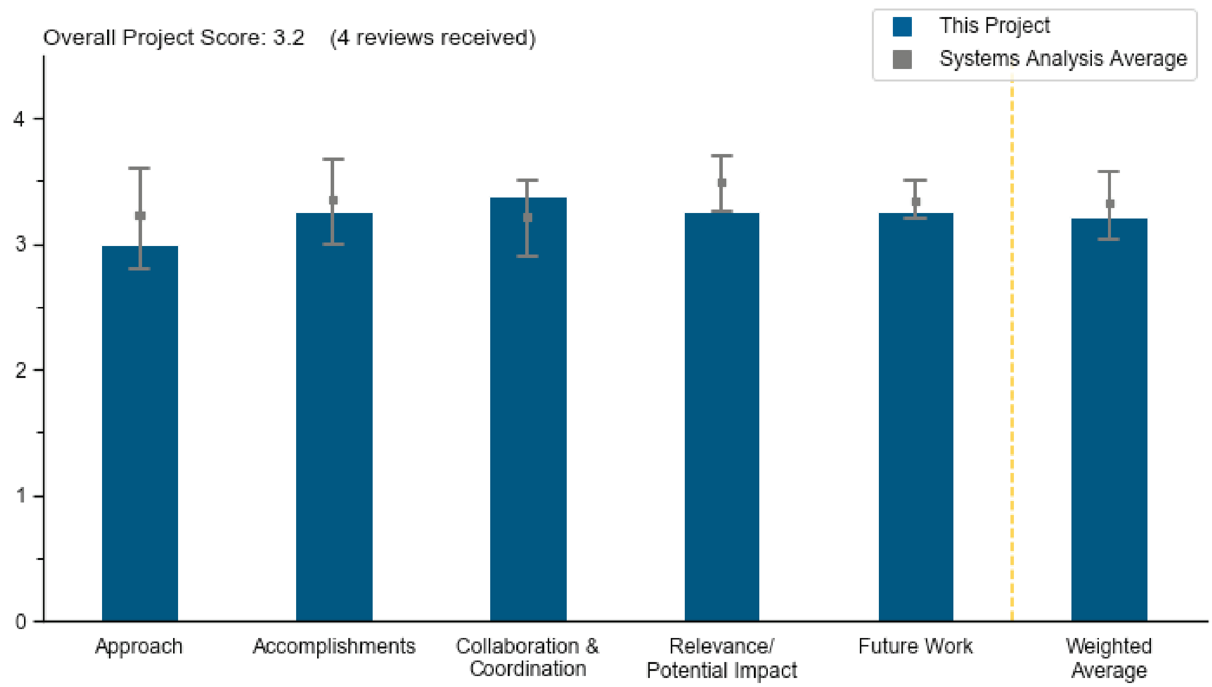
Project #SA-170: Analysis of Cost Impacts of Integrating Advanced Onboard Storage Systems with Hydrogen Delivery

Amgad Elgowainy, Argonne National Laboratory

Brief Summary of Project

This project seeks to evaluate the impact of onboard hydrogen storage systems on delivery and refueling costs. Argonne National Laboratory, in collaboration with the U.S. DRIVE Partnership: Hydrogen Interface Taskforce, Lawrence Livermore National Laboratory, and Energy Technology Analysis, is addressing inconsistent data, assumptions, and guidelines by developing new delivery and refueling pathways in the Hydrogen Delivery Scenario Analysis Model (HDSAM) for onboard systems. By improving understanding regarding refueling pathways for onboard hydrogen storage and providing better models and tools to better evaluate relevant sustainability impacts, the project team aims to accelerate development and deployment of cost-effective refueling pathways.

Project Scoring



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

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 relevant efforts.

- The approach is solid and well thought out. The presenter identified limitations to the approach, such as the boundaries of the system, and included some of these in future work (e.g., incorporating upstream supply chain aspects). The only additional item to potentially consider would be the impact on the vehicle cost that the advanced onboard storage systems would incur. The presenter noted that this was important and that there are limited data available, but if a feasibility or scoping-level cost estimate could be completed to ensure the vehicle storage cost would not dramatically increase, that would be helpful in understanding whether the refueling station changes were worth studying. Perhaps that aspect justifies further funding, as it would be very interesting to see whether both the refueling station cost and onboard storage equipment cost could be reduced simultaneously.

- The project approach is very effective in using existing U.S. Department of Energy tools to evaluate the future barrier between future onboard storage technologies and infrastructure.
- This remains focused on one piece of the puzzle related to bringing down the cost of hydrogen fuel and improving station reliability. This is certainly useful analysis, and the project could benefit from a broader consideration of the supply chain to assess the key challenges that need to be addressed. Examples include (1) upstream supply and distribution (local vs. centralized production, cost of liquefaction, hydrogen delivery options and costs, etc.); and (2) onboard vehicle storage implications (new technology development required, cost, storage durability, storage volumetric and gravimetric density, etc.). Not every aspect needs to be studied in depth, but focusing on just one section of the supply chain makes it difficult to understand the value of completely switching to new technologies. This insight would be very useful to the industry. It appears that similar comments have been made in the past but have not yet been reflected in the project scope.
- The approach to analyzing the impact of alternative vehicle onboard storage approaches is properly developed and applied. The lack of analysis of vehicle cost impact limits the value of the analysis. It is not clear how the work addresses the barrier of "stove-piped/siloed analytical capability" noted in the presentation.

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.

- In the past year, the project has made significant progress in determining the contribution to refueling cost for various on onboard storage technologies. The refueling cost results are helpful in understanding the potential opportunities or barriers for certain onboard storage technologies.
- This project has made strong progress since the 2018 Annual Merit Review, as demonstrated by the accomplishments presented and the journal paper developed.
- Good progress has been made, and the key takeaways are clear. However, the results remain focused on one aspect of the overall project scope. For this project to maximize impact, a broader analysis of the supply chain is strongly encouraged. The presenter articulates the key point that delivering liquid hydrogen (LH_2) to the station is beneficial for essentially every station pathway. If this is the case, it seems odd that this is not done for every station today. Analysis of LH_2 may unlock this riddle and help key stakeholders better understand whether LH_2 is indeed worthy of their investment. A key question raised when discussing hydrogen delivery is the most efficient and cost-effective method of delivering the gas based on the distance and the scale required. The project team is encouraged to consider a comparison of different delivery technologies based on both delivery distance and amount of hydrogen delivery required.
- The project has identified avenues to reduce the cost of dispensed hydrogen, which is a key barrier to fuel cell electric vehicle adoption. However, additional work is needed to understand the impact on total cost of ownership. The project has largely met the analytical objectives established for the project.

Question 3: Collaboration and coordination

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

- The team has done a great job coordinating with multiple stakeholders on approach, data, methods, and validation.
- Individual team members and contributions are described in the presentation and appear to represent the primary areas relevant to the work.
- It appears that reasonable feedback from within the national laboratory network and industry has been solicited. However, the results feel somewhat academic in nature, even though the key intended audience is industry (to aid station design decisions in order to reduce cost). The team should reach out to more industry stakeholders from both the infrastructure and original equipment manufacturer perspectives to clearly understand what challenges they face and what value they would like to see from this work.

- The project has a high level of collaboration with various national laboratories and technology teams, although the collaboration could be improved by including infrastructure companies.

Question 4: Relevance/potential impact

This project was rated **3.3** for 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 extremely relevant to the DOE Hydrogen and Fuel Cells Program (the Program) since the future onboard storage technologies must be compatible with the infrastructure. The results of the analysis could assist DOE in shaping portfolios for both onboard storage technologies and infrastructure. Also, the project outcome can help in establishing research targets for both onboard storage technologies and infrastructure.
- The current limited scope is very relevant to the needs of the hydrogen supply chain, and the project's impact could be greatly improved by expanding the scope beyond the study of a few station technologies. Without significant scope changes over the next year, the value of these results may be lost, when instead they could play an integral role in a very useful supply chain analysis.
- This project is relevant, as refueling station costs are quite high today. However, the bulk of the refueling station cost benefits seem to come from economies of scale and technology maturation over time, as demonstrated by the cost estimates going from $6–$8/kg (current) to $1.94/kg for conventional 700 bar gaseous hydrogen refueling. However, it should be noted that, while reducing the dispensing costs by ~$0.5–$0.75/kg may not be substantial on an absolute basis, it does indicate a significant (~30%) improvement. One thing that was not specifically pointed out was the different capital and operating expense splits of the technologies. Lower upfront investment of the metal hydride and sorbent technologies may reduce the risk to station developers and owners, which could lead to faster station development. This could be an interesting aspect to explore further.
- Cost reduction for hydrogen compression, storage, and transport is crucial to reaching cost targets for dispensed hydrogen, so the work aligns strongly with Program goals. However, the lack of the cost impact of the onboard storage systems limits the ability to draw conclusions from this phase of the work.

Question 5: Proposed future work

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

- The proposed future work should be very interesting, particularly the system boundary expansion and the life-cycle emissions analysis.
- The proposed future work seems very good and appears to address reviewers' comments from the 2018 Annual Merit Review.
- The proposed future work is relevant but should also include vehicle cost impact and compare to LH_2 pathways. Also needed are the technology readiness levels of the relevant components, the timing of potential deployment, and the ability to integrate the components into the then-existing supply and delivery chain.
- The future work is good but could be improved by using the analysis for determining the optimal onboard storage operating conditions for infrastructure cost and compatibility. The previous work also assumes dedicated hydrogen stations for each technology rather than evaluating compatibility of multiple onboard storage concepts at the same station. In addition, the assumptions from the previous analysis could be explored based on a sensitivity assessment.

Project strengths:

- The strength of this project is the team involved in performing this analysis. The principal investigator, in particular, has extensive history and technical expertise in the area of onboard storage technologies and infrastructure. The project results are explained effectively, and assumptions are documented.
- This project evaluates early-stage research and development and does a nice job of systematically evaluating each technology. A variety of technologies are evaluated, and the results are presented in easy-to-understand ways.
- The project provides detailed analytics not previously available on technologies that may improve the dispensed cost of hydrogen in the time horizon beyond five years.
- Strengths include thorough analysis capability and a desire to reduce fuel costs while improving station reliability. The project is encouraged to leverage these strengths and goals on future expanded work.

Project weaknesses:

- The project weakness is the lack of infrastructure company involvement to validate the results. Also, there are some inconsistencies that need to be explained; for example, the hydrogen refueling price on slide 3 does not align with the price on slide 12. The cryo-pump cost should be further analyzed, especially for the different hydrogen delivery pressures (700 bar vs. 350 bar cryo-compressed).
- The defined limited scope limits the positive impact of this project, and the response to previous review comments demonstrates that stakeholder feedback has not been fully captured. The proposed future work attempts to address these comments, and hopefully there will be significant improvements going forward.
- The system boundaries could be defined for more appropriate system-level costs. The future work looks to improve upon this, but the impact on the vehicle cost could be important to consider as well.
- Weaknesses include the vehicle cost impact's not being included, as well as a lack of discussion or analysis of deployment timeline and integration in the existing supply, delivery, and dispensing chain.

Recommendations for additions/deletions to project scope:

- The project should consider the following additions: (1) broader analysis of upstream supply chain considerations, (2) broader analysis for the onboard vehicle storage implications, (3) assessment of scale and delivery distance implications, and (4) increased industry engagement and feedback.
- The project should add the analysis for determining the optimal onboard storage operating conditions for infrastructure cost and compatibility. The previous work also assumes dedicated hydrogen stations for each technology rather than evaluating compatibility of multiple onboard storage concepts at the same station. In addition, the assumptions from the previous analysis could be explored based on a sensitivity assessment.
- Additions to scope could be to assess any non-cost-related factors that these technologies could affect. For example, these different storage technologies could affect refueling time, reliability, consumer perception/acceptance, noise levels, footprint, etc. These factors are clearly out of scope but could accelerate the adoption of hydrogen refueling station technology.

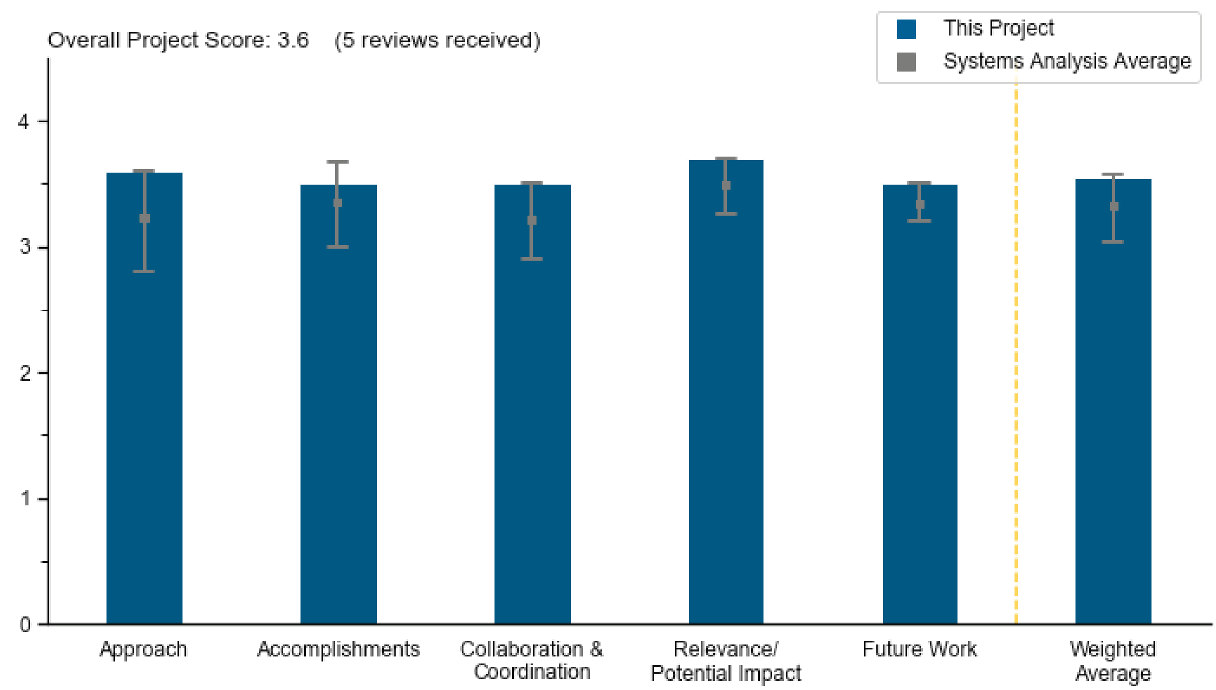
Project #SA-171: H2@Scale Analysis

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 power sector analyses and tools.

Project Scoring



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

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 relevant efforts.

- This is a complex project, and incorporation of a large team using a variety of already existing models is a good approach. Definition of terms, the breakdown into technical and market potentials, and examination of each individual market's supply and demand are all good elements of the approach.
- The approach is very well described and leads naturally into the presentation. The approach is comprehensive and simple, indicating that the researchers have a strong mastery of the subject.
- The supply–demand equilibrium framework is a solid approach for the work. Folding quantitative demand elasticity into the analysis, where available, would improve the strength of the analysis.
- Utilizing a suite of existing models to accomplish new analyses is an intelligent structure for this work. However, one of the barriers identified was the development of new tools to fill in gaps in analysis capabilities. It is not clear what new tools or models are really being developed or, to be fair, whether new tools even really need to be. The project may need to re-evaluate the premise that new tools/models are

needed; perhaps it is only that existing tools need to be leveraged in new ways. In addition, while there was mention of a consumer choice model for forecasting the light-duty vehicle market demand, it was unclear whether a similar model or consideration was implemented for the heavy-duty demand. This may have had an impact on results, as the hydrogen demand for heavy-duty applications seemed small, especially compared to light-duty applications and taking into consideration the much larger per-vehicle hydrogen use for heavy-duty. The modeled hydrogen demand for heavy-duty vehicles also seemed much less sensitive to the evaluation scenario, which seems to indicate it was more of an exogenous or rule-of-thumb assumption. Finally, it is unclear how much the consideration of demand from metals markets truly affects the results, since it seems masked by assumptions about renewables in the corresponding scenario descriptions. Also, given that the metals market is assumed to have some price elasticity in some of the cases, it seems like there could be the same assumption investigated for other markets. In fact, this might help define a path for greater adoption, if consumer price elasticity is assumed to be greater at first and then decrease over time.

- The project's approach and vision of hydrogen as an energy carrier and integrator across multiple industry sectors is bold and broad.
    - However, given the current and projected U.S. energy export levels, the national energy security justification for hydrogen is less compelling. The primary driver for investors and consumers is the potential environmental benefit of hydrogen over existing energy systems. As such, the project needs to quantify and incorporate the life-cycle greenhouse gas (GHG) benefit for the various hydrogen sources or industry sectors and use it as an additional constraint parameter in market growth potential.
    - For the most part, the framework approach used to estimate future economic potential is reasonable. However, the project should modify or expand the national scenarios to include more realistic and likely ones. Given that more than 95% of current hydrogen sources come from non-renewable sources, there should be a plausible national scenario in which decarbonization of existing hydrogen sources, such as via carbon capture and storage (CCS), is seriously considered.
    - Another suggestion is to add a national "high natural gas resource" scenario, in light of the current boom of U.S. liquefied natural gas export investments based on long-term, abundant, low-cost natural gas supply.

Question 2: Accomplishments and progress

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

- The project has shown good progress over this performance year, completing novel national supply and demand estimates for all key demand and supply sources. Several scenarios on key market variables were also completed. These analyses are a necessary foundation for assessing the potential value of H2@Scale to the energy, industrial, and transportation sectors. Some approach to valuation of GHG emission reductions should be added to the analysis without any endorsement of a particular policy framework. Perhaps the low natural gas resource (or a high natural gas price) scenario is a proxy for this in some respects. Carbon regulation should be part of the analysis in states that have adopted such regulation.
- The accomplishments have significant impact on the overall project and DOE goals. Additionally, the project presentation does an excellent job of conveying the information. The information provided is comprehensive, and the presentation enables the reader to easily identify the key conclusion of the accomplishment.
- Developing supply and demand curves for each market is very good. The explanation of the results and formatting of graphical results are very clear.
- The preliminary supply–demand curves and the economic potential results look interesting. Given that the project is only few months old, this is a good start.
- The completion of the economic potential evaluation was a major accomplishment for this past year. A recommended addition to that would be to compare that potential to known benchmarks (such as incumbent conventional fuel market sizes) to help provide context to those who will eventually make decisions based on these results. This analysis should look at both the magnitude of the calculated potential and the rate of growth. If possible, comparison to other advanced or new technologies could also be helpful.

Question 3: Collaboration and coordination

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

- The collaboration effort, including the stakeholder engagement in framing and launching H2@Scale over the last two years, is excellent.
- The project is highly collaborative and is coordinating with researchers and market analysts in each relevant technology and market.
- The project boasts a robust group of collaborators and has clearly benefited from the input of this team.
- Multiple laboratories and industry stakeholders are represented. Noting in the analysis where industry vetting was conducted would strengthen the work.
- The collaboration between national laboratories, with different modeling and analysis capabilities, is exemplary. In addition, the outside collaborators appear to be a fairly balanced mix of fuel providers and policymakers. However, it does seem that there might be room to add more collaboration with representatives of the end-use industries assessed in this study. There also does not seem to be much representation from the renewable energy and electric utility industries, which seemingly would be instrumental to this work.

Question 4: Relevance/potential impact

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

- Quantification of potential growth in hydrogen demand that might be enabled by the H2@Scale initiative has been lacking and is necessary to build industry and government support for the concept. This work makes an important contribution to addressing that gap and applies an equilibrium demand approach not used previously in this sector.
- Studies that are looking at the full-scale potential of hydrogen, and attempting to complete the analysis with a holistic vision, are currently some of the most necessary information resources for decision makers. The proposed future work on regionalizing the results will also be particularly impactful in this regard. In addition, the team may want to consider hyper-detailed analyses for smaller focus areas, such as individual metro areas of interest—or ideally, a combination of select metro, urban, suburban, and rural areas. Exploration of potential impacts of the broader H2@Scale vision on these more localized communities would be very insightful work right now.
- This project goes to the core of H2@Scale, as it will assess whether the entire concept is economically feasible.
- The project is very relevant to the stated objectives of the H2@Scale project.
- The broader H2@Scale effort is indeed very relevant with respect to promoting hydrogen use in the United States, per Hydrogen and Fuel Cells Program objectives. However, the project does not adequately address a few critical questions on relevance. It would be good to know whether favorable market size and resource availability alone are enough to advance the hydrogen economy—in other words, whether new hydrogen sources will be commercialized without demonstrating meaningful environmental or GHG benefits over existing or fossil fuel sources.

Question 5: Proposed future work

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

- Each of the three pillars of future work is merited: expanded economic potential estimates, transition analysis, and development of illustrative business cases. The future work all feeds logically into assisting DOE with research and development target setting.
- The proposed future work is consistent with the project objectives and very much aligned with the next logical step of the scientific investigation.
- The proposed future work on estimating hydrogen transport and storage costs is the next logical step.
- The proposed future work is a logical next step for the analysis. Additional empirical validation of demand elasticity would be useful.
- The proposed future tasks on transportation costs and regionalization of results are great additions and will be valuable for supporting ongoing efforts to expand support for hydrogen and fuel cell vehicles. In addition, it would be good to look at the price elasticity question. That is, early consumers may have some price elasticity, whether real or "virtual" due to policies and subsidies, that could increase the near-term market size and have lasting effects in the long term. However, as the technology matures and becomes more mainstream, the broader audience will have less elasticity in its purchase choices and should be modeled accordingly. Useful insight could be provided through an analysis of the potential benefit of a phased or transitioning deployment target path compared to one that holds ultimate economic equilibrium as the metric at all points in time.

Project strengths:

- The project's strengths are its breadth of analysis, its holistic approach, and its ability to incorporate existing capabilities at many national laboratories to develop large-scale and insightful research results in a relatively short time.
- The project research activities are well aligned with industry needs and facilitate a strong basis for industry to consider in the development of a comprehensive national hydrogen infrastructure. The future work in evaluation of regional markets is also a strength.
- The work addresses a critical knowledge gap by quantifying the long-term demand potential for hydrogen in the transportation, energy, and industrial sectors.
- The project's greatest strength is the success in integrating so many elements of past National Renewable Energy Laboratory analysis into a comprehensive assessment of the supply and demand curves.
- The project is ambitious and well thought out, with broad scope and reach.

Project weaknesses:

- Weaknesses are the limited validation of demand elasticities and the absence of timelines for demand growth.
- Communication of the results is a weakness. The researchers do not clearly indicate the one or two key aspects of the results in the accomplishments. This forces the user to spend extra time considering the results. While the researchers wish to refrain from commenting on policy (and this analysis effort is very close to the policy discussion), the communication of the results would still benefit from some summary notes that indicate perhaps already obvious aspects of the results.
- The project's weakest point is that the results seem to rest heavily on low-temperature electrolysis's reaching $100/kW. This is a very challenging price point to achieve.
- The project's weakness is likely that the devil is always in the details. As noted in the presentation, some of the more global assumptions may not be appropriate or correct when the analysis is carried out on a more focused region. Thus, the regionalization (and hopefully even more finely granular) analyses will be an important step toward ensuring the results of this analysis are valid and useful.
- The project lacks some sort of a metric to gauge the environmental or life-cycle GHG benefits of the various sources or applications, a critical driver for a hydrogen economy. Also, the H2@Scale effort does not differentiate between technology readiness levels of the various hydrogen sources or industry sectors

under consideration, e.g., steam methane reforming vs. electrolysis, or established markets (refineries, ammonia, iron, etc.) vs. new ones such as synthetic fuels made from CO_2.

Recommendations for additions/deletions to project scope:

- The project team should consider adding two national scenarios: a blue hydrogen scenario that envisions steam methane reforming with CCS, and a likely national scenario of "high natural gas resource." The team should also consider adding a market constraint based on quantified environmental benefits of the various sources or industries. Developing a technology roadmap to meet the research and development targets would be very helpful to current and future researchers.
- The regionalization effort is very good and should go further to look into smaller areas, such as cities and towns, and possibly to expand the scope of applications that might be considered at this level of detail (distinctions between privately owned light-duty vehicles and corporate, rideshare, and ride-hailing fleets, microgrid potential, localized hydrogen energy storage potential, etc.).
- No additions to or deletions from the project scope are recommended.

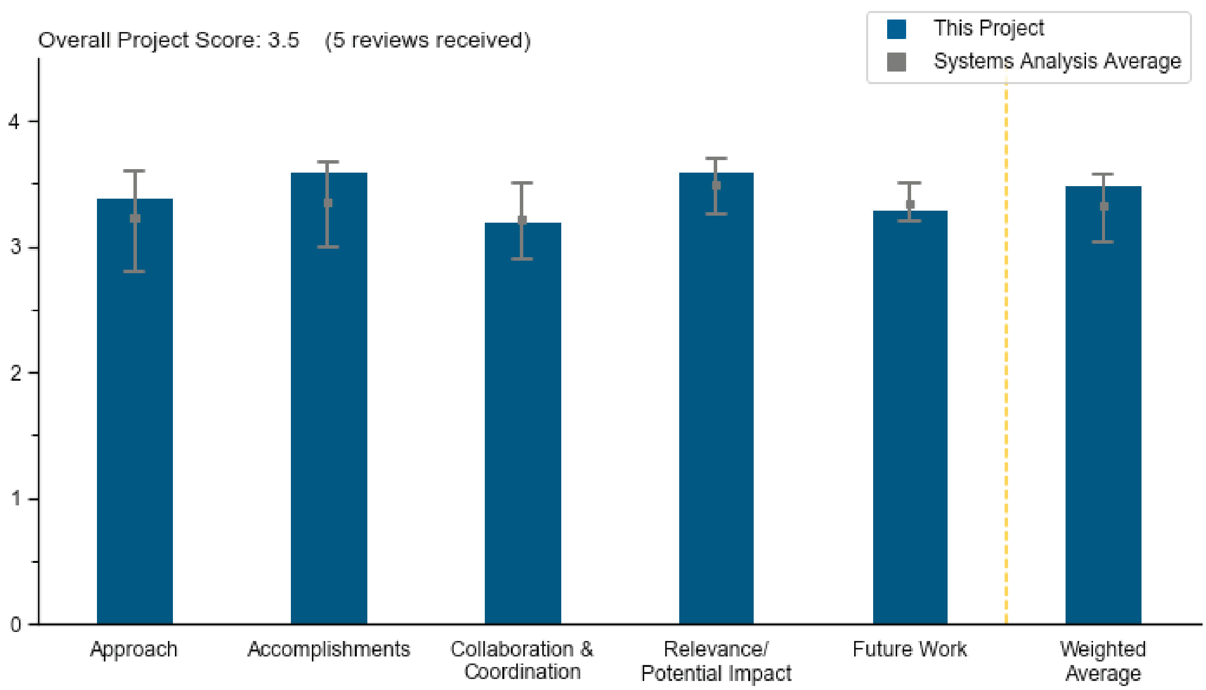
Project #SA-172: Hydrogen Demand Analysis for H2@Scale

Amgad Elgowainy, Argonne National Laboratory

Brief Summary of Project

Hydrogen from clean energy sources can enable renewable energy penetration and serve energy sectors beyond transportation. This project evaluates potential growth in hydrogen demand for existing and emerging applications. Performance and energy market data are collected for both current and potential future markets, including fuel cell electric vehicles, petroleum refining, ammonia production, electrofuels (synfuels or e-fuels), steel refining, biofuels production, and injection into natural gas pipelines. A final report will document all data sources, the modeling approach, and the analysis.

Project Scoring



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

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 relevant efforts.

- The approach of this project accurately addresses the barriers stated and is well integrated into the remaining H2@Scale program.
- The project breaks down demand into key sectors (refineries, ammonia, etc.) and clearly labels the source of data for each. The diagrams of source data are particularly useful and effective.
- The work covers several important sources of current and future demand for hydrogen. The analytical approach for estimating hydrogen demand for refining and ammonia is well developed and makes good use of underlying data to correlate hydrogen demand. The demand analysis for electrofuels (e-fuels) and steel appears to be gross potential, and details for other sources are not contained within the Annual Merit Review presentation. It is assumed that the full report will provide more detail on these areas.
- It seems that a good deal of focus on the hydrogen consumed to support fossil fuel reforming was driven by the U.S. Energy Information Administration's (EIA's) *Energy Outlook*. While this is a respected and

consistent methodology, it would also be insightful to look at cases that differ significantly from this fuel mix. This could be especially insightful for regional analysis, where localized policies and programs may be pushing for energy and fuel demands that would not match EIA projections. In particular, as presented, the work seems almost to assume that fossil fuel demand for transportation would not be undercut by electricity and hydrogen demand as transportation fuels, which may not comport with expectations in all areas of the United States. In addition, for some of the analyses (particularly the e-fuels analysis), it seemed as though estimates for demand were driven primarily by current sources of supply. If true, this seems like it would be misleading, or at least too circular in its logic.
- The approach used to estimate the hydrogen demand from oil refineries, ammonia, and steel plants is laid out reasonably. However, the assumptions in the demand estimation for the e-fuels are unclear. For the three existing markets, the study does not seem to make a distinction as to whether the source of hydrogen is renewable, which is nice to know but not necessary for this analysis. However, for e-fuels, hydrocarbon combustion products CO_2 and water are converted back to hydrocarbon products; if the process is to make sense, there needs to be a clear statement that the input energy (electricity and/or heat) can only be renewable. Otherwise, the conversion process will result in more emissions to the atmosphere. Note that the e-fuels concept is inherently a reverse combustion process. Therefore, the market demand estimates should reflect this reality.

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 provides a comprehensive summary of the current hydrogen demands. This demand summary establishes a strong foundation for assessment of overall market growth. The interaction of this project with other H2@Scale analysis efforts is very well established and demonstrates a very positive synergy of the overall H2@Scale initiative.
- The project team has substantially completed the demand analysis for the applications in scope. This rigorous analysis of potential hydrogen demand makes an important addition to the H2@Scale foundations.
- The team did an excellent job in using historical data to estimate future hydrogen demand for the three existing markets. Obviously, there are more uncertainties for those early or non-existent markets, such as e-fuels, which needs to be reflected in the final results.
- The results are logically and clearly explained. The title of slide 11 states that refinery hydrogen demand has increased significantly. While numerically true, this may be due to recovery from the ~2008 recession. Thus, graphing hydrogen demand prior to 2009 may clarify whether demand is just returning to previous values or is indeed exorbitantly rising. The data source for future trends would benefit from further explanation. For instance, the graphs on slides 12 and 15 are suspiciously flat or evenly increasing. This suggests gross assumptions about future demand predictions. While no one can foretell the future, additional commentary on the confidence level of these underpinning assumptions would be useful.
- The major weight of the accomplishments in the past year seems to have centered on fossil fuel reforming. While this was a good and necessary step, it seems a bit unclear why this received so much attention, especially given the plethora of established demand forecasts for gasoline, diesel, and so forth that could easily be translated into hydrogen demand with relatively good accuracy. Some of the other markets seem to be greater unknowns, especially given that the analyses are assuming there would be some fundamental change to these industries' operations if they were to have a closer tie to a renewable hydrogen resource. It seems the effort could have been more focused on larger unknowns rather than the incumbent, and much more well-known, industry.

Question 3: Collaboration and coordination

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

- The team is collaborating with relevant and experienced groups. No holes in the team are perceived. The presentation would be improved by briefly describing each collaborator's contributions.
- This is a very strong cross-laboratory team. Industry partners are noted in general but not identified, and greater clarity on input received from industry would improve the work.
- It looks like the team has collaboration with key national laboratories and unnamed industry partners. It would be good to disclose what role each collaborator has played in the study.
- Internal collaboration is good between national laboratories, but it does seem that there is a dearth of external collaboration. Since the project is looking to assess hydrogen demand across many different real-world and existing industries, it seems like a more natural collaboration environment would be one that is more heavily focused on industry partners. The project should work to include more industry collaboration as it progresses.
- This project will benefit from collaboration with more industry participants. Workshop activities around the initial results could offer opportunities to engage many perspectives and add nuances to the analysis.

Question 4: Relevance/potential impact

This project was rated **3.6** for 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 has significant potential impact on the Hydrogen and Fuel Cells Program goals and the strategies of private industry. National-scale strategies require this type of in-depth, comprehensive analysis to develop the vision. This vision is further refined as industry stakeholders identify synergies.
- This is a highly useful and informative analysis that synthesizes multiple unwieldy sets of data. Understanding demand and the corresponding hydrogen prices necessary to fill that demand is a very relevant and useful task.
- Quantification of potential growth in hydrogen demand that the H2@Scale initiative might enable has been lacking. This work makes an important contribution to addressing that gap.
- There is no question that this work is very relevant to DOE objectives and is obviously a significant input into the H2@Scale effort.
- The overall goals of the project have the potential to provide significant impact. However, given the noted focus on analysis of fossil-fuel-based hydrogen demand, which is arguably the most easily characterized, it seems that the project in the past year did not provide as much impact as it potentially could. Future work in the project should focus more on the areas where more new knowledge and insight will be generated.

Question 5: Proposed future work

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

- The proposed future work does show signs of moving toward the areas of potentially greater need and greater impact. The work proposed would be breaking new ground in analysis of potential applications of hydrogen. In addition, the regionalization would be a very powerful addition to this work, as it is for the overarching H2@Scale work.
- The proposed future work on environmental life-cycle analysis (LCA) on e-fuels and steel refining processes is excellent. The team should consider the potential demand for low-cost renewable hydrogen blending into existing natural gas pipelines. This could potentially be the "low-hanging fruit" in the decarbonization effort of U.S. energy systems.
- The proposed future work on additional sources of demand ties well into the current work. Other noted future work (LCA, supply chain) is relevant to the H2@Scale initiative, but it is somewhat unclear how this work relates to the current analysis of demand.

- Regional analysis is of interest for future work. The price of hydrogen needs to be considered as part of the regional analysis. It is not just matching supply with demand but rather matching supply at needed price with demand.
- Future work should not focus yet on LCA; it is too early in the development to create detailed LCA of the process. Pathways such as e-fuels are not clearly advantageous and should be validated with industry through workshops before starting an LCA. Additional markets and "advanced" storage and distribution methods and technologies should be considered only at the national level and not in detail for the next phase of the project. Future work should focus on regional aspects of the analysis. The analysis should consider a detailed assessment of the interaction of regions. There are several questions to consider:
    - How much hydrogen moves from the southern or eastern regions into the western region
    - Whether the fertilizer used in California's Central Valley or Oregon's and Washington's eastern fields is sourced from the United States or represents imported "hydrogen" demand that might benefit from the development of significant hydrogen generation capacity in the western region
    - Whether foods and fuels compete or complement when hydrogen energy is more ubiquitous
    - Whether existing regional production (Midwest), substantial wind power sources (Midwest), and hydrogen energy use (California) utilize an existing supply chain system whereby hydrogen already moves from east to west

Project strengths:

- This project does a very good job developing the underlying macroeconomics of hydrogen demand. This enables a deep conversation about the macroeconomic strategy at the national and regional levels. Additionally, the work is credible and well presented, making it easy to access and easy to find key points, and it reduces the likelihood of mistakes in general assumptions formed by the macroeconomic picture. The researchers state the assumptions clearly.
- The principal investigator appears to be executing the project in a very clear, supported, and professional manner. The project appears to draw in the necessary data sets (from collaborators and government databases). This project would fall apart without relevant data, and the team appears to have successfully gathered those data.
- Strengths include the rigorous analysis of the hydrogen demand drivers in refining and ammonia production.
- The strength of the project is the use of historical consumption data for the big existing hydrogen markets.
- The project's greatest strength is the detail exhibited in considering the hydrogen demand pathways. The level of detail shown in the fossil fuel refining and ammonia production analyses needs to be replicated for all applications.

Project weaknesses:

- The hydrogen supply curve should be tabulated and summarized so that the relative hydrogen supplies from each market can be compared. (This is a suggestion, rather than a true weakness.)
- The investigators would be well served by a diverse group of industry participants. While energy providers may be best positioned to advise on the data and data analysis and economists are good as peer reviewers, the team must consider others. Original equipment manufacturers, traditional hydrogen users, and new hydrogen energy users should be allowed to provide perspective to the overall project.
- The weaknesses are the lack of industry collaboration and the focus to date on applications that may not have presented as large a set of unknowns. Analysis of the remaining applications that are more future-oriented is likely to provide the greater impact.
- A cost-competitiveness assessment is lacking for e-fuels and hydrogen for steelmaking (these seem to be technical potential analyses only). The summary table did not present specifics on other sources of demand (vehicles, methane, natural gas replacement), so that portion of the work cannot be evaluated.
- One weakness of the project may be the lack of clear distinction of the source of energy/hydrogen for the assumed market demand, especially for the e-fuels market.

Recommendations for additions/deletions to project scope:

- The team should consider carefully the e-fuel concept. It is speculative and not well validated. It is very difficult to comment on e-fuels and place those next to ammonia or refinery consumption, as the two are very different. Perhaps the team should consider several new and alternative pathways from which it may select a "leading candidate," then present a scenario with that candidate as a surrogate for higher-potential outcomes. Meanwhile, the team should focus on changes in established demand and emerging markets where proven performance is already established.
- The project should consider looking at transportation applications with greater granularity. This could be different types of medium- and heavy-duty applications. The project could also look at different use cases and operating modes for light-duty vehicles, highlighting demand differences between privately owned vehicles, taxis, ridesharing, carsharing, ride-hailing, autonomous vehicles, and other potential applications.
- The project should consider detailed analysis of hydrogen blending to existing natural gas pipeline infrastructure. The team should identify opportunistic low-cost and renewable hydrogen production scenarios, with no storage requirement, along the infrastructure. The market size can be significant and achieved relatively easily.
- It would be good to see the full demand curve generated and discussed (although perhaps this is done under other tasking).
- There are no specific recommendations.