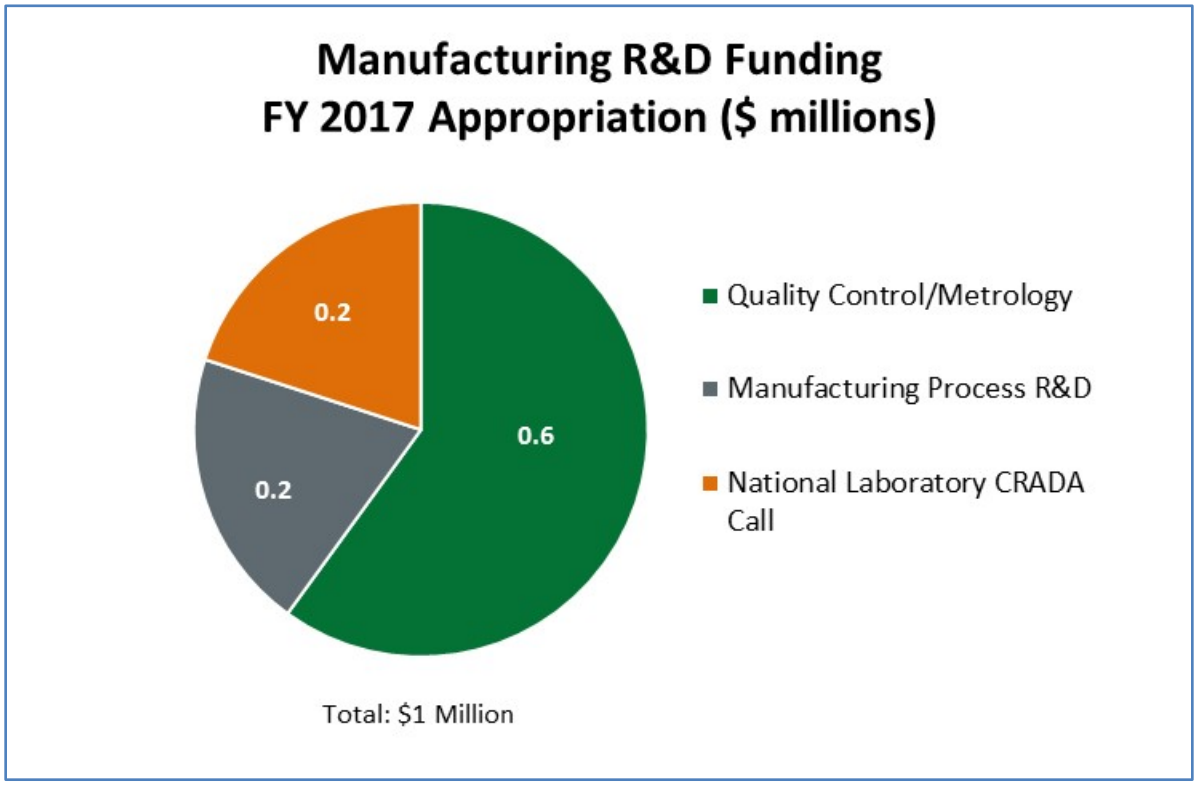
2017 – Manufacturing Research and Development (R&D)
Summary of Annual Merit Review of the Manufacturing R&D Sub-Program

Summary of Reviewer Comments on the Manufacturing R&D Sub-Program:

In general, the reviewers felt that there is great potential to break through the manufacturing R&D barriers and challenges that the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (the Program) faces. They commended the sub-program for supporting projects that are well structured, effective, and significant in reaching goals and milestones. In particular, reviewers recognized efforts to enhance imaging and defect detection techniques in real time that could greatly reduce the cost of high-volume manufacturing of fuel cell membrane electrode assemblies (MEAs). They also commended efforts to create a more comprehensive fuel cell component manufacturing supply chain to enhance industry collaboration.

Manufacturing R&D Funding:

Fiscal year 2017 funding for the Manufacturing R&D sub-program was $1 million. This funding was primarily provided to existing Manufacturing R&D projects for quality control (QC)/metrology, for national laboratory support for development of a new pipeline coupling, and for new cooperative research and development agreement (CRADA) projects associated with the Roll-to-Roll and H2@ Scale national laboratory CRADA calls.



Majority of Reviewer Comments and Recommendations:

This year, seven projects funded by the Manufacturing R&D sub-program were presented and reviewed at the Annual Merit Review and Peer Evaluation. The reviewers' scores ranged from 2.9 to 3.3.

QC/Metrology: Two projects were reviewed in the area of QC/metrology, receiving scores of 3.3 and 3.2. Reviewers generally agreed that the MEA defect detection project had made important progress in defect detection and imaging techniques, which will be helpful in manufacturing membranes and in cost-reduction efforts within the Program. They suggested that the project focus on developing a few techniques to detect critical defects and

variances (as identified by membrane manufacturers) instead of examining and imaging a large variety of membrane phenomena. Reviewers felt that the project could use additional industry collaboration for increased real-world results and real-time feedback in defect detection. Reviewers also noted the relevance and progress of an in-line QC technique, noting that the team is working with a Small Business Innovation Research program Phase II project to commercialize the technique. They suggested it could be highly beneficial to roll-to-roll (R2R) processing and DOE cost/performance targets, and that the future focus should be on increased detection in systems outside of a laboratory.

Analysis: Four projects were reviewed, with two projects receiving scores over 3.0 and two projects receiving scores of 2.9. The reviewers were impressed by the Hydrogen Fuel Cell (HFC) Nexus project for the significant progress toward establishing a website that provides product information on hydrogen and fuel cell components and systems to the fuel cell community. However, the reviewers expressed concern about maintaining and updating the website once federal funding for the project ends. The reviewers felt that the Ohio Fuel Cell Coalition clean energy supply chain project provides an interesting approach to creating and supporting future regional technical exchange centers for manufacturing. However, some reviewers questioned the impact the centers will have on the manufacturing and industrial supply chain needs for hydrogen and fuel cells. Reviewers also recognized the importance of the global and regional competitive analysis of the fuel cell industry, which will help DOE more accurately address barriers to competitiveness. They suggested that future work more precisely target specific fuel cell components. Lastly, reviewers urged more actionable results and clarity of analysis for the hydrogen refueling station analysis project, suggesting more data regarding standardization of stations and intra-country trade flows.

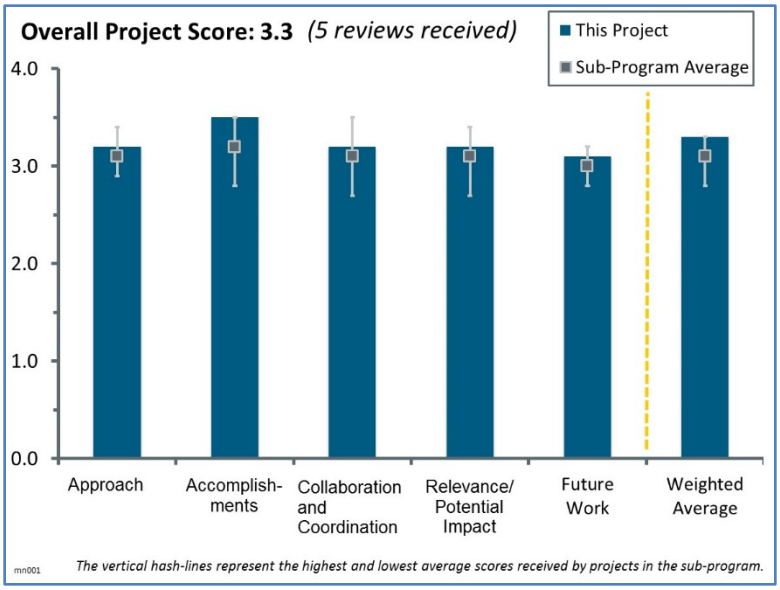
Manufacturing Processes: One project was reviewed in the area of manufacturing processes, receiving a score of 3.2. Reviewers praised the project for its approach in adjusting component materials for the coupler and said that the work will have a positive impact on pipeline safety and integrity. They noted the need to develop a full prototype as the next major objective for the project.

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

Michael Ulsh; National Renewable Energy Laboratory

Brief Summary of Project:

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



Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The National Renewable Energy Laboratory (NREL) integrated its tasks with the subject funding opportunity announcement (FOA). The emphasis was on fuel cell manufacturing technology and on the strengthening technical abilities within the United States to enhance competences in that area. This involved close cooperation with large original equipment manufacturer (OEM) interests, pertinent support for the Fuel Cell Technical Team, and support and guidance for others funded under the FOA who seek to foster efforts to build a U.S.-based supply chain for fuel cell technologies. NREL reported very relevant, interactive support for the entire U.S. Department of Energy (DOE) effort. NREL began interactions with Gore, a U.S. company with extensive experience in membrane electrode assembly (MEA) technology, another solid part of the team's approach.
- The tools that are being developed are very important, including the segmented cell to determine local effects that might not be visible at the full cell level. The table breaking down total cell versus local effects and the longer-term impact on performance helps provide industry relevance. If possible, it would also be good to look at commercial electrodes as well as simulated defects. The General Motors (GM) half cells are a good example. It is also good to see alternate test cycles that may better inform degradation mechanisms.
- The approach of this project is good. However, the project should be a lot more focused. It seems like the partners are trying to do many things, which dilutes the project's impact. It would be better to see the principal investigator (PI) focus on a few techniques, clearly quantify their impact on fuel cell performance/durability, and transfer the technology to industry. For example, the researchers are developing techniques to look at membrane thickness variation, membrane pinholes, membrane irregularities, catalyst layer loading uniformity, bare spots, etc. It would have been better to identify key problems faced by roll-to-roll (R2R) MEA manufacturers and develop tools specifically to solve those problems.
    - NREL seems to be studying many interesting phenomena without regard to their importance. For example, it is not clear why the team wants to measure membrane thickness variations. It is not clear whether there is a need. It is not clear what the current variation in thickness of commercially available membranes is, what its effect on performance/durability is, or whether there is a need to monitor this. The impact of this good project would have been excellent/outstanding over the decade of this project if the PI had focused on a few important techniques and commercialized them to make an impact on U.S. manufacturing.
- Some effort should be placed toward using "real" defects in accelerated tests to see whether failure occurs similarly to manufactured defects.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- The technical focus was on the development of new and improved techniques that serve to evaluate the physical properties of the MEA, which includes evaluation of individual components of that device, for example, the polymer electrolyte membrane. The developed procedures were suitable for R2R manufacturing. This is a tough task. The materials are subject to contamination or damage throughout the several manufacturing steps. Clearly, it is necessary to disqualify faulty materials as soon as possible. Therefore, the focus appropriately was on diagnostics for polymer sheet materials.
- There is excellent progress. Many results have been shown in this DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review. Modeling from Lawrence Berkeley National Laboratory should be used more extensively to supplement the limited experimental data and to analyze the effects of various defects at different levels. Other projects within the Program could be leveraged for this purpose. For example, the Fuel Cell Consortium for Performance and Durability can be leveraged to get durability data that will enhance the value of this manufacturing project; the team can then focus on developing techniques to improve manufacturing reliability and decrease costs. Relationships with OEMs should also be leveraged to address real-world problems.
- Good progress has been made in setting up defect visualization equipment.
- The differentiation of membrane thickness and impact of defects makes sense but is useful to quantify. Leveraging these techniques to understand the sensitivity of advanced materials to defects is key to defining manufacturing specifications for electrode manufacture—thinner membranes will require tighter manufacturing control. The imaging capability is also a significant accomplishment to provide additional understanding into failure mechanisms. Full electrode imaging at a reasonable timescale would be a huge benefit versus point measurements of loading, which can be misleading.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- There are good collaborators. The addition of Gore is much welcome. The results from duPont's N211 and N212 membranes might not be relevant to state-of-the-art membranes. The addition of Gore and development of techniques specifically for advanced membranes is a big step in the right direction.
- NREL played a key management role in the funded FOA on manufacturing. It worked cooperatively with a major U.S. OEM and cooperated with, and perhaps encouraged, other FOA participants, helping those participants to achieve better results. NREL has also begun cooperation with a fuel cell membrane supplier. This seems to be all just well done.
- The team has a diverse skillset that addresses a number of critical items. Efforts should be made to attract new collaborators with specific expertise in creating/identifying defects of interest.
- Interaction with Tufts University and GM are well described with examples. The Georgia Institute of Technology's role was not a focus. A project this important should also have additional industry involvement.
- It would be good to see how the team can leverage any previous work done in photovoltaics (PV) on R2R technologies and its experience with defect detection.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- The results are in a one-for-one agreement with the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. Impact is hard to assess, but the potential impact is significant. Even so, this same sort of diligent engineering will be necessary for every component in the fuel cell systems, so this activity is just the beginning of manufacturing engineering.

- The project is very relevant, especially the focus on technique development, which is the strength of this project. This project will be more impactful if the team focuses on this and leverages OEMs and other projects to figure out what the needs are in this area (rather than mapping the impact of various defects on performance and durability).
- This type of work and understanding is essential to driving understanding and manufacturing. The goals beyond automotive fuel cells are not really defined at the manufacturing level yet.
- This work helps support the cost-reduction goals by potentially reducing waste and understanding the process improvements necessary to increasing fuel cell efficiencies.
- This effort, if the results are adopted by industry, can significantly lower the cost of MEA manufacturing.

Question 5: Proposed future work

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

- There is plenty of future work possible with this project, but it is difficult to lay out a plan without an assured budget. The team is working to mitigate this through collaborative efforts and cooperative research and development agreements.
- Certainly, the work is ongoing and will continue throughout fiscal year 2017. The present plans to extend or modify this activity are not clear. There is much to manufacture in a fuel cell system. Emphasis on the MEA is appropriate and has considerable promise to enhance durability and performance targets.
- This project has been ongoing for a decade. It would be beneficial to see more of "seek opportunities to demonstrate and implement diagnostics in industry" and less of "study the effects of relevant defects on cell performance and failure onset." Before developing a new technique, the team should make sure there is actually a market for this and it is actually an industry need.
- It would be interesting to understand the feasibility of implementing a real-time feedback loop for adjusting process parameters or the use of real-time predictive modeling.

Project strengths:

- The NREL team is excellent, and DOE has provided resources to NREL to allow it to acquire, install, and operate quality instrumentation and hardware. The strength is people who are knowledgeable and facilities that permit those people to accomplish the tasks. It is also a great strength that NREL has a fully interactive fuel cell team, perhaps the best and most useful collaboration on this activity.
- There is lots of great work on a variety of things of relevance to manufacturing and the impact of manufacturing defects on fuel cell performance and durability. The team is working on the Small Business Innovation Research Phase II project to commercialize the technique developed under this project. The project has the potential to affect U.S. manufacturing in a positive manner.
- The analysis techniques that have been developed for catalyst layers and membranes is impressive. These have improved over the course of the project, becoming higher-resolution and more closely tied to performance. The addition of modeling and more fundamental analysis to understand the mechanism of failure adds to the value of the work.
- This work opens the doors for having a platform to build tools for in-line process optimization.
- The utilization of R2R equipment in real time to identify defects is a project strength.

Project weaknesses:

- It is not clear whether manufactured defects and real-world defects are similarly visualized.
- The largest focus has been on platinum catalyst layers; there was some preliminary work on other materials, but it would be good to keep up with the work on electrolysis catalysts and non-platinum-group-metal fuel cell catalysts as these two areas gain momentum to further leverage this capability.
- It would be good to see connectivity and collaboration with other projects funded by DOE.
    - The project should leverage thin-film PV work with R2R defects and link to other funded fuel cell and MEA projects.
- Fuel cell technology is being explored throughout the global community. Through the last two decades, a certain pathway has developed in the United States that may or may not be what actually dominates the

future marketplace. This project correctly focuses on what the community knows and accepts. The possibility that others have different approaches exists. The other weakness is that others are now manufacturing hundreds of thousands of fuel cell systems. Each manufacturer faces quality-control issues and selection of techniques to access quality control. Successful approaches will be held as intellectual property and not shared. The fact that the fuel cells now being marketed tend to work for a long time suggests that many quality control issues have been addressed successfully.

- It seems as if the PI is developing all the techniques that he can and looking at the impact of various defects on fuel cell performance and durability without regard to need or impact. Therefore, the science is good, but the impact is low. It would be good to see more focus to steer this great team to have a greater impact on a few problems of relevance to the MEA manufacturing industry.

Recommendations for additions/deletions to project scope:

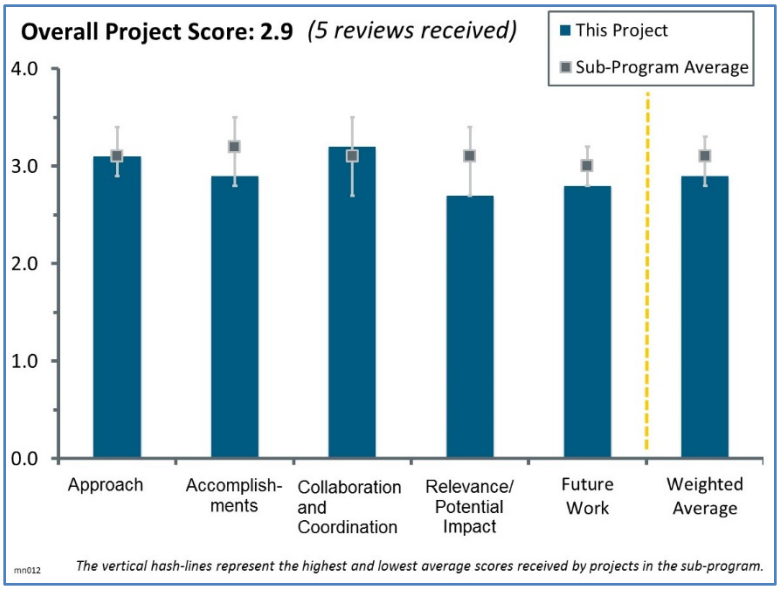
- This project is valuable to continue, and it should be expanded to understand the range of technologies to which it can be applied.
- Identical quality control issues confront other fuel cell systems and electrolysis systems. It would make sense for the NREL team to bring its many skills into those areas as well. It is well understood in any technology, like in fuel cell technology, that the greatest majority of financial resources are spent not in fundamental or basic research but in bringing promising technology to the marketplace.
- A study of “real” defects, their identification, and the effect on life should be conducted. A more scientific approach to understanding defect effects on life would give manufacturers a better idea of how to address defect occurrence.

Project #MN-012: Clean Energy Supply Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cell Technologies

Pat Valente; Ohio Fuel Cell Coalition

Brief Summary of Project:

The objectives of this project include the following: (1) establishing regional technical exchange centers to increase communication between original equipment manufacturers (OEMs) and hydrogen and fuel cell component and subsystem suppliers; (2) establishing a web-accessible database containing inputs from suppliers and OEMs along with a supplier contact list;
(3) standardizing component and subsystem component specifications; and (4) developing strategies for lowering cost, increasing performance, and improving durability of components and subsystem components.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- This project was chosen competitively as a response to a U.S. Department of Energy (DOE) funding opportunity announcement. Clearly, this selection is the result of an application that addressed specific DOE goals. It is apparent that manufacturing competitiveness involves manufacturers that have both the competence and resources to design, develop, and manufacture components for hydrogen and fuel cell technologies, while they are being rapidly commercialized in the global community. Pat Valente took on the task of building from the ground up a group of U.S. companies that could be part of a "supply chain," making parts that are essential for final, successful products. It is obvious that there were no clear, well-identified pathways to have this happen. However, Valente proposed a pathway that was similar to what is done in the U.S. automotive industry. Certainly, this was the place to begin. This task involves the initiation of a supply chain for hydrogen fuel cell components, and the plan is to do exactly that.
- The approach includes focused workshops and intense "speed dating" events to facilitate in-person, face-to-face information exchange on OEM requirements and supplier capability. Consideration of possible component standardization could prove to be very beneficial to the industry and keep costly duplication to a minimum. Compilation of a list of possible suppliers and technologies will facilitate development and market penetration. It is not clear what fuel cell types are being considered.
- The approach of "speed dating" has considerable potential to facilitate fuel cell supplier interactions. The approach of implementing working groups on selected topics (e.g., part standardization) delivers a high probability of some (limited) shared benefit to the U.S. supplier community. The geographic distribution of the data exchanges is reasonable.
- This project now focuses on the technical exchange centers while leveraging MN-013 for the website. This is a very good approach. However, it seems as if the principal investigator (PI) is just putting up one exchange after the other without understanding the actual efficacy of these exchanges and improving them with time. It would be good to see more metrics developed for "success criteria" rather than counting OEM–supplier matchmakings or survey scores. Maybe the team could track actual sustained supplier–OEM relationships and actual purchases made from the suppliers by the OEMs.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- The mere ability to get interested parties in same room for dialogue and discussion of common topics of interest is a significant accomplishment. Data exchanges were modestly well attended by a good/appropriate mix of suppliers and integrators. The selection of components on which to focus ongoing component standardization discussions is a significant achievement.
- The accomplishments are that a "supply chain" has been birthed. The activity is small, involving U.S. companies that currently manufacture stuff and are interested in selling into the hydrogen market. None of the reported activities are focusing on essential hardware, such as the fuel cell stack. Rather, the initial interest is in other components, such as filters, which although essential are a minor component. The details of the interested "supply chain" participants are not available. Most likely the filter company already manufacturers and markets filters. Hence, the accomplishments are small steps, perhaps, but visible steps. This is the beginning, and there has been progress and commitment.
- The project appears to be on track, but it is difficult to assess the overall impact on DOE goals for fuel cells. Exchange meetings have been held with good attendance and very positive feedback. The number of follow-up contacts was significant, but their effectiveness was not known. Substantive standardization discussions were held, revealing possible candidate balance-of-plant components for joint development. Cell/stack components were generally excluded because of the proprietary nature of the fuel cell technology. It would be informative to report what types of integrators participated (automotive, backup, etc.), what components/technologies were offered (sensors, humidifiers, compressors, plates, etc.), and what technologies were covered (fuel cells, hydrogen storage, etc.).
- In fiscal year 2016, the second quarter (Year 1) milestone was "[Ohio Fuel Cell Coalition] produces brochure to attract new suppliers." This task was supposed to be in progress even at the last DOE Hydrogen and Fuel Cells Program Annual Merit Review. However, this seems to be moved to September of 2017. It seems like this project has just evolved into putting up these regional exchanges every few months. While this is the strength of this project, the scope seems to be far less than originally intended. It is not clear why this is not reflected in the budget. The PI needs to provide concrete evidence that the supplier–OEM meetings from the first few exchanges are actually helping either the supplier or the OEM. It is understood that these are well attended and that may be an indication of value, but the difference between each of these exchanges (other than location) is not clear. It seems like a better idea would be to focus each of these on a specific theme, get a few people, and actually make a difference—instead of making it like a conference where everyone goes their own way after the meeting and very little technical collaboration is fostered. This field is not mature enough to benefit from such broad exchanges. More needs to be done to accelerate the development of a robust supply chain.
- International and regional connections should also be sought for integrators to obtain the best components for their applications. Lessons learned from similar foreign efforts of similar scope should be sought.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Collaborators are appropriate and correctly do not include industry or suppliers that might have specific parochial agendas. Communication among the named collaborators and with industry stakeholders is pervasive by the nature of the project, which has hundreds of contacts.
- The PI has made excellent attempts to coordinate with other projects, including MN-013, which is very valuable for DOE.
- The project team has significant fuel cell experience and seems to represent a well-integrated, well-rounded set of participants. Interaction with other DOE-funded efforts (James Madison University, GLWN) adds significantly to the project. The team is seemingly limited in other non-DOE/non-project collaborators. Interactions with industry groups/associations were not shown.
- The collaboration is somewhat disappointing. Partners are those in the fuel cell technology area, but the people have limited experience in building manufacturing companies. Joel Reinbold, a "collaborator," heads the Connecticut Center for Advanced Technology, an organization that is working in parallel on the

fuel cell/hydrogen component development task. It would seem more appropriate if partners were more involved with the development of fuel cell/hydrogen devices. Interestingly, Ohio houses two technology powerhouses, NASA Glenn and the Wright-Patterson U.S. Air Force (USAF) Base. Both institutions have decades-long experience developing specifications and empowering vendors for fuel cell parts. Partners might have included staff at the Japanese Ministry of International Trade and Industry or a German institution that has recently been tasked with the development of fuel cell components. (Siemens sells a fully useful polymer electrolyte membrane fuel cell submarine, a boat full of fuel cell parts, for example.)

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.7** for its relevance/potential impact.

- Certainly, as of now, the impact is minimal. However, because of Pat Valente's efforts, some number of U.S. engineers and other managing manufacturing firms have been alerted to these new market opportunities. The project is barely half finished, and it is too early to actually decide on "impact." It would take only one "big success" to demonstrate impact. That could happen with any of the interactions that are the result of bringing a potential supplier together with a potential manufacturer, if productive. U.S. industrial history is a story about such interactions and successes.
- The potential impact is positive but limited. It is suspected that many of the critical interactions would have occurred even without the intercession of this project. However, the project does facilitate those interactions and thus has a (modest) benefit.
- It seems like there is much reluctance from OEMs to share their needs. This is a critical handicap of this project. Unless that is fixed, the impact of this project will be low (it is understood that this is not in the hands of the PI, and this is how things are). An alternative would be to look at OEMs for non-transportation and early market applications, such as fork lifts (Nuvera, Plug Power, and Ballard). If these OEMs are more willing to share their needs, then OFCC can make more progress in these early market applications.
- It is not entirely clear how this project directly advances the Manufacturing R&D sub-program goals, which are cost-related. It is not clear whether this project is really necessary. The OEMs surely know how to find suppliers for their requirements.

Question 5: Proposed future work

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

- Substantial work is laid out; there is much to be done even after the data exchanges are completed to ensure that something useful and lasting comes out of the exercise. The most important future activity is the establishment (and exercise) of the standardization working group.
- The focus on standardization is good. Identification and exploitation of U.S. technical advantages is crucial for U.S. competitiveness. It is not clear what happens in August 2018 when this project ends.
- Future work is mostly the continuation of the existing policies and functions established now. This is appropriate. The "supply chain" conferences seem to be worthwhile and useful.
- New engagement with the Fuel Cell & Hydrogen Energy Association (FCHEA) will help.
- OFCC needs to better quantify the impact of these regional exchanges before just doing more of the same.

Project strengths:

- The project is run in a professional manner that entices significant industry participation at the multiple data exchanges. Prodding the industry in pursuit of standardized fuel cell components is a major effort and may ultimately be more significant than the database and/or data exchanges.
- The PI is well skilled in component development. He seems to know many people who could affect project success. The project seems to be merging into a national effort, which is a very good direction.
- The large and comprehensive database of suppliers and integrators is a project strength.
- There is good collaboration with other projects.
- Regional engagement of both suppliers and integrators is helpful.

Project weaknesses:

- The United States has, in general, limited ability in this sort of endeavor. Certainly, the U.S. Department of Defense knows such a drill. One creates intelligent engineering designs and specifications for all necessary components as well as for the subject hardware. Strict attention is given to material quality, assessing details such as exactly which mine produced ore that resulted in the necessary parts. Therefore, this activity is admirable and necessary. Even so, it is a long shot. DOE deserves credit for having the insight and courage to accept the challenge and address it. There is always risk. Reward is less certain.
- Engagement is somewhat limited and should be expanded to a wider network of fuel cell industry representatives.
- There is weak discussion of the efficacy of the workshops and exchanges meet-and-greets. It is not clear what percentage resulted in non-disclosure agreements or other formal arrangements.
- The project has not completed the OEM needs brochure yet, which was due the second quarter of this project. It seems like a very low-impact project, especially without critical OEM involvement. If the OEMs are not that keen to participate, maybe this supply chain is not a problem, and maybe DOE should not invest as many resources.
- The benefits of a supplier database are fleeting and run the risk of being obviated by commercial (public access) databases that have a multiyear lifetime (because they have an incentive to keep them fresh/ updated). The value of (or focus on) a "brochure" of project findings is questionable. It is unclear whether this is the same as a report. It is unclear whether the list of information gained is so short that it fits in a bi-fold brochure.

Recommendations for additions/deletions to project scope:

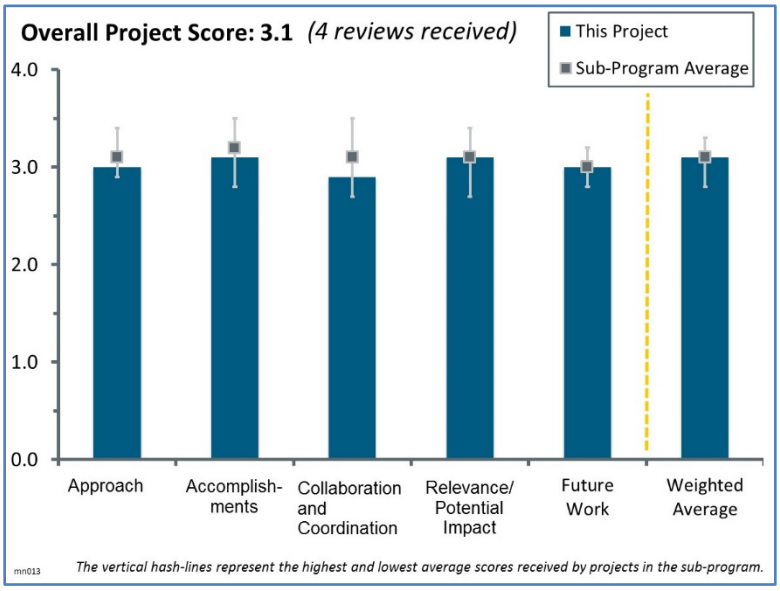
- It might make sense to explore the NASA and USAF staff who worked earlier to develop fuel cell hydrogen hardware. The staff may have insight into other contacts and opportunities. There is also expertise in the intelligence community, which might be useful.
- OFCC should place greater emphasis on creating and using the standardization working group. Most important, the project needs to establish a platform that lives on past the duration of this DOE-funded project. Having a few data exchanges and building a (limited) website are beneficial to project total goals, but they are ultimately inadequate if they fall apart upon project end. Consequently, the project should place great emphasis on establishing entities/events that live on (preferably without DOE funding) past the end of the project.

Project #MN-013: Fuel Cell and Hydrogen Opportunity Center

Alleyn Harned; Virginia Clean Cities at James Madison University

Brief Summary of Project:

The project aims to facilitate the widespread commercialization of hydrogen and fuel cell technologies by expanding the domestic supply chain of hydrogen components and systems. The Fuel Cell and Hydrogen Opportunity Center is building and populating a comprehensive communications database and using an aggressive outreach campaign to drive U.S. companies to the database website.



Question 1: Approach to performing the work

This project was rated **3.0** for its approach.

- As is apparent from the title of the project, the intent of the Hydrogen Fuel Cell Nexus (HFC Nexus) is to create a web-based computer platform that highlights individual companies or individuals that are active in the business of fuel cells and hydrogen technology. The principal investigator (PI) Alleyn Harned is associated with Virginia Clean Cities and is well skilled in promoting new clean technology. Alleyn Harned works to enlist companies to submit data that are posted at hfcnexus.com. The approach is apparent when one thinks about the goals. This is a project to create and manage a new website. HFC Nexus went down that pathway. Obviously, selecting a group of people who excel in web-based projects was an important part of the approach.
- Given the goal is to address the lack of updated, readily available supplier information, a website (and updating structure) to do that is a reasonable approach. The intent is to reach a critical mass of suppliers within the database, such that future/remaining suppliers will sign up on their own. This strategy addresses the critical need to have a self-sustaining method of database perpetuation.
- This is a very focused project with clear deliverables.
- The approach appears to have been executed exactly how it is proposed. It is difficult to assess the success of this effort in addressing barriers without metrics based on successful matches made.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- The progress is excellent. The website is up and running and has plenty of information. Maybe the PI can advertise this at the Fuel Cell Seminar, the Electrochemical Society meeting, and other meetings where original equipment manufacturers, fuel cell researchers, and suppliers are expected.
- The website is professionally done and contains relevant information for a variety of suppliers. Window scalability and a U.S. map with clickable entries are nice features. The website and database are an overall well-executed project. The website has ~337 organizations out of an estimated several thousand of eligible companies: a small percentage.
- Evaluating progress and accomplishments of this project is not simple. Clearly, the number of companies that have submitted information is substantial. The task also involves weeding out inaccurate or inappropriate listings. Hence, there is a considerable amount of effort in this endeavor. There are a good number of other similar global hydrogen fuel cell companies, and no effort was made to compare the quality or quantity of such similar activities. There was no mention that Harned had attended global

technical meetings, perhaps the Fuel Cell Seminar, to display his wares. The DOE selected Harned as a Hydrogen and Fuel Cells Program (the Program) participant and judged his proposed activities to be in consort with the Program plans. On a positive note, opening his website shows an artful, well-done information set. The progress seem to be exactly what was promised.
- It is extremely difficult to assess progress toward the project and DOE goals when the only metrics are the number of vendors participating and the number of website hits.

Question 3: Collaboration and coordination with other institutions

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

- Partners are in the Virginia Clean Cities staff at James Madison University and Robert Rose's Breakthrough Technologies Institute (BTI). (Rose is a well-established spokesperson and advocate for hydrogen and fuel cell technology and brings with him considerable grassroots contacts.) Harned also has tasked the Birch Studio to build his website, which seems to be well done. There is no indication that interactions with other groups promoting fuel cell technology were established.
- Collaboration with BTI is a critical element because it has historical perspective and specific knowledge of the fuel cell marketplace. However, there does not appear to be much collaboration outside of the project team.
- There is good collaboration with other projects.
- It would be nice to see some collaboration between Virginia Clean Cities and the Ohio Fuel Cell Coalition, because these projects have essentially the same objectives.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- It takes a large number of excellent companies to develop new excellent technology. Much depends on getting groups together that choose to work cooperatively to make necessary progress. Making those associations happen is essential. A project such as this facilitates progress, or it can do that.
- There is excellent relevance. It would be good to see more quantitative metrics. It is not clear whether there is any way to track actual exchanges facilitated by this website.
- Reducing barriers to hydrogen education is a worthy goal, but how this project accomplishes that is less clear. It is not clear that other websites are not accomplishing the same mission.
- The relevance is difficult to assess.

Question 5: Proposed future work

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

- The proposed work is to continue the existing work. Importantly, the website needs to be maintained, kept current, and expanded, a continuing task for skilled people. Obviously, questions arise about the durability of the website, especially after DOE funds are depleted. It is not clear whether this task, a necessary task should the United States decide to compete in fuel cell technology, needs governmental support. One might argue that this is a more appropriate task for the U.S. Department of Commerce than DOE. However, it is very clear that it needs to be done only once, and it needs to be a U.S. project, not a task funded by a state or local government. It is an easy task to identify similar ongoing tasks in China, the European Union, and Japan, for example. For now, it is in the DOE portfolio. It is an asset.
- It seems like most of the work is already done and the focus is on maintenance. It is very critical to keep this website updated and relevant to the community and to continue to advertise it after the end of this specific project.
- Future work rightfully focusses on expanding the breadth of the website and securing sponsor(s).
- This project is entering its final year. It is not clear how the website created is to be sustained without continued DOE funding. A plan needs to be created and executed.

Project strengths:

- Alleyn Harned seems very competent and able, bringing necessary skills to the project. The Birch Studio does good work. The concept of having a thorough, available list of competent suppliers seems obvious, should one be concerned about the future.
- The project has set realistic goals and achieved them.
- The website is professional and functions clearly.
- The website appears to be online and very functional.

Project weaknesses:

- The obvious weakness is that the United States is trying to play "catch up," competing with some rather well-staffed global economies, and this very small project has keen competition. It is very clear that the fuel cell electric vehicle business is serious, real, and offers a broad range of compelling advantages, both technical and social. DOE gets good marks for doing the correct thing by sponsoring this activity. One hopes that the "too little, too late" thought is not appropriate.
- The project team needs to plan for the sustainability of the website. Metrics are needed to show true success (e.g., number of partnerships created).
- The project needs more quantitative metrics to assess the impact on industry.
- It is not clear that competing websites are not duplicating the function of this project, making this project redundant/obsolete. A website of companies is only marginally beneficial in assisting fuel cell business-to-business interactions. The website/database will be quickly out of date unless a sustainable method is developed for updating and recruiting the participation of new/emerging companies. A strategy to develop a self-perpetuating mechanism for database maintenance/rejuvenation has not been articulated.

Recommendations for additions/deletions to project scope:

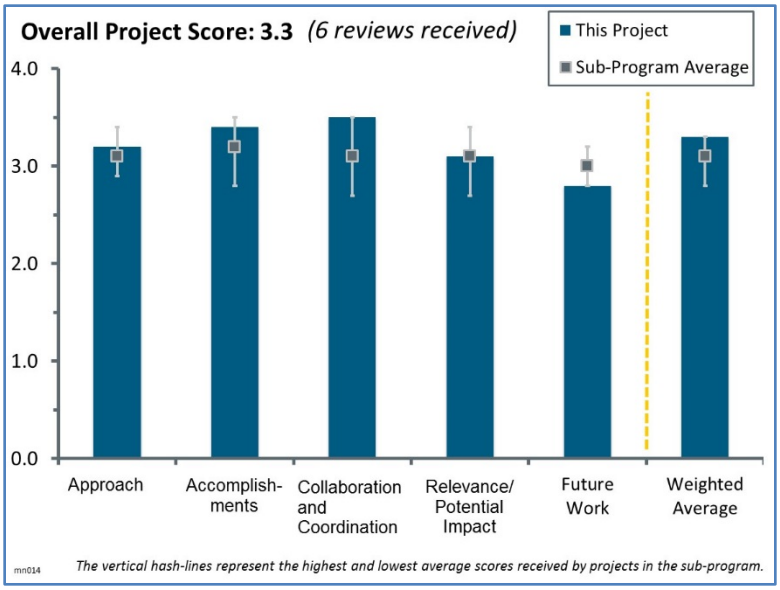
- The project team should focus efforts on identifying a strategy to make suppliers want to update their company listings.
- There needs to be a thorough study of global competition in fuel cell/hydrogen technologies. The trouble with focusing on U.S. companies is that the excellence is most likely not based in the United States. Hence, the appropriate next task would be to determine the nature and identity of companies that are now providing global fuel cell and hydrogen components. The business remains a global one, and a competitive global one.

Project #MN-014: U.S. Clean Energy Hydrogen and Fuel Cell Technologies: A Competiveness Analysis

Patrick Fullenkamp; GLWN – Westside Industrial Retention & Expansion Network

Brief Summary of Project:

This project falls under the Clean Energy Manufacturing Initiative mission to increase domestic manufacture of clean energy products and increase energy productivity. Competitiveness is driven largely by cost, so GLWN is examining current and projected costs, supply chain evolution, and global trade flows of clean energy hydrogen and fuel cell technologies. Project results will help identify strategic investments, identify technology areas for research and development (R&D) investment, and lay out a prospective future supply chain.



Question 1: Approach to performing the work

This project was rated **3.2** for its approach.

- The team actually traveled to multiple sites to assess suppliers and original equipment manufacturers (OEMs), which is the only way to really understand the manufacturing status. This is probably one of the few analyses that is this grounded.
- The approach is what would be expected from a quality engineering concern. A good team was built. Initial activities led to the selection of a few key issues. The project was done well enough. The team includes an excellent European engineering firm, adding considerable talent and scope to the study.
- The project clearly presents a summary of the current state of the industry and regional strengths and weaknesses.
- The cost analysis benefitted from Strategic Analysis, Inc.'s (SA's) involvement, but it was unclear whether the project unnecessarily duplicated any of SA's cost projections. The Approach slides do an adequate job of describing what is being done and the associated tasks, but they do not adequately describe how the tasks fit together to arrive at a competitive position. Some additional information on the interviews, such as the nature of the questions and their weighting, would be instructive.
- This is great work, but U.S. manufacturing competitiveness will be based on OEM demand.
- It is unclear how much, if any, effort was spent on generating cost estimates. The project should use the data generated by SA and focus on improving manufacturing competitiveness.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The competitive analysis part of the project is essentially complete. Conclusions are clear and instructive and intuitively reasonable. The remainder of the project is collection of market data.
- The project met the goals of the Program. As an analysis task, it does not directly advance the technology toward the DOE goals, but it helps in providing a roadmap of important indicators and priorities.
- Progress is great.
- It is not obvious that the "barriers" are totally valid. For example, "lack of high-volume [membrane electrode assembly] processes" involves some definition of "high-volume." For example, when 1,000 fuel

cell vehicles are produced and assuming each fuel cell stack has 100 cells, the production volume is 100,000—perhaps not "high-volume," but high enough to get much attention paid to production technology.
    - The interviews and plant visits were a good idea. It was interesting to understand the percentage costs, such as for the "pressure vessel," vary with production level.
    - It was also interesting that the "catalyst ink and application" accounts for only 12% of the fuel cell system cost, even though DOE has spent considerable resources to lower that cost. (Of course, a customer buys not a fuel cell system but a car that has a fuel cell system. If the car costs $60,000 and the fuel cell system costs $15,000, the "catalyst ink and application" comes to about 3% of the cost.) Therefore, the data collection was good work.
    - Interesting results were obtained (Figure 9) that indicate the "Direct Labor Jobs" give nonsense results. That 30–40 people are required for the bipolar plate, for example, totally ignores the people needed to dig the iron ore and so forth. ("Indirect Labor" will be far higher.)
    - The competitive analysis sections seemed haphazard. Broad generalizations are seldom correct. For example, saying that a U.S. strength is a "high technology domestic automotive industry" is okay, depending on whom you talk to, but there is no doubt that this is also a strength of the European Union, Korea, China, Japan, India, etc. The United States does not have a "high corporate tax rate"—in fact, the actual tax rate (after subsidies) is one of the lowest in the world. Therefore, Chart 10 seems inaccurate and full of "I wish it were true" sort of stuff. A competiveness position means the United States has an advantage over competitors. No credible thoughts were presented as to what might influence the existing situation, changing it for the better.
- The presenter did not present a clear slide with milestones and deliverables, so it is difficult to judge the progress.
- The project does not go far enough as to what could be done to overcome regional barriers using local resources or from exploiting strengths or possible synergies between regions—i.e., how a global company might help overcome certain barriers.

Question 3: Collaboration and coordination with other institutions

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

- With the resources available, collaboration was well done. Figure 11 (the existing markets) was informative. The fact that deployment of stationary fuel cells was a highly successful endeavor by Japan is apparent but not widely understood. It would have been better if the "by fuel cell technology" was displayed by kilowatts rather than by number. Some of the stationary units, say molten carbonate in Korea, are large-scale devices. No information was given about procedures required to gather the data and who did what. That said, the work resulted in excellence, a wonderful and interesting snapshot of "Fuel Cells Today." It would have been useful if the team had also interviewed other governmental agencies, such as the Japanese Ministry of International Trade and Industry, to better understand status and goals within the global community.
- The project team members are well known, well connected, and well respected domestically and internationally. Interactions (interviews with fuel stakeholders and suppliers) were apparently successful.
- This whole project hinges on engagement with industry, and detailed interviews and visits provide strong evidence for the conclusions.
- Having 8 OEMs and 21 suppliers participate in interviews is good. The SA partnership is excellent.
- This is good work with a diverse supplier base globally.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.1** for its relevance/potential impact.

- Leveraging this work to set strategy in manufacturing and investment is very important. The work clearly points out the lagging position of the United States in many component areas, which is disappointing given

the strength and depth in the United States in fuel cell and electrolyzer technology and scientific understanding.
- Results from this competitive analysis provide DOE and industrial stakeholders with insight into areas in which additional R&D resources could technically and economically benefit the U.S. fuel cell industry and suppliers.
- This project was funded by DOE, with funding provided to the team that submitted a winning proposal. It is apparent that this report directly addresses exactly what was called for by DOE, based on the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. The results can serve as a guide for future technology studies and as a guide to instruct investors. The information is clear and informative. The "impact" depends on those who read and consider the results.
- The project identifies strengths and weaknesses and potential areas for future work.
- The impact is not very clear. The cost analysis by SA seems to be the basis for much of the input. The rest of the project seems very qualitative. It is not clear what guidance will come out of this project that will help DOE.

Question 5: Proposed future work

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

- The project is pretty much complete, and future work focuses on final reports and other DOE tasks. It makes sense to maintain this team and monitor future flows of cash and hardware in the global fuel cell endeavor. Those concerned about competitiveness would do that.
- Future work is straightforward and comprises completion and publication of the competitive analysis report and continued collection of market data by fuel cell application/technology and region.
- Future work should provide recommendations on how to overcome the challenges identified and what type of global collaborations would be required or improve the global situation.
- The project appears to be winding down and is mainly in a reporting mode.
- The publication of the global competitive analysis report will be a major deliverable for this project. It is not certain that having market survey data will be that useful, as there are many sources for this kind of data, and this information has been readily available historically.
- The most important work has been completed. Future work and its potential value are poorly defined.

Project strengths:

- The approach in gathering the information via site visits was a key strength. Another key strength was the global survey providing a comprehensive look at the field, including U.S. competitiveness. The division of the survey by volumes also provides an important perspective of the state of the technology (ability to produce a consistent and reliable product at low volumes) vs. the state of manufacturing (ability to produce high volumes).
- The quality of the team is apparent. Their approach was well-thought-out. The datasets are most informative and suggest both opportunity and danger to those attempting to create manufacturing activities in the United States.
- Project strengths include (1) a good summary of the current state of the industry and (2) clear and concise data.
- Strengths include assessment of global technologies and cost analysis of fueling station components.
- Worldwide analysis is a project strength.
- There is good collaboration with SA.

Project weaknesses:

- It would be good to extend this work to related components for related applications.
- Some of the conclusions seemed arbitrary. An example are the conclusions of what to manufacture and where to do that. It is apparent that there are many "auto jobs" in the United States that have absolutely nothing to do with manufacturing. One example is a banker who makes car loans. It is true that fuel cell vehicles will be different from internal combustion engine vehicles, but much remains exactly the same.

One issue is the creation of capital to finance such endeavors. Many industries in the United States are profitable only because of considerable federal investment. A good example is airplane manufacture, an endeavor that borrows heavily from U.S. Department of Defense technology assets. It would have been interesting for the team to consider synergies in the U.S. economy that, when utilized, would promote and subsidize fuel cell vehicle markets.

- The principal investigator (PI) uses only current vendor thoughts and does not consider what the future will hold, how the manufacturing technologies will change, or what technological and economic changes would alter this analysis.
- The PI needs to be clear on milestones and progress and how this project helps U.S. manufacturing.
- There is not much insight as to what needs to change to move each geographic region's ranking in the categories studied.

Recommendations for additions/deletions to project scope:

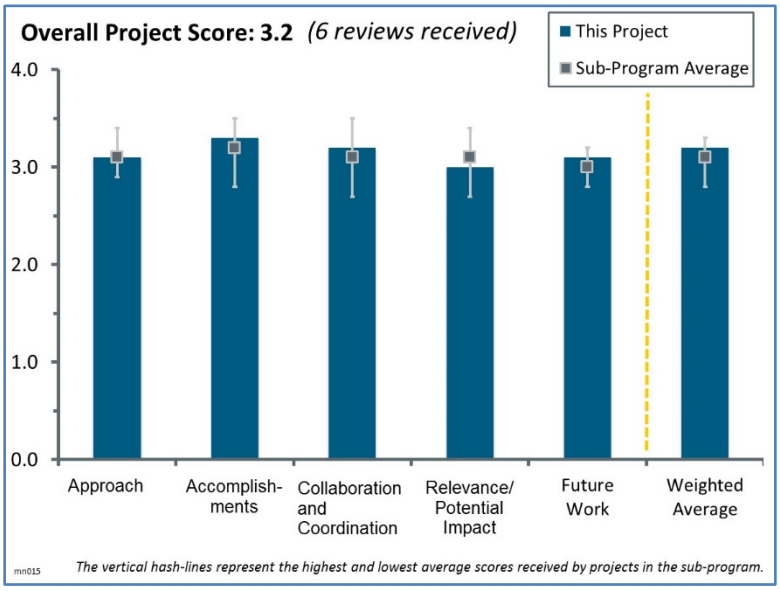
- This analysis would be hugely interesting and informative to do for polymer electrolyte membrane electrolysis. The supply chain is rapidly expanding, and the United States will likely be similarly left behind in this area, but understanding the extent and quantitative growth in this area would help prove this point.
- The rest of the world is into fuel cell buses, trains, boats, and planes. It would be most interesting to continue this effort with a far broader brush.
- A scenario analysis should be performed on possible future occurrences (wide use of additive manufacturing, wide acceptance of smart/connect car technologies, etc.).

Project #MN-015: Continuous Fiber Composite Electrofusion Coupler

Brett Kimball; Automated Dynamics

Brief Summary of Project:

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



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- This task proposes a new piece of hardware that will serve to join (connect) two lengths of polymeric tubing useful to the transport of pressured hydrogen. The concept involves a fitting that accepts the ends of two lengths of tubing, and when inserted into the device, it couples the tubing, making it suitable for underground installation. The approach was appropriate, with identification of the problem, a review of existing, competing hardware, a design of an improved piece of hardware with enhanced performance, and manufacture and testing. This is exactly what one would expect in any quality engineering house.
- Working with an established pipeline component supplier is a major advantage. Use of existing components/pipelines to the extent possible is a critical design approach. The project showed flexibility in switching from an all-composite design to a mixed metal composite design.
- The approach shows efficiency in following up on the previous problem with modified tactics, enabling full learnings from prior work, as well as incorporation of new solutions. The approach appears to minimize added costs or costs associated with "starting from zero." Incorporation of National Oilwell Varco (NOV) components and understanding appears to be very important. New addition of finite element analysis (FEA) modeling fatigue appears to be a good decision, regarding the large unknown associated with the key target of a 50-year lifetime. Parsing the approach to address each of the separate mechanical challenges seems prudent. The one thing that is not clear, with regard to the approach, is related to the problem statement on slide 3. The fundamental problem is stated to be replacement or maintenance of existing seals that are already underground. It is not clear how these couplers can be installed in already-in-the-ground pipes and (similarly) how the electrofusion for sealing will actually be performed. The researchers should clarify this in their presentation next year.
- The performers made a quick decision to move from the adhesive approach and rapidly gained confidence in their composite materials approach. The project is on track for success if they can prove that fatigue is not an issue during the next project year.
- The approach is one of application of mostly existing technologies to the design of hydrogen pipe couplers. Cost is barely addressed.
- The approach should start with more clarity about challenges with existing piping and coupling systems.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- Progress seems to be strong, and it appears that key initial decisions have been made successfully with regard to design aspects (all-plastic versus composite design). In particular, the key 2016 go/no-go testing targets were all met. All partners appear to be contributing well. It will be good to see the FEA modeling results next year.
- The current design has achieved pressure and leakage goals and is on track to meet other goals. The design concept maximized use of existing design coupler technology. The use of electricity to melt/cure thermoplastic/thermoset material for sealing is an elegant solution. While cost analysis has not yet been conducted, the design is expected to be low-cost and implemented quickly in the field (<30 minutes).
- An appropriate coupler has been identified as critical for the success of any hydrogen pipeline based on reinforced thermoplastic pipe. The performers have made significant progress toward development of this coupler using an innovative approach.
- The project is funded at about $1.8 million, cost-shared, with a federal cost of $1.5 million. This seems generous, but obviously such hardware will necessarily demand strict manufacturing standards. Such specifications were not discussed. Progress seems apparent, and technical targets were achieved. Of course, the big question is durability, with the target set to 50 years, and it will take decades before convincing durability has been demonstrated. There are no assurances with that important target. The design involves "electrofusion" of a thermoplastic-coated plastic, polyethylene, and fiberglass-enforced polyethylene. Apparently the polymer-coated wire is wound around the tubing end, and the electricity flows through the wire, resistance heating, to "fuse" the connector to the tube. Automated Dynamics staff seem to know what they are doing and documented passing all go/no-go criteria. As of this presentation, required progress was demonstrated.
- The first go/no-go was passed, according to slide 8's first bullet, but slide 7 shows the go/no-go as "on track" for December 2017. The prototype has been fabricated and passed initial testing.
- The work addresses the new coupler but does not attempt to quantify the potential cost benefits. It is unclear whether there are benchmarks on traditional pipelines that could be used for comparison.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- The collaborations with Savannah River National Laboratory (SRNL) for testing, NOV for pipes and components, and recently, Materials Research & Design (MR&D) for modeling appear to create a strong team with excellent capabilities for the development of the coupler. A higher score would have been given if there were an established pipeline "owner" or "end user" on the team who could provide actual in-application demonstration for the new design.
- It is clear that Automated Dynamics has established excellent working relationships with SRNL (development partner) and NOV (pipe manufacturer). When the researchers identified that fatigue was the primary issue that needed to be addressed, they brought on another partner (MR&D) to support fatigue testing.
- Although it is understood that this project applies to hydrogen pipelines, involvement of a hydrogen fueling station "expert" would be beneficial. Current collaboration outside the project team is not evident, but development of additional partners is underway.
- NOV is an experienced partner and a good addition to the team. Not much other collaboration is indicated (other than among project team members).
- There seems to be good collaboration using each of the partners' expertise to fabricate the new coupler.
- Collaboration was not well described. One of the partners was DOE, the sponsor, so that does not count. SRNL was involved, but their role was not described. The assumption is that they had minimal technical roles, but that is not necessarily the case. NOV is an oilfield supplier, certainly people who know how to join pipes. Role and participation were not discussed.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- Many people in the global community are scheming about a hydrogen economy. The DOE's H_2@ Scale is one example. Bringing hydrogen into the urban environment is probably far safer than bringing in gasoline. Even so, a significant hydrogen "event" is not something desired. The impact of this project, if successful, will never be mentioned but is still essential. No one will report that "no hydrogen pipelines burst today." So this could turn out to be money well spent. There is no way to compare this design with competing designs. Even so, the engineering appeared credible and well done. One suspects the highest risk to hydrogen pipelines will be a backhoe, and safety will be much the result of careful documentation and regulation, with competent management. Certainly, the pipes must not leak, but they also must be protected from malpractice.
- The project is relevant to achieving hydrogen delivery goals. Existing coupler technology will require maintenance for underground service. The project projects a 50-year life for the subject coupling (to be validated in 2018).
- Focus is on the coupler: exactly where it should be, as the coupler is the slow point of the installation process and a failure point source. Achievement of a 50-year, no-check lifetime would be a significant pipeline advance.
- The reinforced thermoplastic pipe is one potential material approach that is being considered for hydrogen pipelines. Thus, even if successful, the coupler being developed will be viable only if the reinforced pipe approach is successfully developed and the cost of the reinforced pipe is reduced to required levels.
- To those with little expertise in pipelines, it is not at all clear how the developed coupler will be installed, and the electrofusion process initiated, on an already-underground pipe coupling. Thus, it is hard to understand how the pursued approach fully addresses the stated need (maintaining existing underground seal components). In the larger picture, the effort seems to clearly address future needs relative to build-out of a pipeline infrastructure with characteristics necessary for hydrogen service.
- The potential impact to total installed costs needs to be quantified more clearly.

Question 5: Proposed future work

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

- Future work appears to be straightforward, with the need to finalize design elements and complete required mechanical testing. One element that the presenter mentioned, but that is not shown on the "Future Work" slide, is a cost analysis. In the application, it seems critical, and DOE must be able to ultimately judge whether the new solution will be cost-effective, relative to overall infrastructure cost targets. The results of the FEA modeling, as related to the stated need for a 50-year life, are anticipated with interest.
- The primary focus of work planned for the next year is, and should be, focused on addressing the question of fatigue life. It will also be important for the manufacturing process and manufacturing cost of the coupler to be considered. A stated goal of the project is to take the coupler technology from technology readiness level (TRL) 3 to TRL 5. It would be worthwhile for the performer to define the transition plan for taking the technology all the way to TRL 9.
- Future work is predictable: complete the design and make prototypes. Fatigue testing brings risk to the enterprise and will be addressed. In the end, the task is to bring the coupler from a TRL 3 to a TRL 5, a good progression forward.
- The safety aspects should be the first issues to be addressed, and this seems to be the case.
- The milestone chart details next steps very concisely.
- Future work involves validation testing of the design for repeatability in terms of fabrication and performance/durability. Fatigue testing to failure will be performed to establish 50-year service life. It is not at all clear how the tests will be performed, under what conditions, and what criteria will be applied. It is unclear whether there is an established American Society for Testing and Materials or ASME protocol. Slide 12 looks like the basis for testing. Future work also includes development of relationships for commercialization.

Project strengths:

- This is a good team, with testing, components, modeling, and industry knowledge all well covered. Leveraging the prior project to the fullest extent is a strength. Capabilities and knowledge at SRNL are strengths—it is good to see leveraging of laboratory capabilities.
- This is a simple design concept with fast field installation and flexible project execution to allow changes of design without imperiling the schedule.
- Collaboration among the team, a pragmatic approach to development, and an understanding of the technology are all strengths.
- The project offers the potential to join pipes more quickly, saving time.
- There is a good understanding of design requirements and approaches.
- The staff at Automated Dynamics seem excellent.

Project weaknesses:

- It is not clear how the pursued solution will be relevant for back-fitting an already-underground pipe. This detail should have been made clear. The lack of a specific end user for actual in-field testing as a current weakness should be addressed over the next year.
- The budget seems a bit high for design/fabrication/testing of a component with limited size, limited cost, and non-exotic materials. The presenter (partially) addressed a question about the 0.5% leakage target. Actual leakage should be presented in same units as a goal, and the basis for the numerical target should be discussed (even though this target comes from DOE). There is concern that the target is not low enough.
- There is no baseline cost data for comparison. The team should offer a comparison of current to future costs and the project's impact on total cost. It is unclear whether there are well-published data on current costs. New pipe material could outweigh the benefits of a coupler. It is not clear how the new pipe cost compares with steel pipe.
- Utilization of the coupler technology depends on other successful transitions of reinforced thermoplastic pipe for hydrogen pipelines.
- A minor weakness is the apparent lack of refueling station perspective.

Recommendations for additions/deletions to project scope:

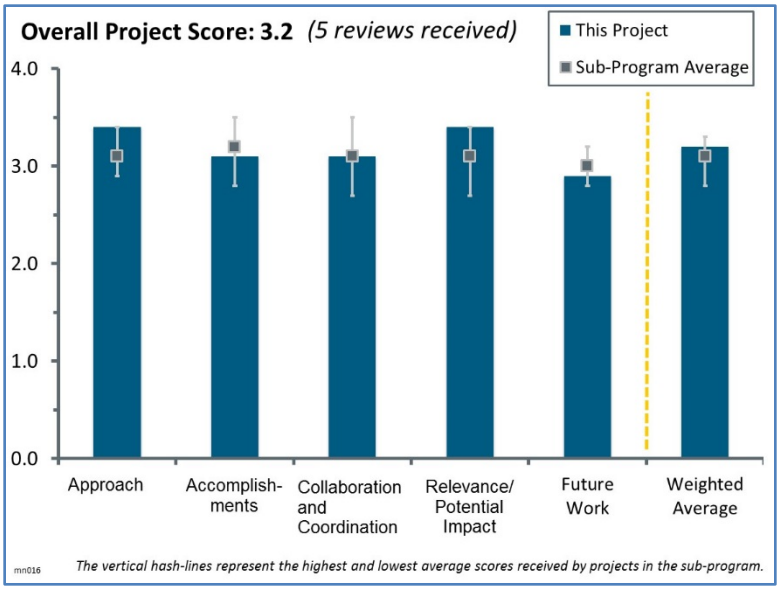
- It seems like Automated Dynamics researchers have defined a set of tasks that lead to technical feasibility assessment. They do not seem to be unsure of their design. Therefore, their concluding tasks are appropriate and do not need to be changed. This project is focused on a specific engineering hardware solution and evaluating the proposed hardware.
- Total cost stack should be developed for traditional piping materials and joining systems for benchmarking. Expected cost versus benefit for a new system should be developed, if the project moves through all gates.
- It is recommended that DOE ensure that a cost model is presented and that in-field testing is performed with an end user. These may be planned, but it was not clear from the presentation.
- Testing should be accelerated as much as possible to allow introduction of (minor) design changes (and re-testing) within the three-year project timeframe, should they be needed.
- Cost analysis and transition planning should be added.

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

Paul Yelvington; Mainstream Engineering

Brief Summary of Project:

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



Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The investigated approach is appropriate to address the main barriers and to reach the technical targets.
- The approach and testing plan are basic and elegantly simple.
- The approach is exploratory and seems usual and expected. The concentration on camera speed was unexpected. Again, the approach to address optical issues (camera speed) seems well thought out and correct.
- Automated optical membrane inspection is an obvious method that needs to be developed for high-speed quality assurance/quality control.
- Mainstream Engineering should provide a better understanding of material defects and impact on downstream processes, allowing for improved process control.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- The progress seems satisfactory. The technique (cross-polarization) is complicated and perhaps difficult to use effectively because of localized strain in the polymer material. Even so, there is much potential in this specific spectrometric technique, and it may take time to explore the full possibility and scope. Certainly this addresses DOE goals of getting manufacturing costs lowered. It is very foolish to use inferior membrane samples to formulate membrane, and the membrane electrode assemblies (MEAs) would be doomed to fail. It is far more intelligent to screen membrane samples and eliminate bad material.
- This Small Business Innovation Research project has made significant progress towards developing high-speed, polarized light inspection methods.
- There was good progress at the midpoint of the project, although the web speed is only half of the target, and the defect size is much larger than the target. Nonetheless, the approach is very promising.
- Progress is good regarding the defect detection in particular for supported membranes, but no clear evidence of progress has been presented on membrane thickness determination or on other membrane applications (same slides as last year). For the membrane thickness determination, it would be

interesting to study the sensitivity of this measurement for lower membrane thicknesses (<15 µm), as the current trend is. The National Renewable Energy Laboratory (NREL) has indicated that defect sizes lower than 10 µm have no effect on performance. If so, then it is not clear why the remaining target of defect detection is at <4 µm at 100 feet/min.
- The project is on track.

Question 3: Collaboration and coordination with other institutions

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

- The project is a good example of technology transfer from a national laboratory to a small business.
- This project collaborates with NREL and with those NREL staff working on manufacturing. Indeed, there are somewhat parallel NREL activities that support these efforts. The project also utilizes Dr. Harris, who prepares test samples. However, there are many endeavors that produce large areas of polymer film, and there did not seem to be any interaction with the technologists who are capable in that area.
- Incorporation of three different groups ensures consideration of a variety of perspectives/ideas. The project would have benefited from incorporation of an industrial partner.
- Collaboration with NREL and Georgia Institute of Technology appears well coordinated. Collaborations with MEA manufacturers would be appreciated.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- The project is highly relevant to the DOE Fuel Cell Technologies Office goals. In-line defect detection is critical to roll-to-roll (R2R) processing, and R2R processing is critical to low system cost.
- The relevance and potential impact of this in-line defect determination is of most importance to reach MEA cost targets as performance and lifetime targets.
- The project will help membrane manufacturers identify flaws that limit fuel cell durability.
- Useful fuel cell systems require useful components, and the soundness of materials needs to be assessed throughout the manufacturing process. Defective membranes need to be discovered and discarded early on in the process, well before the expensive catalyst ink is deposited. This technique for screening membranes has potential for impact in lowering device costs. The emphasis here is the use of cross-polarization spectroscopy to evaluate fuel cell components in an R2R process. Clearly this is just one of many options for such quality control technology. There was no discussion about alternative approaches.
- It is unclear whether the expected outcomes can be better quantified as to how much cost impact could result from better process control. The current cost of quality for various defects is not clear.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The future proposed work seems appropriate and worthwhile. Improvements, both in hardware and software, continue to open up new possibilities for detection of a variety of parameters. One interesting measurement is the thickness of the material. This is important because “thinning” of membrane materials can precede the beginning of crossover leakage. Additional analysis of the cross-polarization optics seems useful and doable. Some of the tasks involve “scale-up” to large sizes and higher speeds. That may be politically necessary, but the questions should remain focused on what you can measure and not how fast you can measure. Speed is easily addressed with multiple cameras. The issues with “defects” at this time are whether one can see them and how serious they are. It is also important to discern whether the “defects” are the result of manufacturing technology or result from improper handling, shipping, and storage of subject materials.
- Real web testing and feedback cost data seem critical to understanding the cost benefits and practical implementation of learnings.

- The Gantt chart lays out the next steps in the project, but the timeline is confusing. This is a three-year project, but the Gantt chart shows only two years. Current status is not clear. The "Remaining Challenges" list is very clear, concise, and identifies the essence of each barrier.
- The future work is generally good; however, it should address methods to assess smaller defects than what is presently proposed for next year's work.
- The proposed future work is just a copy/paste of last year's review. Specific work for the coming year has not been presented.

Project strengths:

- The Mainstream Engineering team seems fully competent. Dr. Tequila Harris has learned how to create "defects" in subject membranes in very small sizes and in ways that are precise and reproducible. It appears that Mainstream Engineering is able to find the micro defects that Dr. Harris creates. This is a good team.
- The technology of defect detection and its maturity evolution are strengths. Collaboration with NREL is of high value to speed up the development and the validation of this technology. This technology may be applied on membranes other than for fuel cells.
- This is a practical approach to methods used to identify defects. The project has stayed on track and maintained focus on key priorities.
- This is a seemingly effective solution to an important in-line diagnostic problem. The project team is well balanced.
- The science and engineering approach is very sound.

Project weaknesses:

- This sort of thoughtful quality control technology needs to extend to all of the fuel cell materials, and techniques need to be developed that result in useful tools for complete membrane and electrode materials, including components such as the diffusion layer. Much as it makes no sense to continue manufacture with bad membranes, it makes no sense to assemble a stack with a bad MEA. Bad actors need to be eliminated as early as possible. There is much for Mainstream Engineering to accomplish, and much left undone.
- Current performance levels are significantly lower than targets, although the targets may exceed what is operationally needed.
- Closer collaboration with MEA manufacturers would be appreciated in order to validate the technology on real industrial web lines.
- More collaboration with MN-001 seems to be an opportunity for additional learnings.
- Collaboration with a membrane manufacturer would strengthen the project.

Recommendations for additions/deletions to project scope:

- Mainstream Engineering should revisit the level of detection truly needed. Mainstream Engineering should address the following:
    - The scanning speed reported in area per minute should be defined more fully/completely.
    - There should be fuller discussion of whether computer processing speed will be a limited factor.
    - The effect of membrane thickness on performance (especially thickness measurement and in light of the current generation of membranes being substantially thinner than those used within the project) should be defined more fully.
    - The effect of supported (versus unsupported) membranes on performance (since the support is expected to reduce detection performance) should be defined more fully.
    - The statement that 40 µm pinholes do not have a performance impact should be revisited/ explained.
    - The project should test using supported 10–20 µm membranes.
    - The total in-line diagnostic system capital cost should be estimated (for a specified web width and web speed).
- It would be interesting to provide information on the cost of this technology once implemented on an industrial web line and the impact of this quality control on the cost of an MEA. How to follow the evolution of cameras, filters, and computers—which is very fast—is unclear, as is how that evolution will affect, or not, the current developments.

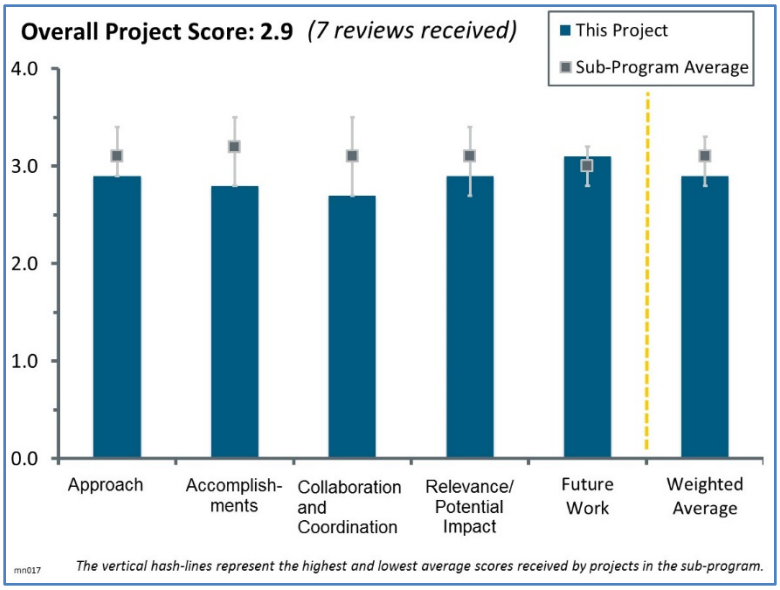
- It is appropriate and necessary to complete the work. There is nothing obvious to delete. Additions are perhaps another project.
- The project should ensure real web data are developed and gather actual quality versus the impact of costs in downstream processing.
- The project should identify a membrane manufacturer and test the technology on production-sized equipment.

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

Margaret Mann; National Renewable Energy Laboratory

Brief Summary of Project:

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



Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The project addresses the key components that drive the HRS costs and provides good detail on cost breakdown, which is consistent with industry experience and data.
- The approach is comprehensive and well constructed. Benchmarking against existing products is a very important step.
- The approach is rather ordinary. There is nothing particularly incorrect, but the theme tends to ignore that HRSs are now deployed in significant numbers globally. There are credible global concerns that are designing, collecting parts, assembling, and installing these stations. One would expect that the opening play would be to evaluate current hardware. It is also apparent that market opportunities are influenced by codes and standards, and those are hardly standardized in the global community. Also, the idea of subsidies and incentives was not described. Certainly several of the concerns now selling fuel cell vehicles are also encouraging HRSs. This project tended to conclude that an HRS has a fixed design, with a certain number of identified components. The approach is acceptable, but if successful, the results may not be exactly what is being experienced in the marketplace. There seems to be a lack of concern for durability, as well as any reaction to the concern that HRSs have some difficulties in reliability.
- It is not certain that there is any value in doing a study of HRSs between four national laboratories without the involvement of any industry (any one from slide 36) or Strategic Analysis, Inc. It seems like the California Energy Commission (CEC) is well ahead of the U.S. Department of Energy in this regard (slide 42). Perhaps DOE should use the CEC data from all the deployments and not have a separate project on this.
- Slide 5 should be more detailed to expand on the approach. It is not clear what (quantitative) metrics will be used to assess competitiveness. It is not clear what cost estimation methodologies are being used (e.g., Design for Manufacture and Assembly). Key milestones and go/no-go's must be presented with dates. It is unclear how international inputs are obtained and what industry (original equipment manufacturers and suppliers) input is used.
- The proposed approach seems to be working in particular for the manufacturing cost model but not for the HRS rollouts and trade flows, where data appear not at all complete.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.8** for its accomplishments and progress.

- There was considerable discussion about global trade in components that are useful in HRSs. These data were interesting, even though it was apparent that those regions that are installing HRSs dominate the picture: the European Union, the United States, Japan, etc.
    - The team decided to focus on cost reduction of components, specifically a hydrogen heat exchanger and a compressor. It was interesting that "labor" costs are always a small component, even though trivial differences in labor costs are discussed as if they were significant. Far more significant was "profit margin" and the fact that high profit margins in some companies must result in lack of competiveness in those places.
    - There was no discussion about the cost of a "gasoline refueling station," which, although clearly less, is far from zero. It is interesting that gasoline is almost always dispensed from buried tanks, which are conveniently out of sight and have no footprint.
    - Hydrogen tanks tend to be inconveniently large and troublesome. The polymer electrolyte membrane (PEM) electrolyzer costs were interesting, especially the cost variation with volume. It would have been interesting to include costs of contemporary commercial electrolyzers at times that high-current devices have some predictive insight into the scaling issue.
- Trade flow maps are a very useful illustration of global trends. From the question-and-answer session, the "Rest of the World" category also includes trade flow of unknown nationality. Given the size of this flow, it seems reasonable for more work to be done to figure out where those products come from and whether they are from truly from the "Rest of the World" or primarily from Europe/Asia/North America.
    - The detailed component and cost list for the refueling station is a good addition.
    - It is not clear how margin is applied/varies with manufacturing rate. The basis of manufacturing rate cost reduction ("20% discount per 10x increase in purchased quantity") is not explained.
    - From the country-to-country comparisons, the part costs appear identical. It is unclear whether this is a reasonable assumption. Also, it is noted that Mexico has an advantage in building costs, yet the building category is not even visible in the stacked column chart.
- When comparing with the 2016 presentation, only a few changes and new information are noticed. This is consistent with no change in the same 75% complete project as in 2016.
    - New information is about PEM electrolyzer stack cost. The added value of this information for achieving the project objectives is not demonstrated. This cost analysis may already have been done in the Hydrogen Production sub-program.
    - The trade flow mapping is difficult to understand, with clear missing information. For instance, Japanese bars are very small, whereas more than 90 HRSs are in operation with a majority of domestic production. France is only exporting, whereas 15 HRSs are in operation with a majority of domestic production. Norway is mentioned but with no bar at all. Germany has high bars, but only 23 HRSs were in operation at the end of 2016, plus 10 in commissioning.
    - Dispenser cost analysis has focused on H35 and dual H35/H70. It is not clear why the team did not focus on single-hose dispenser H70.
    - It is not clear how this project addresses the current barriers.
- The estimated minimum sustainable price (MSP) of several key components was presented geographically to show where the United States stands with respect to international competition. References for the international data would be helpful. HRS capital cost is reported by geographical region and capacity. Slide 7 energy flows should be revisited and verified, especially Japan and the "Rest of the World" (it probably is not important for the project).
- Data seemed unreliable since a number of well-established international stations were not accounted for. Intra-country trade appears very large but not analyzed. The "Rest of the World" is too large to be lumped together and needs to be analyzed.
- It does not appear that the effects of standardization and scale were clearly addressed. These should be key drivers for reducing costs.
- Much work has been done on this project, but there was no clear slide with milestones to quantify progress.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.7** for its collaboration and coordination.

- The National Renewable Energy Laboratory (NREL), as usual, contacted a wide range of experts, and the collaboration is obviously well done. It was mentioned that NREL needs to "involve more organizations" in the hydrogen refueling study. It would make sense to get into Chinese technology and data, as there is some evidence that the technologists there have done recent work to reduce cost and enhance durability. It would also be interesting to understand technology deployed by the U.S. Navy, such as their "oxygen generating plants," used for naval submarines to supply oxygen for the crew, with byproduct hydrogen production.
- In addition to the three national laboratories on the project, NREL has collaborated with a suitable mix of component suppliers and developers.
- Collaborations include three national laboratories and "other industry advisors and experts." "Industry experts" include foreign and domestic suppliers of compressors and HRS installations. Additional experts in other areas would add credibility to the analysis. Recognition of other cost studies might provide insight (e.g., Battelle, Strategic Analysis).
- There was good collaboration on the diffusion-bonded compact heat exchanger (DCHE). However, there should be more work with industry to understand how scale could motivate more competition and bring others into the space. Perhaps interviewing companies that have the capabilities, but little incentive without scale, could provide insight as to how much competition could result (e.g., nozzles, hoses, dispenser systems).
- No clear new, complementary collaboration since last year has been presented, whereas there is a need to involve at least some HRS electrolyzer manufacturers. International collaboration is focused on Japan, and none is mentioned with Europe. This would allow more precise data on trade flows.
- This needs to be significantly strengthened. The team needs to add at least one industry that actually deploys HRSs. The project should come up with a clear plan to leverage the information with CEC.
- International contacts need to be strengthened with the aim of obtaining a better understanding of their current position.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.9** for its relevance/potential impact.

- Cost information, broken down into the components, gives a clear understanding of the cost of an HRS and will be valuable for focusing future R&D on the critical components.
- It is well recognized that it is hard to sell fuel cell vehicles in places where gaseous hydrogen is unavailable, so there is considerable possible impact resulting from this project. NREL is well positioned to evaluate a wide range of hydrogen production techniques. Therefore, this study can produce better understanding of costs and routes to reduce costs. It would be interesting to bring in some of the results of monetary considerations resulting from improved human health as a result of fuel cell vehicles cleaning up the urban atmosphere (work done by Lawrence Berkeley National Laboratory). NREL should consider the "full cost" of technology, now and then, to supplement detailed cost for one specific technology.
- The project cost and competitiveness analysis will provide insight into HRS cost structures, high-cost or high-uncertainty components, and the U.S. technoeconomic position, thus revealing high-impact R&D opportunities for DOE.
- Understanding of HRS cost drivers, issues, and projected future costs is critical to the fulfillment of the DOE Fuel Cell Technologies Office mission.
- Lowering costs of HRSs and accelerating deployment is a worthy goal. However, it is unclear how this project achieves that goal.
- The project should create compelling arguments for standardization and scale. Actionable results are not clear.

Question 5: Proposed future work

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

- Future work is the logical continuation of manufacturing cost analysis for the remaining key HRS components and continuation of development of industrial relationships. Future work also includes investigation of the effect of qualitative factors.
- Proposed future work is right on. There is a current return to methanol and considerable improvements in small-scale methanol production hardware, so a look at methanol reformers, with an eye to the future, might be valuable. It would be interesting to fully understand the costs of production and distribution of other fuels in the United States. Obviously the methane distribution system is universal. Someone pays for installation of the distribution system. Gasoline is also broadly distributed. The costs are covered somehow. There might be some learning possible and perhaps better routes to finance HRSs regardless of what they cost.
- Future work should include electrolyzer manufacturers or people having participated in previous projects on electrolysis cost analysis to avoid duplications. Regarding the study on hydrogen prices, operating expenses (OPEX) should be taken into account. It would be interesting to analyze the impact of future technologies on the associated OPEX of these new HRSs. International trade flow activity should be decreased or even stopped, as it is difficult to see how it contributes to leverage the current barriers.
- Examination (and comparison) of PEMs and alkaline electrolyzers is of value.
- Standardization and scale should be a key priority this year.
- The project has clearly identified the remaining challenges and barriers.
- The electrolysis system needs to incorporate compression to achieve 350 or 700 bar.

Project strengths:

- NREL has grown strong capabilities in technology evaluation. The fact that NREL also has capable, stable technologists working on new stuff is very much part of that excellence. It would be hard to suggest a better place to dive deeply into the costs of hydrogen technology. The keynote presentation at the 2017 DOE Hydrogen and Fuel Cells Program Annual Merit Review suggested that the excellence in the national laboratories in the United States is recognized. The project team is fortunate to have the NREL team on board.
- This project shows a good understanding of component trade flows and good accurate details on dispenser costs. Heat exchanger cost and production process analysis provides good insight into producing this key component that drives a large portion of the HRS OPEX.
- This is a comprehensive and methodically executed project with a clear display of results and (most) key assumptions. The comprehensive integration of manufacturing cost with trade flows to assess potential cost differences between countries is a project strength.
- Comparison and analysis of component costs in other countries with those in the United States are revealing and instructive.
- The cost analysis of the different components of an HRS is a real strength of this project.
- The cost analysis is extensive.

Project weaknesses:

- At times, NREL is too U.S.-centric and perhaps not fully aware of others in the global community. The results showing global trade are a good start, as was clear in this presentation. It makes sense to explore how others are financing their hydrogen refueling facilities and seek to get some “real” numbers about actual costs. How these funding techniques affect the cost of fuel for the consumer is the only thing that really matters. This study was all about capital expenditures (CAPEX). There needs to be some thought about OPEX and the real costs required to service and maintain hardware so that required reliability (filling up a customer’s tank when the customer wants to do that) is achieved.
- There is not enough industry participation. This would be helpful in understanding what market conditions would bring more players into these new markets. OPEX is not taken into account with CAPEX. For example, the DCHE may be more expensive, but refrigeration power costs could be greatly reduced. It is

unclear how the project team would address this. The project seems to be wandering in many directions and should be focused on HRS costs.

- Use of weighted average cost of capital (WACC) is not well explained, and WACC may not be an appropriate value to use within the analysis. While some new technologies were contemplated (i.e., compact heat exchangers), overall, the impact of new technology on future cost of systems is not explored.
- International trade flows appear not to give the real picture of the current situation. The project addresses the supply chain, but no information is given, either on the name of component suppliers or on the number of manufacturers for each component.
- The right partnership with industry is needed, as is more collaboration with CEC to provide DOE more value.
- A wider variety of industry partners would bolster the analysis and resulting conclusions.
- Understanding of international capabilities is lacking.

Recommendations for additions/deletions to project scope:

- The following additions are recommended:
    - Additional new technologies (at least as part of the sensitivity analysis) should be explored as a way of illustrating cost drivers and the potential for future cost reduction.
    - Additional cost benchmarking is needed for all system components. Inclusion of graphs (in backup material) was a good start, but the data does not differentiate between competing technologies and thereby potentially masks cost trends.
    - The “Rest of World” trade flow data should be further identified.
    - It is clear from the country-to-country comparison that WACC is the driving factor in the MSP differences. More attention needs to be paid to the use of WACC and also to whether the resulting cost differences are substantial enough to have significant impact on trade flow.
    - The process flow diagram would be improved with the addition of key processing parameters for each step.
    - Microchannel heat exchangers should be cost-benchmarked against a conventional 16 kW heat exchanger.
- NREL should stay focused on HRS costs. Onsite production seems to stray from the original scope. The analysts should concentrate on standardization and scale effect. They should allow OPEX to be part of the analysis and use the DCHE work as an example. More industrial players should be brought into the discussion and results development.
- NREL should dive deeper into the global technology base, with concerns for financing routes, actual costs, and other issues that are critical in refueling systems.
- How the results of this study will be disseminated and transferred to the industry should be described.