2019 Hydrogen and Fuel Cells Program Review Summary

This Appendix shows the results of the Hydrogen and Fuel Cells Program-level peer review for the 2019 Annual Merit Review (AMR), including feedback from a subset of the reviewers attending the AMR. A total of 132 Program-level reviewers were invited to provide feedback, and 29 reviewers responded.

1. Program Reviewer Fuel Cell Expertise Selection: Are you a reviewer with general Hydrogen and Fuel Cell Program expertise, Solid Oxide Fuel Cell (SOFC)-specific expertise, or expertise in both program areas?

(Your response to this question will change the set of questions that you are asked to evaluate below. You will have the option to skip any questions you do not feel qualified to answer).

General Hydrogen and Fuel Cell Program Expertise (Limited or no Solid Oxide Fuel Cell Experience): 22 reviewers
Solid Oxide Fuel Cell Program Expertise Only: 3 reviewers
Both Solid Oxide and General Hydrogen and Fuel Cell Program Expertise: 4 reviewers

2. The Hydrogen and Fuel Cells Program has a mission and strategy that are clearly articulated and has appropriate goals and milestones, as well as quantitative metrics that are SMART (Specific, Measurable, Actionable, Relevant, and Timely).

Please comment on the overall Hydrogen and Fuel Cells Program (including activities in the U.S. Department of Energy [DOE] Fuel Cell Technologies Office, Office of Fossil Energy, Office of Science, Office of Nuclear Energy, and ARPA-E), as well as each subprogram/activity area, as appropriate. (Note: Hydrogen delivery is now included under the Hydrogen Infrastructure [Research and Development] R&D area. Technology Acceleration includes the prior-year subprograms Technology Validation, Manufacturing R&D, and Market Transformation.)

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

	Hydrogen and Fuel Cells Program Overall Rating	Hydrogen Production R&D Subprogram Rating	Hydrogen Storage R&D Subprogram Rating	Hydrogen Infrastructure R&D Subprogram Rating	Fuel Cell R&D Subprogram Rating	Technology Acceleration Subprogram Rating	Safety, Codes and Standards Subprogram Rating	Systems Analysis Subprogram Rating
Average Score	8.9	9.1	8.2	8.7	8.9	8.6	8.6	8.8
Number of Responses	22	20	20	20	20	20	20	20

Comments:

- It is great to see an increased emphasis on reliability and cycle life of the proposed technologies, even for early-stage (low-technology-readiness-level [low-TRL]) programs. Technologies need to be evaluated on a regular basis based on both the initial and end-of-useful-life performance. Statements of project objectives should include highly accelerated life testing protocols, early in the development, to eliminate solutions that do not meet the life targets.
- The Program has produced a wealth of significant results. It explores in depth the most important research topics. It has clear goals and horizons. Its budget is well distributed across sectors. Consortia have an

important impact—they mobilize the expertise needed to explore new avenues and advance the frontiers of technology. Investigating theory-guided applied materials R&D has growing importance.

- The Program as a whole is highly evaluated not only for advanced technology R&D but also for its work in safety codes and standards, cost analysis, etc.
- The subprograms are strong overall. Oral presentations and, for the most part, poster presentations showed that principal investigators (PIs) receive clear instructions and are aware of Program requirements.
- The general focus of the activities is aligned well with industry's long-term needs for developmental objectives.
- Yes, this was repeatedly and clearly emphasized in statements and presentations.
- Communication of Program priorities is excellent, as are Program management and leadership. The Program should be commended for transparency and clear articulation of goals and milestones. The AMR is among the best program reviews in the government. It serves a critical role in communication of priorities and also significantly enables engagements across the international hydrogen stakeholder community. The Program should consider expanding priorities to include activities that are not technology-specific. One example is a need to ensure participation of diverse groups in science and engineering. The lack of diversity is particularly pronounced within the hydrogen community, and lack of diversity is correlated with less creative solutions to complicated problems. The Program should articulate goals around diversity. The Program should also consider developing specific goals to ensure a balance of investment in various stakeholders, including small business, university, large business, and national laboratory. The current portfolio appears heavily weighted toward large business and national laboratory, even in early-stage research activities in which universities should play a more pronounced role. The Program should also articulate quantitative safety-related goals within each Program element. Currently very few programs have any safety goal, despite the stated importance of safety among all stakeholders. Safety needs to be considered and incentivized at all stages of technology development and deployment.
- The plenary presenters articulated the Program-wide targets for hydrogen cost per kilogram, energy efficiency, and durability unambiguously and with explanatory context. The 2019 AMR plenary speakers presented and explained the related dependencies and assumptions. They also described the status of "where we are" in reaching "all of the above strategies." The Hydrogen Production R&D plenary presentation, however, could have been more successful had less material been presented. Hydrogen Production R&D is an extremely important area, but because of the accelerated, packed presentation (too fast and too much material to be practically presented), some information about the Hydrogen Fuel R&D subprogram's SMART metrics was lost. Therefore, a lower rating, compared with others, is given. In addition, most of the section leaders of the Program who presented at the 2019 AMR plenary were too humble to take credit for the progress in hydrogen R&D across sectors in H2@Scale. Perhaps they can be coached on taking credit, speaking about tangible benefits, and speaking about their vision, as leaders. As follow-up to the 2019 AMR plenary presentations, it would be good to consolidate and publish the techniques used to meet the DOE targets across the entire Program. The purpose is so that others may apply the same techniques. Also as follow-up, it would be good to know what companies and organizations are doing to reward employees/researchers for meeting the Program targets. Perhaps the 2020 AMR can explain which organizations met the targets and the impacts of not meeting the targets. It would also be good to know what would happen to the U.S. energy industries and energy users if a lesser number of hydrogen and fuel cell projects meet targets. The community would benefit from "missed target" information, and perhaps new directions can be established.
- In general, mission, strategy, and goals are clearly articulated and appropriate. Based on the plenary, consortia, and other overview presentations, milestones (what must be realized when) and metrics (which performance/specification must be met under what conditions) seem to be less developed and consistent. Hydrogen Infrastructure R&D, for example, has no separate target for distribution and dispensing. There is only a target including production ($7/kg). Metrics and milestones are most elaborated for Fuel Cell R&D

and Hydrogen Storage R&D. They largely seem to be lacking for Technology Acceleration; Safety, Codes and Standards; and Systems Analysis, which may be due to the diverse nature of the topics.

- It would be good to see two changes as metrics/adjustments to targets. The first is that so many of the targets and therefore the Program efforts are geared toward cost. This is especially true of the Fuel Cell R&D subprogram. However, pure cost (of manufacture or other general economic/business activity) seems too restrictive a metric for a technology that will likely be introduced in phases or waves and is looking to serve a variety of use cases. For example, strict cost targets for price parity with conventional (hybrid) vehicles ignores the aspects of potential consumer adoption. Early adopters may have more price elasticity. They may find value in fuel cell electric vehicles (FCEVs) because of capabilities. There are many other metrics. While we know consumers are influenced by purchase price, translating that into strict cost targets across all Program areas may be too restrictive. Indeed, it may end up pushing research to focus too heavily on more difficult, longer-term research projects that pull needed effort from programs that makes advances sooner—advances that could still translate into value propositions for the ultimate customer. The second suggestion is related. The Program targets are not really addressing the timeliness of needed advances. With momentum building nationally for zero-emission vehicles, and the amount of market- and mind-share that battery electric vehicles have captured in the public and among decision-makers, it seems that this Program is not yet realizing the urgency of advancements, demonstrations, and transitions to commercial products that are needed. This may be true of the FCEV and hydrogen industry broadly, but perhaps the Fuel Cell Technologies Office's (FCTO's) programs could be a strong catalyst for pushing for faster timelines.
- It seemed that decarbonization priorities, especially in terms of greenhouse gas (GHG) emissions, were not coming through strongly enough during the plenary presentations.

3. The Hydrogen and Fuel Cells Program is well focused and managed, and is effectively fostering research and development (R&D) to enable innovation and advance the state of technology for hydrogen and fuel cell technologies to be competitive and achieve widespread commercialization and deployment by industry.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Average Score	**8.8**
Number of Responses	22

Comments:

- The extent to which the Program is well focused and managed has impacts on the entire industry. Fortunately, the Program is well focused and well managed (said wholeheartedly). The focus on cost reduction of hydrogen fuel, storage tanks, electrolyzers, and fuel cells is integral to the success of hydrogen refueling for light-, medium-, and heavy-duty FCEVs. The focus and success on technology transfer from the national laboratories to the field is also crucial. Advanced onboard hydrogen storage, flexible hydrogen dispenser hoses, and electrochemical compression are just a few examples of research presented at this AMR that are needed in the short term for already installed hydrogen refueling stations and in the longer term for stations that are planned and not yet operational. No matter what the pace or sequence of applications, development in hydrogen at scale across sectors remains a key factor in cost reduction of the fuel and the equipment. In 2018, hydrogen supply limitations resulted in fuel shortages and customer impacts. The Program focus on problem-solving equipment that will lead to more reliable, redundant, and resilient supply is needed. The Program is leading the energy industry to hydrogen production at scale, which the industry needs.

- It is impressive how the Program "walks the talk" of thoroughly informed decisions and consideration of feedback for setting priorities and making adjustments.
- The Program was able to obtain premier speakers from around the world in important Program areas.
- Seen from the outside, this reviewer strongly agrees concerning focusing and managing R&D to enable innovation and advancements in the state of technology for hydrogen and fuel cell technologies and acceleration of the uptake/transfer of advances to industry. The Program structure, consortia, and other collaboration instruments seem to make this possible. Whether the Program enables competitiveness and widespread commercialization remains to be seen. This depends on creation of markets, which is outside the scope of the Program. Without solving market failure, conventional use of fossil fuels will likely continue to dominate in the foreseeable future. Widespread commercialization requires more than basic and applied R&D.
- The Program is extremely well managed. The work of DOE's teams is impressive. Developing closer links to industry needs is advisable. The Program is focused more on technology than on industry targets. Research-wise, it is excellent, but the road to widespread commercialization is not apparent. The horizons are excellent, but it seems that more interaction with industry would accelerate the deployment of hydrogen technologies.
- Overall, the Program has clear and well-thought-out objectives and milestones. It is especially beneficial that DOE focuses on the early-TRL R&D-stage technologies that are too early for the private sector. That said, active engagement of industry in the subprogram technology teams and/or projects is likely to help the focus and progress of research in the right direction.
- The Program management is excellent and is a model of effective management among the federal agencies. The subprograms consistently enable hardware innovation and addressing commercialization problems that industry does not address. The portfolio could be strengthened with regard to computing enabled innovation and software development.
- The competitive and widespread commercialization push does not seem strong enough in the overall Program, especially when considering timeliness. Having said that, there is good management practice evident across the Program, and many advances are being made. However, the ability for these advances to have real impact on vehicle deployment nationally is not as clear.
- The Program should continue fostering collaboration with national laboratories, universities, and industry. Duplication with other agencies within or outside DOE should be avoided.
- Industrial partners' more frequent participation in project activities would accelerate the uptake of developed technological solutions and would ensure the alignment of activities with industrial objectives.
- Regarding fuel cells, the Program is very much focused on basic research, and so commercialization seems to be many years ahead.

4. The Hydrogen and Fuel Cells Program's portfolio of projects is appropriately balanced across research areas to help achieve the Program's mission and goals.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Average Score	**8.3**
Number of Responses	22

Comments:

- The Program portfolio reflects many energy sectors; this is highly appropriate and useful. The portfolio reaches across many early-stage research areas to achieve cost reduction of technologies and systems, improved durability of the technologies and systems (realistic cycles of use), and competitive component and system development from a number of stakeholders. The emphasis on consortia and projects funded through funding opportunity announcements (FOAs) yields highly focused projects. Several presenters explained the breadth of the stakeholders under consortia arrangements and the ability to leverage and share expertise among stakeholders. The consortia approach is a smart way to address the collection of needs for a broad portfolio of energy projects. The only issue is how to connect consortia to consortia.
- With California's experience showing that station deployment gets vehicles on the road, it seems like the Program should shift more of its funds to the Hydrogen Infrastructure R&D subprogram. In addition, because the customers interface constantly with hydrogen fueling, they are constantly face-to-face with the cost of hydrogen. This is not currently a barrier, thanks to original equipment manufacturer (OEM) subsidies, but this will not always be the case. Low-cost hydrogen is a near-term priority for continued expansion of hydrogen networks. Therefore, hydrogen production and distribution funding should be increased.
- Although the Program diversifies, it still leans heavily on basic research. Better understanding of the basic principles may guide finding better (laboratory-scale) solutions but is not yet a guarantee for adequate performance under practical conditions. Consideration could be given to strengthening the pilot and demonstration component to complement basic research with more "learning by doing" (a good example is the hydrogen station data collection and analysis).
- The portfolio is fairly well balanced, but going forward, it is clear that low-cost electrolysis (low electrolyzer capital cost) is key to large-scale integration of hydrogen, as a low-carbon energy carrier, into the national energy system. It would be good to see increased emphasis on projects that help move electrolyzer technology to lower cost and larger manufacturing scale.
- More emphasis on manufacturing and less on new fuel cell catalysts should be considered. Industry needs more support with industrialization of the technology. The Hydrogen Storage R&D and Hydrogen Infrastructure R&D subprograms seem well balanced, although compression technologies could be looked at more intensively.
- The Hydrogen Materials—Advanced Research Consortium (HyMARC) is not well coordinated. There is too much focus on very specific materials, which does not seem so promising. The work seems to focus mostly on $Mg(BH_4)_2$—these materials have serious recycling costs and logistics problems that are not being accounted for. Almost all of the consortia members work on this material, which does not make sense. The subprogram should have begun by down-selecting the materials after deciding on the criteria for good hydrogen storage/carrier characteristics. Most of the more mature projects are very organized and constructed to reach the goals set by the FCTO, specifically the Electrocatalysis Consortium (ElectroCat) and the Fuel Cell Consortium for Performance and Durability (FC-PAD). FC-160 achieved the goals set in terms of activity and went beyond them, showing remarkable progress in platinum-group-metal-free (PGM-free) development and performance in membrane electrode assemblies (MEAs). It seems the most important challenge is to increase the atomically dispersed iron content and catalytic site density. There are still open questions regarding durability and degradation mechanisms. These topics are currently the biggest hurdle in the field and should be given more emphasis in the future.
- Two comments on Program portfolio balance. First, the Safety, Codes and Standards portion of the budget has been flat for years; this is a significant decrease in net spendable dollars year over year and urgently needs to change. Both cost and safety continue to remain highly verbalized priorities by DOE and by stakeholders, yet year after year, cost reduction and technology development receive nearly 10 times the funding of safety. Second, the portfolio is heavily focused on hardware and materials research, with a

largely experimental focus. A more balanced portfolio would include more analytical and computational activities and system-level research.

- It seems that the decarbonization dimension does not necessarily come through in a prominent way, especially for the projects dealing with infrastructure and systems related to H2@Scale activities. Some very low-TRL activities, such as photoelectrochemical water splitting or development of hydrogen storage materials, will likely not have a significant impact on the Program's targets in a foreseeable timeframe.
- Ideally, achieving greater commercial industry participation in some of the developmental areas would be helpful.

5. The Hydrogen and Fuel Cells Program's R&D aligns well with industry and stakeholder needs, and is appropriate given complementary private sector, state and other non-DOE investments. Please comment on the overall Hydrogen and Fuel Cells Program as well as each subprogram/ activity area, as appropriate.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

	Hydrogen and Fuel Cells Program Overall Rating	Hydrogen Production R&D Subprogram Rating	Hydrogen Storage R&D Subprogram Rating	Hydrogen Infrastructure R&D Subprogram Rating	Fuel Cell R&D Subprogram Rating	Technology Acceleration Subprogram Rating	Safety, Codes and Standards Subprogram Rating	Systems Analysis Subprogram Rating	Fossil Energy Solid Oxide Fuel Cell Subprogram Rating
Average Score	8.7	8.5	7.7	8.6	8.2	8.7	8.6	8.8	8.8
Number of Responses	21	20	20	21	21	21	21	21	4

Comments:

- There is excellent alignment between the big picture (hydrogen economy) and specific technologies/ capabilities needed to achieve it.
- Work on electrolysis is important, world-leading research.
- The industry perspective enhances alignment of Program goals with industry objectives and timelines.
- Excellent systems analysis work has been done over the past several years under the H2@Scale initiative. This work should continue, with engagement from hydrogen industry experts and potential users, where possible. Perhaps the Program should also look at broader value chains: e.g., the value of the oxygen co-product; the value of renewable hydrogen in various applications, given current incentives such as the California Low Carbon Fuel Standard; where renewable hydrogen presents a logistics challenge; and where renewable hydrogen presents an advantage in terms of production rates, buffering, and distribution.
- Non-DOE investments complement the projects presented at this AMR. However, there is a difference between the two vantage points. DOE national laboratory staff conduct work from a vantage point that achieves innovative solutions for systems analyses of hydrogen production, storage, infrastructure, and technology acceleration. Perhaps non-DOE-funded projects also achieve this, but the proprietary nature of non-DOE work may preclude public reporting of their work products. The DOE systems analyses are useful in that they are highly technical and, sometimes, theoretical. The more technical and theoretical analyses show insight, experience, and new ways to approach these complex problems. One question is whether more effort can be placed on connecting the output of the AMR process to non-DOE-funded

projects to benefit both types of projects. Perhaps a panel at the next AMR could report on this connection: "How we applied the DOE systems analyses in our environment and how this helped us achieve our stated goals."

- Industry and stakeholder participation is considered an important indicator to assess whether the Program aligns well with their needs. Regarding Hydrogen Production R&D, the presentation materials indicate significant industry participation in electrolysis production projects but much less participation in high-temperature thermochemical production and photoelectrochemical production. Industry and stakeholder participation in Hydrogen Storage R&D seems even less, or is not indicated well enough. Fuel Cell R&D shows a varied picture with considerable participation in projects for "Fuel Cell Performance and Durability" and "Catalysts and Electrodes" but clearly less involvement in, for example, "Membranes/Electrolytes" and "MEA, Cells and other Stack Components." In general, the Hydrogen Infrastructure R&D presentations indicate considerable industry and stakeholder participation, with five out of nine presentations presented by industry representatives. The same holds for "Technology Acceleration," which may be explained by the fact that it covers activities that are closer to the market. Finally, activities on Safety, Codes and Standards and Systems Analysis align very well by nature with industry and stakeholder needs because they provide an essential framework for product development and hydrogen and fuel cell activities in general. Assessment of differences in industry and stakeholder participation in various parts of the Program might be used to improve focus and alignment with industry and stakeholder needs.
- The focus of the R&D subprograms at DOE is well aligned in general with industry needs and objectives. It would be better if there were even more participation and/or inputs from commercial companies.
- It is difficult to see how the Fuel Cell R&D subprogram is really reacting to industry needs. In addition, while it is logical to look at storage mediums other than compressed gas because of insurmountable physical limits, it seems that the Hydrogen Storage category is focusing too heavily on materials storage, when industry stakeholders have not indicated a willingness or readiness to transition their development plans away from gaseous storage. Indeed, gaseous storage on today's vehicles often provides sufficient range for drivers' needs. This may indicate that either automotive OEMs are finding other system-level ways around the physical limitations of gas storage, which would indicate that new storage mediums may not be necessary, or that the technology targets simply are not in line with more recent understanding of consumers' needs. Re-evaluation may be necessary, with guidance from industry. The needs and impacts on station operators and the hydrogen production/distribution community should also be considered. A paradigm shift to a different storage medium could have far-reaching ripple effects on these industries' costs and plans, and their long-term plans and needs must be accounted for as well.
- Most of the research is performed together with industry partners. Given the targets of the Program, the Program portfolio is appropriate given complementary non-DOE investments. However, the Program could have more impact on the economy if the Program targets were discussed jointly with industry, in particular the energy and transport industries.
- The focus on solid-state hydrogen storage is closer to fundamental research than to industrial/market applications. Electrolyzer research should have a stronger focus on polymer electrolyte membranes (PEMs).
- The Fuel Cell R&D subprogram is focused on basic research, while the other subprograms allow for applied research and are more directly related to industry needs.
- Given DOE's objective of achieving "cleaner," or low-carbon, fuel and the insignificant market share of non-fossil-based hydrogen, the current resources allocated to hydrogen production are not sufficient. Integration with low-cost renewable energy is critical R&D that needs more attention. Boosting resources associated with Safety, Codes and Standards is appropriate and requires international engagement.
- Although ElectroCAT has been making very good progress, it seems to neglect work on Pt, which is the industry choice. Hence, more basic work is needed on Pt-based catalysts to provide new designs.

6. The Hydrogen and Fuel Cells Program is funding high-impact projects that have the potential to significantly advance the state of technology for the hydrogen and fuel cells industry. Please comment on the overall Hydrogen and Fuel Cells Program as well as each subprogram/activity area, as appropriate.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

	Hydrogen and Fuel Cells Program Overall Rating	Hydrogen Production and Delivery R&D Sub-Program Rating	Fuel Cell R&D Sub-Program Rating	Hydrogen Storage R&D Sub-Program Rating	Technology Acceleration Sub-Program Rating	Safety, Codes and Standards Sub-Program Rating	Fossil Energy Solid Oxide Fuel Cell Sub-Program Rating
Average Score	8.8	8.5	7.8	8.8	8.5	8.8	8.8
Number of Responses	21	21	21	21	21	20	4

Comments:

- Achieving infrastructure R&D targets is essential; energy efficiency, integration, and cost reductions in hydrogen and fuel cell technologies, especially, are high-impact projects. Projects that expand R&D beyond light-duty vehicle (LDV) fueling operations to medium- and heavy-duty vehicles (MDVs and HDVs) will "push" MDVs and HDVs beyond the "start-up" period the LDVs experienced. As a result, time and resources will be saved. Testing actual MDV and HDV fueling in the field is needed to support industry expansion into hydrogen MDVs and HDVs and complement the LDV rollout. The work in HydroGEN on fuel production also has the potential to advance today's processes. The Hydrogen Materials—Advanced Research Consortium (HyMARC) also advances the state of the art. These consortia should continue.
- The number of results produced by HydroGEN is overwhelming. Data management will be crucial. The consortium has well identified that cost reduction and technology remain key metrics. HyMARC research on storage is important. Their approach is very good: "design rules" are needed to guide materials discovery. The development of models and the analysis work is a strong component of DOE's Program. Fuel Cell R&D is well focused; it is a very strong subprogram. Cobalt may not be a good replacement for platinum. Safety, Codes and Standards is an excellent subprogram providing important results. The creation of the Center for Hydrogen Safety will play a major role in helping industry to develop hydrogen technologies.
- Many of the independent fuel cell companies lack the ability to make advanced R&D investments and tend to have shorter-term focus. The DOE-funded R&D provides key forward-looking investment that will be essential to the ultimate hydrogen and fuel cell commercialization, adoption, and commercial applications.
- The Fuel Cell R&D subprogram is very focused on basic research, so the impacts might be in the long term. H2@Scale activities already have impacts and are attracting strong interest from around the world. Also, the Systems Analysis subprogram provides guidelines to the global community.
- The Program should continue work on heavy-duty trucking sector analysis and work on energy carriers such as ammonia and methanol. It would also be interesting to understand what renewable hydrogen can do

to lower the GHG footprint of existing U.S. corn ethanol (both through fertilizer pathways and possibly as a feedstock for liquid fuels for farm machinery).

- The Program's project integration and coordination with other government agencies and industry is the standard for DOE and the nation.
- The projects are evaluated highly since they focus on high-impact technologies. They are also evaluated well when they set cost targets clearly.
- The Program seems to set well-informed R&D priorities with a mix of high-risk, novel, potentially game-changing R&D.
- Systems analysis and hydrogen infrastructure-related topics seem to be the areas where the Program shines the most in this regard.
- In general, this statement is quite true, although there are a few projects that do not seem to show prospects. Specifically, in FC-170, the path to the development of Mn-N-C—the why and how—is not clear. Some of the data interpretation does not seem to be accurate, and most of the conclusions are based on electron microscopy. The concept must be re-evaluated. In general, some fuel cell R&D projects do not follow the DOE testing conditions and accelerated stress test (AST) protocols, which makes it very hard to analyze and compare results between projects. All must adhere to the same conditions and protocols. The hydrogen storage analysis was very important and very well done, breaking the chain into parts and explaining what needs to be done to lower prices in the future. ST127 places too much emphasis on specific materials that do not seem to be very promising. In addition, when selecting and studying such materials, full life cycles should be considered, not only theoretical hydrogen storage, which may be exaggerated in some cases. Efficiency and safety are also neglected.
- The reviewer tends to agree with this statement, considering the importance of the vast majority of the topics that are addressed. However, it is difficult to assess to what extent the totality of project results contributes to improving the state of the art of the various technologies and, for example, what the relation is between the project results and the detailed cost analysis for fuel cells systems and storage tanks. The coherence between these activities could perhaps be improved, while similar (detailed cost) analysis might also be worthwhile for other technologies and systems, such as different types of electrolyzers. Indications/summaries of the state of the art of electrolyzers and the progress therein through, for example, successive spider web diagrams (as for storage tanks) might also be helpful.
- Data collection, validation, dissemination, and analysis are under-used in multiple aspects of the Program. Knowledge exchanges, analysis, and policy activities should also be seen as high-impact activities. The activities in Safety, Codes and Standards are mostly qualitative, expert-based, and somewhat incremental; this subprogram needs a larger budget to be able to make more meaningful advances. Data collection activities need to be accompanied by data dissemination activities; otherwise, the data remain behind national laboratory firewalls.
- Industrialization of hydrogen production should be looked at more intensively. Maybe through systems analysis, there would be some space to include more specific technoeconomic studies.
- Based on talking to several PIs during the poster session, it seems as if they have to prioritize technological advances over fundamental understanding. This may not the most prudent approach in the long term. (This does not seem to be a universal sentiment among PIs.)
- This question is strongly related to the previous one. It is difficult to foresee a clear future path for activities focused on a very low TRL.

7. In your opinion, what were the most significant accomplishments within the Hydrogen and Fuel Cells Program during the past year? Please consider the entire AMR content and entire DOE portfolio, including poster sessions, rather than the plenary talks alone.

Please respond for any subprogram/activity area as appropriate (e.g., hydrogen production, hydrogen storage, hydrogen infrastructure, fuel cells, technology acceleration, safety, codes and standards, solid oxide, ARPA-E, Basic Science, etc.).

Comments:

- There are a number of significant accomplishments: PGM-free electrodes demonstrating reasonable current densities in MEAs at typical cell operating voltages; one of the first MEA demonstrations of PEM-based water electrolysis with PGM-free oxygen evolution reaction catalyst at practical operation conditions (Argonne National Laboratory); demonstration of continued performance improvement for completely PGM-free anion exchange membrane electrolysis (Northeastern University); encouraging 2.5x improvement of PGM-free fuel cell catalyst, although it is still almost a factor of 3 away from the target; progress in development and understanding of MEA fabrication methods; development of Coriolis flow meters that achieve 2% accuracy during SAE J2601 fills; validation/experimental verification of a pressure consolidation strategy for hydrogen filling stations with an outlook for significant cost reduction; and completion of rigorous safety analysis, leading to an outlook for significant reduction (20%) of safety distances for hydrogen filling stations, to be formalized through implementation in National Fire Protection Association (NFPA) 2 (Sandia National Laboratories and the National Renewable Energy Laboratory).
- This AMR included a significant number of ongoing, practical cooperative research and development agreement (CRADA) projects. This includes developing costs per kilowatt-hour and kilogram across the H2@Scale sectors to provide a better perspective for hydrogen and fuel cell stakeholders. The Center for Hydrogen Safety kicked off and anticipates increased proliferation of safety practices in new areas. The HyMARC material compatibility test and evaluation with hydrogen is needed. This includes the embrittlement work for storage vessels, which are presently expensive components, and assessment of overall station life expectancy due to obvious and nonobvious materials used in components. Some hydrogen refueling station developers state their plans for stations that will last 10 and 20 years, and what is needed are tests that help the investment community and public funding agencies understand whether the stated life expectancies at the beginning of projects, or even prior to funding, are realistic.
- The activities of Systems Analysis and Technology Acceleration (H2@Scale in particular) define a background against which benchmarking business cases becomes possible. The subprograms' role in providing a tool for measuring progress in market development is also extremely relevant. Regulations, codes, and standards (RCS) activities and Hydrogen Materials Compatibility Consortium (H-Mat) activities are extremely important, at not only at a national but an international level, for accelerating and enabling widespread penetration of hydrogen technologies.
- The H2@Scale analysis is a significant accomplishment -- it has made great progress over the past year, and there is much more to be done. Ideally, this analysis, including a look at the policy landscape, will serve as the foundation for roadmap work and feed into Program priorities and target-setting. The success of fuel cells in material-handling equipment over the past decade is encouraging, and the Program contribution to that success is evident. Further systems analysis can help to answer the questions of what is next, when, and how big the prize is.
- The hydrogen production and storage cost analyses are critical for industry, and good work has been done there to help decision-makers in industry. ElectroCat has been showing new activity records while getting closer to understanding and mitigating durability issues. The recent progress in the development of new catalysts is one of the most significant accomplishments during the past year. Another important

accomplishment is the study of corrosion-resistant materials, including synthetic routes such as ceramic aerogel materials.

- In considering the biggest Program accomplishments during the past year, three points come to mind: (1) the successful rollout of the H2@Scale initiative, (2) DOE's (in particular the FCTO director's) strong coordination and support for the industry-led U.S. Hydrogen Roadmap study, and (3) the new initiative on "e-fuels" since there is a strong, but often ignored, link between CO_2 conversion and availability of low-cost "green" hydrogen that needs to be fully explored.
- In general, the Program management systems seem comprehensive and very well managed to keep the Program relevant and value-added year after year to very diverse stakeholders. Specifically, the magnetocaloric liquefaction of hydrogen clearly has huge potential benefits.
- The innovative intelligent networks project by Ivys, the magnetocaloric liquefaction project at Pacific Northwest National Laboratory, and the advanced mobile fueler developed through Electricore seem like potentially high-impact projects from this year's Program.
- The announcement of the Center for Hydrogen Safety is a significant step forward toward addressing a major need for all stakeholders in all of the hydrogen-related technology spaces. The extensive interagency activities are commendable.
- Accomplishments include progress in exploring the potential of non-PGM fuel cell catalysts and progress in reducing costs of hydrogen production.
- Accomplishments include progress on the applications enabled by DOE investment over the years. The Program is striving to maintain U.S. participation in the hydrogen revolution worldwide.
- There was a clearly deliberate focus on durability projects across the portfolio. This topic is critical to developing technology that will be commercially applied.
- The R&D consortia are producing remarkable results. They have a major impact on the organization and the optimization of research efforts. This is one of the best uses of national laboratories.
- There has been remarkable progress in quickly setting up H2@Scale.
- Progress and accomplishments on codes and standards were great; completing changes to the upcoming NFPA was key to enabling more deployments and locations of hydrogen infrastructure. Continued advancements in roll-to-roll are also very good, but more industry participation is needed.
- All aspects of the Hydrogen Production R&D and Hydrogen Storage R&D subprograms seem to be doing well. In particular, the work on $Mg(BH_4)_2$ -> MgB_2 appears to have progressed nicely. Safety, Codes and Standards might need more guidance, but it was difficult to get feedback from many PIs at the poster session (posters in general were not always attended).

8. Early-Stage Research and Development: The Hydrogen and Fuel Cells Program is focused on early-stage R&D as aligned with Administration objectives for federal research funding. Please provide suggestions for early-stage R&D that the Hydrogen and Fuel Cells Program should consider for promoting its goals and objectives.

Comments:

- The focus of the Program is consistent with current administrative priorities, as required.
- There is a need for emphasis on early-stage R&D aimed at reducing the costs of electrolyzer designs and operations (for all sizes of electrolyzers) so the energy industries can increase electrolyzer use. Other suggestions include:
    - Early-stage R&D to develop more resilient hydrogen production systems. This would include autonomous and continuous operations supported by software that anticipates maintenance, carries out the maintenance, and logs maintenance.

  - Early-stage R&D that decreases the cost of renewable hydrogen production by generating hydrogen through ancillary services that optimize electrolyzer applications and complement the grid at the same time.
  - Work on electrolyzer configurations and footprints that provide flexibility to fit the equipment into small physical spaces.
  - Innovation in early-stage hydrogen energy carriers and the most viable applications that will work across industrial sectors that use hydrogen as an energy carrier.
- Research activities related to circular economy, reduction of raw materials, and materials footprint could be introduced/strengthened. These activities could potentially play a role across sectors and technologies and encourage the development of a more mature value chain (if this qualifies as early-stage). Manufacturing activities for hydrogen technologies could be further improved (if this qualifies as early-stage). Development of durable low-PGM catalysts for electrolysis and fuel cells is already happening and, because of its importance, could be further strengthened. Hydrogen production through advanced bioengineering solutions could be further explored, too.
- Given the early-stage research focus, more involvement of universities seems necessary in the H2@Scale and infrastructure and systems R&D activities. The Program should expand the early-stage R&D activities, which currently focus on materials engineering research and technology development tasks. Early-stage research also includes theoretical, computational, communication, and analytical research activities, which are not well-represented in the Program portfolio.
- Electrolyzer technology, in both design and manufacturing, seems immature in comparison to fuel cell stack work. At the same time, dramatic drops in solar and wind capital costs are making electrolysis more and more relevant. DOE should continue to fund work on electrolysis concepts, as well as work on novel alternatives (direct solar water splitting), if they can show promise in competing with electrolysis.
- Exploring new storage strategies is needed, as compression is limited and cryogenic storage even more so. Scientific understanding of manufacturing issues for fuel cells, electrolysis, and compressors is required to enable industrialization and supply chain development, ultimately for product cost reduction and reliability.
- Several PIs, especially for the Hydrogen Fuel R&D subprograms mentioned that the milestones are still too technical, given the state of the field. More early-stage research/structure–property investigations are needed.
- Although studied for many years, alkaline fuel cells have shown significant improvement in recent years. Together with new findings related to the durability of these cells, this technology seems to deserve more attention.
- One suggestion is a project focusing on lifecycle GHG emissions analysis of various scenarios of e-fuels pathways and plausible hydrogen sources.
- High-temperature electrolysis, maritime, and rail sectors have high potentials. These sectors would need significant increase in early-stage R&D.
- The Fuel Cells R&D subprogram might investigate the impact of manufacturing processes on fuel cell performance and degradation behavior.
- Membrane and MEA durability improvements and onsite hydrogen production costs are possible early-stage R&D topics.
- Cryocompressed hydrogen storage vessels is a suggested topic.
- Larger-scale storage and transportation are suggested.

9. Energy Materials Network (EMN) Consortia: Do you have any comments or recommendations on the Hydrogen and Fuel Cell Program's EMN consortia approach? Please state what is working effectively and areas that may benefit from further improvement.

Comments:

- The EMN is an effective approach for connecting a core consortium team's R&D and experimental work with materials used with hydrogen systems. The work includes storage systems that are often purchased as an afterthought. The EMN requires strong leadership, which it appears to have. The EMN is a good work effort and program that looks at the long-term viability of materials. Perhaps it would be possible for more hydrogen stakeholders to provide input to the EMN consortia. The input could be as simple as tracking the correct and incorrect uses of materials in field installations. Other input could be on hydrogen-related safety events due to the use of incompatible materials in a hydrogen system. The trust in the technology is bolstered by increased knowledge and confidence in the selected materials, and these consortia will contribute to both.
- The EMN concept is a good platform with the potential to drive discovery and collaboration on multiple applications that require advanced material development. However, the stated measures of success are not as clear and sometimes appear to reward mere collaboration or "contact" with another national researcher more than results. Perhaps the governance structure could be refocused a bit to make it less constraining to the researchers and give them more leeway so they could focus on actual deliverables.
- The concept of using the consortium approach seems logical and well structured. It also seems to be providing opportunities for more efficient utilization of cross-laboratory capabilities and knowledge transfer. One potential point of improvement could be developing a greater distinction between FC-PAD and ElectroCat—or at the very least, considering why there need to be two separately defined consortia for the overall goal of low-cost, high-performance, highly durable fuel cells.
- The overall consortium approach in materials has many advantages by providing better focus and enabling faster commercial adoption.
- The EMN seems very well organized. It seems a good support structure for the research and should continue to yield benefits, adding to the Program's success.
- The size of the EMN network is impressive. Data production is intensive. The EMN has high potential, but consortia need to identify their targets in close collaboration with industry to be successful.
- The activities of some consortia seem to be historically focused around the same cluster of topics and issues (especially certain material classes). Reprioritization should be encouraged and fundamental research discouraged if, after a certain amount of time, no results that can be brought to a higher TRL are achieved. Clear go/no-go processes could be established with guidelines and participation at a Program level.
- Method(s) should be developed to easily assess the significance of project results against a benchmark (state of the art) and targets so that results can be compared easily.

10. H2@Scale: What are the strengths and weaknesses of the H2@Scale initiative? Do you have any recommendations for other H2@Scale research topics or recommendations to enable the scale up and value proposition of H2@Scale (e.g. a region with low electricity prices, excess curtailment, and hydrogen supply opportunity along with a co-located demand for hydrogen, etc.)? Please provide any other recommendations on H2@Scale.

Comments:

- H2@Scale remains invaluable. From a communication perspective, the value of the "image" of the model is excellent and useful when communicating how scale matters. When someone faces the question of how costs will decrease, the image works. The only recommendation for H2@Scale is the development of case studies that show the impact of scale on a multi-sectoral business application. The study could include the "before" and "after" economics, addressing questions such as when scale "kicked in." There is a need for more people who can teach H2@Scale theory and when and how scale matters. Also, perhaps a case study of utopia could be added, i.e., "This is how H2@Scale would work in the best case scenario," followed by a discussion of how utopia seems impossible and the changes to H2@Scale that result when utopia is not met. There are plenty of hydrogen refueling stations that can be used to explain the impact on those stations when hydrogen production is scaled up through shared and co-located business opportunities. As far as electricity prices, it would be good to know how H2@Scale can be reverse-engineered to show utility providers the impact on hydrogen refueling with price changes. A management question is how this model will be maintained. A rhetorical question is what could possibly be better than this model.

- H2@Scale provides a holistic solution for the hydrogen economy, from energy harvesting to hydrogen production and use. It is well organized, and the FCTO is doing a very good job identifying and developing new programs (such as HyMARC and H-MAT) while maintaining the older and much more developed programs. These new programs, together with cost analysis of hydrogen production, storage, and use on a large scale, are definitely in line with the initiative goals. One recommendation for the use of fuel cells in private homes is for the development of reversible fuel cells. These can serve as buffer systems that can store energy and generate it on demand, depending on price and need.
- The H2@Scale concept is beneficial in that it provides researchers and technology developers the opportunity to integrate with different hydrogen sectors and potentially save on the cost of development. However, to be more useful, H2@Scale needs to develop a deep-dive version with targeted and more practical value propositions. Here are a couple of potential topics to consider: (1) another H2@Scale scenario based on technologies with compatible TRL levels, maybe +/-1 or, alternatively, based on near-term and long-term time horizons; and (2) hydrogen sector integration opportunities based on region or subregion, e.g., the U.S. Gulf Coast region. Also, given that 95+% of current U.S. hydrogen comes from fossil-fuel-based sources, it is critical to have meaningful projects that explore the benefits of incorporating carbon capture and sequestration (CCS) to reduce the carbon footprint of large-scale hydrogen supply.
- H2@Scale is an important program. The results presented at the AMR allow one to have a vision of future hydrogen deployment in the United States. The coherence of the efforts is impressive. The study of the transition to equilibrium should be the next step. Investors interested in the hydrogen sector need guidance on the profitable investments needed to accelerate the deployment of hydrogen technologies.
- Hydrogen availability governs the principal enabling of fuel cell deployment and adoption. The initiative is extremely important to overcoming the current limitations due to either geography or the cost of the hydrogen needed to enable FCEVs and other fuel cell applications.
- H2@Scale shows a strong commitment to the world. This is globally very motivating. The initiative should aim at global alliances and international collaboration.
- The strength is that H2@Scale involves as many stakeholders as possible.
- In the discussion of the market potential for H2@Scale, there seemed to be a surprising amount of focus on the fossil fuel market as a hydrogen consumer. While there is not really any getting around the reality that fleet turnover will be slow and fossil fuel refining will be a major part of the fuel system for some time, it seemed the market potential still dominated too much, given the several legislative and executive actions taken at the state level. To this same point, it seemed that, overall, the analysis did not consider technology-forcing actions in place and that could be in place in the future, and the HDV hydrogen consumption analysis seemed off. There also seems to be a good deal of focus on industrial uses of hydrogen when the H2@Scale market studies themselves show these as certainly the smaller potential future markets. However, the H2@Scale project as a whole is a great example of a timely research effort, as governments and decision-makers are calling for a more holistic understanding of the possible role hydrogen can play in the energy future, especially since this seems more fleshed out or easily understood for electricity. One recommendation is to get a fast start on the effort of regionalizing H2@Scale analyses and working with

the regions' state-based stakeholders to develop analyses that not only are projections but that also allow the states to be involved in a more exploratory manner. The topic does not require simply placing charts and numbers in front of decision-makers. This is a complex topic, and the arguments supporting hydrogen have to overcome incumbent biases. Thus, building an H2@Scale research program with a high degree of collaboration with the states will likely be absolutely necessary to spread the concept.

- One recommendation is identification of the most promising regions through a multi-criteria analysis (potential demand, demand density, availability of renewables, availability of infrastructure, energy prices, policy conditions, etc.) to create hydrogen regions (establish complete and various value chains). The idea of excess curtailment is probably not useful—this is not likely to occur unless there is bad planning or overly stimulating policy. It is unlikely that anyone will continue to invest in renewable energy source (RES) generation capacity if periods of curtailment increase and prices decrease as a result. Development of RES potential and hydrogen should go hand in hand. Hydrogen is a means to keep using fossil fuels but in a decarbonized way in combination with storage of the carbon content, and/or hydrogen is a means to capture solar and wind energy and to make this energy available to the energy system in a form that can easily be stored, transported, and used as fuel for applications where batteries or electrification are not possible, insufficient, too expensive, etc.
- Different business models should be reviewed as well. Considering that hydrogen at scale would supply fuel for transportation, it seems one may not rely only on excess renewable. Similarly, considering that electrolysis has a strong dependence on electricity price, an energy company that produces hydrogen would likely invest in its own electricity generation. Therefore, the company's cost of electricity would be different from the utilities' costs. Building more cases for hydrogen utilization only helps validate the H2@Scale initiative. Also, clearly linking the work from HydroGEN and the Advanced Water Splitting Materials Consortium in the pipeline of H2@Scale as a strategy would be very relevant.
- It would be helpful to integrate analyses of lifecycle energy use and emissions more closely with the H2@Scale effort (if it is not already being done). For example, there seemed to be an increased focus on R&D related to liquid hydrogen at this year's AMR. While potentially important to reducing costs and increasing hydrogen's viability across different applications, the use of liquid (rather than gaseous) hydrogen could significantly increase life-cycle energy intensity and emissions, particularly if hydrogen is produced from natural gas. It would likewise be helpful to understand energy losses associated with chemical carriers (e.g., ammonia and methane) from a life-cycle perspective, as new research in this area was discussed at the AMR. One of the biggest benefits of hydrogen and fuel cells is the potential to lower GHG emissions and help states meet air quality goals. Increased attention to the significant variation in energy and emissions profiles for different hydrogen pathways (production, storage, transmission, and use) at this early market stage for hydrogen could have big impacts in the future.
- Strengths include big-picture thinking and potentially transformative impact. Regarding weaknesses, the basis for all activities centers on the national laboratories, with which it is notoriously difficult to partner. This is limiting the engagement of stakeholders beyond national laboratories. The H2@Scale vision may need to become more focused to facilitate achieving its goals through a portfolio of smaller activities over a longer time frame.
- Very good work has been done to date, but this is a complex area, particularly when it comes to interaction with the electric power grid. A good next step might be to build on the Hydrogen Analysis (H2A) type of framework and put together some end-use economic model cases, e.g., hydrogen from solar/wind to interstate truck stop fueling in several parts of the country, hydrogen from wind/solar to fertilizer in the farm belt, and hydrogen from wind/solar to low-carbon methane/methanol production. It would also be good to understand where steam methane reforming with CCS might be a strong option.
- The development of demonstrations, especially in conjunction with utilities, industries, or regions, is encouraged. The actual benefits (environmental in particular) for carbon capture and utilization pathways is a topic that should be further assessed.

- There is potential to have large-scale model validation demonstrations at fixed installation sites. Hydrogen as energy storage for the grid is a prime example.
- There is a lack of targets, and metrics are needed for hydrogen carriers.

11. Collaboration: The Hydrogen and Fuel Cells Program is collaborating with appropriate groups of stakeholders. Please add any additional comments, particularly on which stakeholders (e.g., academia, companies, small businesses, types of industries, etc.) should be more engaged and in what manner.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Average Score	**8.57**
Number of Responses	22

Comments:

- Working with stakeholders is one of the biggest strengths of the Program. The day-long interagency track showcased the strong engagement across the federal government, as well as with state and local governments. Sector-specific workshops such as H2Rail are appropriately bringing together diverse stakeholders to focus on deployment barriers and solutions.
- The collaborations that DOE takes on through this Program are exemplary.
- Collaboration in the Program is truly amazing—DOE-best.
- The Program has good industry and government engagement and perspective, including international stakeholders, and this should be continued, given the importance of global cooperation and adoption of these technologies. The engagement with industry and with national laboratories is strong. It is unclear to what extent the needs of other stakeholders are being considered (e.g., users and communities impacted by the technology). The Program could articulate who these other stakeholders are and ensure that those needs are also addressed. The Program should engage with academia more directly.
- Interaction with state agencies seems very minimal. There is opportunity to leverage these resources/ initiatives through joint university and corporate projects. The addition of the DOE Office of Fossil Energy's Solid Oxide Fuel Cell subprogram to AMR is working well and allowing for greater interactions.
- Although the FCTO is the most established office in U.S. fuel cell R&D, in recent years there have been large investments and efforts in other parts of the world to develop fuel cells. It is recommended that the Program find ways to open the U.S. programs to international collaboration, which is currently lacking. Such an initiative will benefit all sides.
- A strong and clear engagement with multinationals, such as those who founded the Hydrogen Council, would be desired. However, it is not recommended that the FCTO provide funding to those organizations but rather co-invest through subject matter experts, national laboratories, and academia.
- The constraints of government resources and policies are understandable, but more collaboration and coordination with other government agencies would be useful, e.g., the National Science Foundation (NSF) on EMN-related research or the National Energy Technology Laboratory on CCS-related projects. Such coordination also avoids some overlap.
- It is difficult to get a clear and complete overview from the presentation material. There is certainly a good deal of collaboration happening, especially between national laboratories and universities. It seems that

private-sector participation can be strengthened, especially in H2@Scale and Technology Acceleration subprogram activities.
- There is good collaboration between academia and the national laboratories and, on some specific activities, with industry. There could be more industry participation, but finding willing participants is always challenging.
- More frequent participation of industrial partners (both subject matter experts, where appropriate, and large industries) in project activities would accelerate the uptake of developed technological solutions and would ensure the alignment of activities with industrial objectives. The interaction with other institutional stakeholders seems good.
- Deployment of hydrogen technologies needs acceleration. More collaboration with stakeholders is recommended. The Program is well built in terms of technology but not so well in terms of economics. Increased collaboration between research and industry, in particular with energy operators and automotive industries, would be profitable.
- Military bases around the country are potential customers for validating models through hardware demonstration.
- Perhaps future FOAs could explain that awardees (and non-awardees) can opt to participate in core consortia teams. This approach could broaden the reach of the FOA projects.
- Some types of collaborations seem to be in the initial stages, so it is too early to tell.
- It would be good to see more engagement with industrial gas players.

12. International Collaboration: The Hydrogen and Fuel Cells Program collaborates through a number of international partnerships. For example, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is an international partnership to coordinate activities on hydrogen and fuel cells across 18 countries and the European Commission. The U.S. assumed the chair role for IPHE in 2018. Please comment on actions DOE in conjunction with IPHE can undertake or activities that are effective/need improvement to accelerate progress in hydrogen and fuel cell technologies.

Comments:

- Several international initiatives are discussing the importance of hydrogen, in particular, Mission Innovation, the International Energy Agency, the Clean Energy Ministerial, and the G20. The actions of DOE in conjunction with IPHE would be important to linking these initiatives to stakeholders in a global action plan. DOE should also continue to contribute to IPHE in the domains of outreach, regulations, codes, standards, and safety. DOE's contributions in these domains are outstanding.
- International hydrogen leadership is crucial for those companies that want to build and market technologies and systems worldwide. This applies to equipment used in hydrogen refueling stations or FCEVs. Players want to design one hydrogen refueling station and system to be used worldwide. The same is true with FCEVs. Perhaps the IPHE could undertake work projects in international best practices for H2@Scale; this would allow hydrogen refueling station developers to apply best practices internationally. Also, companies in "adjacent H2@Scale sectors" could save time by applying others' related best practices. This effort could differ from international standardization in that the effort could produce public best practices with verbiage and examples that do not necessarily lend themselves to international technology standards. As examples, an international project could address optimal approaches to need assessments or risk assessments for hydrogen refueling stations.
- A priority for DOE should be harmonization of international standards and code development. An example is the push for higher-capacity tanks included in the LDV version of J2601, simply because the International Organization for Standardization (ISO) standard moved in this direction. However, in both cases, this seems like a quick, clumsy solution to a short-term problem that would best be addressed

through other standards development means. DOE could help guide the conversations and help provide reasoned analysis for the best paths forward in standards development that avoids such short-term focus. In addition, DOE should collaborate internationally to understand the opportunities for the U.S.-based hydrogen industry to gain financial independence and accelerated growth through export of our technologies/products.

- International work is especially important in establishing common materials, components, and system test protocols; fueling protocols; and safety, codes, and standards. DOE funding of U.S. expert participation in international forums has been extremely helpful to U.S. industry and should be continued.
- It is suggested that the Program work closely with other countries, such as Canada, to align funding cycles to maximize the ability for international collaborations. Maybe a portion of funding should be dedicated to co-funding with other countries. National laboratories are clearly great points of contact for such.
- IPHE is a very important aspect of realizing true commercialization of fuel cell technologies. The presentation by Australia's chief scientist was very informative, and increasing participation by having more international participants present at the AMR would be beneficial.
- There is excellent government-level outreach that is focused and effective. Continued community and student outreach would be welcome.
- There should be a stronger focus on safety in international fora such as IPHE, and the establishment of international workshops is a positive initiative.
- International projects between institutes or companies are still difficult to set up and should be promoted in the future. International collaboration, such as that with IPHE, is very helpful.
- Although officially this collaboration exists, very little outcome is presented in the AMR. It may be that the incentives for collaboration between laboratories are lacking.
- There appears to be an obvious gap in opportunity to collaborate with international auto companies, especially given the clear lead of Japanese autos on hydrogen and fuel cell deployment.
- The Program involves many organizations, including IPHE.
- From the science viewpoint, collaborations are mostly on paper, not true collaborations.

13. Prizes: Agencies have shown interest in implementing prizes and competitions as a mechanism to complement the conventional grant process. Examples include the H-Prize (H2Refuel) for a small-scale hydrogen fueling appliance that complements large retail stations. Please provide comments on the prize/competition approach and provide any suggestions for future prizes or competitions that would align with the goal of accelerating the widespread success of hydrogen and fuel cell technologies.

Comments:

- The Program might consider a competition or prize related to education and outreach. For example, DOE could host a student "hackathon" to develop apps or other tools to assist commercial fleet operators or city managers weighing the purchase of fuel cell trucks, buses, or vocational vehicles (with data from existing tools such as Fleet DNA as the underpinning). A prize to incentivize broad public education on hydrogen could also be useful (e.g., developing a school curriculum or a social media campaign) for a relatively low dollar amount.
- Competitions are recommended in the areas of (1) electrolyzer efficiency advancements and cost per kilogram of hydrogen and (2) achieving stack durability >20,000 hours in automotive applications.
- Prizes are important to identifying leading scientific research groups and acknowledge their importance for the development of the field. The award ceremony is important for the community. A specific prize for the most important result of the year is suggested.

- Prizes are a good way to spur competition and something that corporations and startups can be proud of as they try to disseminate new technology. They usually end up creating multidisciplinary teams at universities—driving distance, for example.
- Prizes are notable. For example, a prize could “sweeten the deal” for a company that did not receive a funding grant. A prize could be given for a company that implements some of the DOE energy efficiency, durability, and cost reduction targets, among others. A prize could be all the encouragement a company needs to apply for a grant and follow through on the execution and completion of the grant. The prize could be for positive impacts from implementing DOE targets. One area where this could be beneficial is in the production of liquid hydrogen.
- Since public awareness and acceptance is so important, there should be an award for best public awareness video.
- A prize around renewable hydrogen production, with emphasis on low capital cost, is suggested.
- It is a very good idea to acknowledge leaders in industry for their efforts and achievements. Companies can leverage these prizes to attract more investments and media coverage.
- There should be competitions, especially if these were open to co-applications with international collaborators.
- Prizes are of questionable value in motivating technology development. Recognition of innovation is important, though.
- Prizes are an incentive that might favor bigger players and therefore suppress the most innovative approaches.

14. Please comment on the overall strengths and weakness of the Hydrogen and Fuel Cells Program and its portfolio of projects. Please provide strengths and weaknesses for each subprogram as appropriate. On which technology areas should the Hydrogen and Fuel Cells Program put more or less focus for future activities?

Comments:

- The concept of seedling projects seems to work quite well in allowing many concepts to be investigated. On a similar note, one strength compared to European funding is that the Program selects several projects per FOA, whereas the European Union typically selects only one. This has the advantage of not “pre-selecting” the winning technology and instead letting the go/no-go criteria do the down-selecting.
- The interagency activities section is an excellent part of the agenda that allows attendees to see the fruits of all the technical work being done. Applications of hardware and additional technical needs are highlighted in this section, further informing the stakeholders.
- H2@Scale is one of the more key aspects because of the global view of hydrogen production. Advanced manufacturing is also key; as we begin to see commercial growth in stacks and applications (FCEVs) this is a key aspect of adoption.
- The increased focus on MDV and HDV fuel cell applications is a Program strength and will be critically important in advancing adoption in these sectors. Particularly key is the Fuel Cell R&D subprogram’s work to develop lower-cost (and lower-PGM) fuel cells able to meet the higher power and durability requirements of applications beyond LDVs. Shifting more Program resources toward R&D in these other sectors (MDVs, HDVs, non-road, rail, ports, etc.) with the goal of advancing adoption could also complement growth in battery electric vehicle adoption happening in the LDV sector.
- Many projects and programs do a good job of integrating computational modeling with experimental work.
- The Program is very strong and well managed overall.
- The Program is strong in basic and applied R&D concerning PGM-free catalysts for PEM-based technologies and storage tank R&D. The Program is also strong in analysis-guided target-setting and systems and cost analysis. More emphasis could be put on the Hydrogen Infrastructure R&D subprogram

(e.g., the possibility and impact of hydrogen admixing in natural gas grids), the Technology Acceleration subprogram, and the Safety, Codes and Standards subprogram. Much technology is already available, although not yet perfect. In addition to new technology, optimization through practical experience can also lead to improvement and cost reduction. Furthermore, cost reduction will have to be achieved to a large extent by scaling up (system size and economy of scale). The longer implementation is delayed, the longer it takes before this potential can be used. The Systems Analysis subprogram could focus more on (energy) transition analysis.

- The merging of manufacturing R&D with infrastructure R&D diluted its impact. The Program should build more activities under manufacturing. There is significant need for fuel cell manufacturing, from which results can be applied to electrolysis and electrochemical compression. Quality control R&D requires a good deal of scientific understanding and is a great area for international collaboration. H2@Scale and the HydroGEN consortium are coming across as very strong, especially around electrolysis. Other means for hydrogen production seem secondary in the Program and should be reconsidered to either reduce or increase the intensity of activities. The Safety, Codes and Standards subprogram is strong and would also be conducive to strong international collaborations. The FC-PAD and ElectroCat consortia seem out of phase with industry needs. The relevance to current needs is not clear. The value for future needs is clear, but the intensity of effort in those directions should be reframed.
- The most important strength of this Program is its cumulative memory. The Program must protect that resource and maintain important research fields, even if they do not look very promising in the near future. So far, this Program has been very successful at doing so. One of the biggest weaknesses is lack of adherence to comparable measurable parameters. For example, in the case of hydrogen storage materials, the total energy (well to power and back to well) must be calculated for each material—the full life cycle. Without that, it is impossible to make any kind of comparison. Another example is found in ElectroCat, as not all use the same ASTs and testing conditions; in one specific case, a record in activity was presented, but it was measured at temperature and pressure more elevated than the standard set by the FCTO.
- The Program is very good at developing project portfolios that attempt to address known challenges from a variety of angles, thereby increasing the chance of success. However, it may be time to re-evaluate the structure and framework of the goals themselves. The current targets may need to remain as ultimate goals, but targets that are designed along a transition period may help accelerate deployment of technologies in the short term. There is a risk that the pursuit of longer-term goals may inhibit the pursuit of incremental improvements that could increase near-term technology deployments. Simply put, the FCEV and hydrogen community needs near-term proof of its value in the commercial customer market, and the current targets may be too restrictive to enable a near-term impact on deployment.
- Program strengths include excellent program management, major advances in materials research and in technology development, and interagency activities. AMR is a model activity for promoting communication, stakeholder engagement, review, and more. Program weaknesses include a lack of quantitative metrics for safety and a lack of a high-level champion to increase funding for the programs. In addition, many activities are centered around national laboratories that are difficult to collaborate with and that limit information-sharing.
- The Program seems well balanced. A significant strength is the safety, codes and standards work and the technoeconomic analysis performed. Some activities with a very low technological maturity could be deprioritized or assessed more critically if they are not evolving according to the Program's objectives.
- The only weakness is the apparently decreased effort in hydrogen station technology validation. Perhaps on-board hydrogen storage could be beefed up, and paths/off-ramps for technology transfer could be strengthened. The Program should focus on the end cost of a product in the early research stage and how research directions affect the projected cost of a product. The Program could also set up an online system with cost reduction targets, energy efficiency targets, and durability targets and how the targets could best

be achieved to attract companies and industries to take over once an R&D project reaches completion. The results of the R&D should be applied to save time and money.
- In the poster session, many projects that started at the beginning of 2019 were presented. These projects do not have results at that stage, so it is not really helpful to present them.
- The Program is well balanced. Suggestions include more focus on the maritime and rail domain, as well as heavy-duty transport.
- The Office of Energy Efficiency and Renewable Energy may not be the right place for Hydrogen Infrastructure R&D. Perhaps there is a more appropriate place within the overall funding landscape.

15. Do you have any other comments or suggestions to improve the overall effectiveness of the Hydrogen and Fuel Cells Program or any of its specific subprograms?

Comments:

- The overall effectiveness of the Program is excellent. It is clearly one of the best R&D programs on hydrogen in the world.
- The AMR process, as it is, is plenty effective. The Program might consider holding a series of virtual AMRs that address H2@Scale cost reduction, energy efficiency, durability targets, and technology transfer targets as a result of the early-stage R&D. These sessions should discuss what needs to be done to continue achieving the targets and the impacts of not meeting the targets. Perhaps we can have virtual AMRs that explain the cost of meeting and not meeting energy targets. It would also be good to receive training on how to use the results of early-stage R&D. This may seem like a naive suggestion, but many of us do not work in research but do read about research and want to benefit from the research.
- Overall, the work that DOE is completing is, at the end of the day, invaluable to this community. While some of the framework may be due for a refresh, it is important to acknowledge that so many of the projects completed by DOE have had a role in launching the first FCEV market in the United States. DOE should not think of the current state of FCEVs and their deployment as taking place "eventually" or "slowly over the next xx years"; this simply will not work in the real-world political and retail marketplace.
- Suggestions include developing methods to increase collaboration, building on completed projects, and determining how to advertise success and move technology from the initial stages to deployment. The best way to do this is not obvious, but opportunities to discuss results (such as at the poster session) seem to go a long way toward building connections.
- The willingness to share R&D advancements and progress is great for overall commercialization. It would be even more beneficial to see other countries offer similar opportunities for presentation of their R&D activities and accomplishments.
- The Program should investigate further collaboration opportunities with the Bioenergy Technologies Office, including fertilizer from renewable hydrogen, farm fuels from renewable hydrogen, and oxy-combustion of biomass/waste using the oxygen co-product from large-scale electrolysis.
- The Program could benefit from bringing on board outside researchers or managers to inject fresh ideas. An NSF-style 1- to 2-year sabbatical from academia or industry might be introduced.