Sub-Program Comments Provided by Reviewers

Hydrogen Production and Delivery Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- This was an excellent overview of the sub-program, which is challenging to do because of the technical breadth. The current sub-program manager is technically and scientifically highly skilled, and this comes across in his presentation. With his background, he is more than capable of understanding and conveying the intricacies of the sub-program, from the engineering and technical end of the spectrum to the deeply scientific reaches of the sub-program.
- Yes, the sub-program was clearly described. The overall strategy was focused on delivery (including the cost of production, storage, and transfer) of hydrogen at <$2/gasoline gallon equivalent (GGE). The presentation highlighted that natural gas reforming is already able to deliver hydrogen at less than $4/GGE. Thus, the focus of the sub-program is on hydrogen production from renewable energy sources and improving delivery.
- Yes, the sub-program was adequately covered.
- The sub-program was adequately covered. The presentation was perhaps too detailed; it is not necessary to cover as much as was included in this presentation, which was clear at the end when the presenter ran out of time. (An additional note: as in the project review sessions, the moderator should start on time regardless of whether the audience is ready.)
- The sub-program was covered thoroughly. However, there was way too much information to be conveyed and absorbed in 30 minutes. The presentation deck will be a good reference document, but it was difficult to get that much out of the presentation itself because it was so rushed.
- Yes.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes, there is an appropriate balance between near-, mid-, and long-term research and development (R&D).
- The sub-program is very well balanced both in terms of technology development and R&D.
- The portfolio is well thought-out and well managed. It is underweighted on near-term opportunities for early wins.
- Yes, near-term efforts focus on lowering the cost of delivery using established methods of production (e.g., natural gas reforming). Mid-term projects revolve around emerging technologies, including electrolysis, for large-scale production. Long-term efforts are in photoelectrochemical (PEC) and solar thermal hydrogen production.
- Yes, there is an appropriate balance, although it is not always clear what topics fall under long-term research—this could be clarified in the presentation.
- Yes.

3. Were important issues and challenges identified?

- Key challenges were highlighted, including the durability of hoses, the cost of the delivery station, and electricity cost as a driver for the production of hydrogen via electrolysis.
- Yes, the need for reducing the cost (dollars/kilogram) of hydrogen dispensed at the nozzle was identified.
- Yes, all major issues were identified.
- The challenges in this area were very thoroughly described and clearly presented.
- More thought should be given to identifying key challenges to “bridging” production technologies that would lower the cost of hydrogen and expand availability in the near term, which could accelerate the growth of fuel cell electric vehicles (FCEVs).
- Yes.

4. Are plans identified for addressing issues and challenges?

- The sub-program features well-thought-out plans that have led to a well-balanced portfolio that seeks to address the short-, medium-, and long-term challenges for hydrogen production and delivery.
- The plans are described in detail in the respective project presentations.
- Yes, plans are identified, but the plans appear largely focused on small stations and small-scale production capacities (even with an acknowledgement that the amount of hydrogen needed for "X" number of FCEVs would outpace current U.S. capacity). In addition, the hydrogen cost-reduction targets are not associated with small-scale production.
- Each of the challenges is being actively addressed with new materials discovery efforts. However, the presentation provided very little articulation of the challenges and innovative efforts in solar PEC production of hydrogen.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Yes—progress in each of the core areas of solar hydrogen; solar thermochemical; polymer electrolyte membrane (PEM) electrolysis; and compression, storage, and dispensing (CSD) was discussed in detail.
- Yes, progress was clearly benchmarked against the previous year.
- Progress, as usual, was clearly described against prior years' work.
- No, it was not clearly benchmarked, other than via some budgets for fiscal year (FY) 2015 and FY 2016.
- No.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, the projects in this technology area are clearly addressing the broad problems FCTO is trying to solve.
- Absolutely. Development and understanding of this area are critical for the entire fuel cell enterprise to exist.
- Yes, efforts in this sub-program are well aligned with the objectives of FCTO.
- Yes. *(2 responses)*

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program is very well focused, even though it is technically very broad, with activities ranging from pipelines and corrosion to hydrogen-producing bacteria. This is a very well-managed portfolio, and the sub-program manager is technically competent and well informed. It is terrific to see such scientifically and technically competent managers running a portfolio in an applied technology office.
- Yes, the sub-program features a blended mix of near- and long-term efforts. The near-term efforts focus on cost-effective storage and delivery, and the long-term efforts focus on solar hydrogen.
- Yes, the sub-program appears to be well managed.
- Yes, it does appear to be focused, but there are some exceptions.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- An example of a project standing out as a strength is the project involving nanosonic and new 700 bar hose development. There is currently only one supplier in the U.S. market. An example of a project standing out as a weakness is the H2FIRST Reference Station Design project. This project clearly showed that at the sizes of stations chosen, $4/kg will not be achieved.
- The sub-program's projects have no weaknesses. The strength is in a good balance of short- and long-term technology development activities, and a very good medium-to-longer-term R&D component looking at

renewable hydrogen pathways. A key strength is the coupling of technoeconomic analysis early in the project lifetime to maximize impact.
- The solar pathway projects stand out as being innovative and forward-looking.
- One project not even mentioned in the sub-program highlights deserves a higher emphasis—the Lawrence Livermore National Laboratory (LLNL) liquid hydrogen compressor project seems to offer a major solution to the primary cost component of hydrogen stations: compressor capital expenditures and reliability. One weakness is the emphasis on solar thermochemical (STCH) projects. At the current cost of solar heliostat fields (i.e., $4,352/kW average of literature sources), the cost of hydrogen for just the capital recovery of the heliostat and power tower capital costs would be $7.94/kg (assuming 25% annual solar capacity factor and a 12% annual capital recovery factor; this calculation also assumes the STCH electrolyzer is free). However, Savannah River National Laboratory claims it can achieve STCH hydrogen cost of $4.35/kg or less. It was mentioned that this cost assumes heliostat cost reductions under the U.S. Department of Energy (DOE) "SunShot" program. It is not clear whether these SunShot cost reductions are achievable. It is also not clear whether the STCH projects have undergone the rigorous design for manufacturing and assembly (DFMA) cost analysis that most hydrogen research areas have used. It would not be fair if these STCH projects are funded at the expense of other hydrogen production pathways that receive lower funding due to negative DFMA cost estimates. At the very least, the STCH projects should provide the assumed cost reductions in the heliostat and power tower used in deriving their low hydrogen costs.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes, they do represent novel and innovative methods to approach these barriers; the solar pathway projects are particularly novel and innovative.
- Yes, they do represent novel and innovative methods to approach these barriers, with the exception of the LLNL liquid hydrogen thermal compressor concept that was not emphasized.
- Given the breadth of the technology represented within this portfolio, this is almost not a fair question. Clearly there are highly innovative approaches being supported in the R&D portfolio; the technology development area is also solid, but of course it may not appear to be as innovative. Integrating such a broad portfolio into an effective overall sub-program is perhaps innovative.
- The approaches are not particularly novel, but the sub-program stresses the discovery and development of novel materials to enable high performance from known device architectures.
- Yes.

10. Has the sub-program engaged appropriate partners?

- The sub-program has engaged a multiplicity of partners across the breadth of the sub-programs. This collaboration is conducted at a more-than-appropriate level, considering how critical this sub-program is to the overall FCTO goals. Without a solid hydrogen production and delivery portfolio, the rest of FCTO would suffer.
- The sub-program features so many collaborations that it is not clear how it keeps track of all of them. However, it appears the list does not include analogous government efforts in Germany and Japan, which are also doing a lot of work in hydrogen/FCEVs.
- Yes, the sub-program has engaged the appropriate public laboratory and private industry partners.
- Yes, it has engaged appropriate partners, but the collaborations can be expanded. The sub-program is missing collaborations with other federal agencies, such as the U.S. Department of Transportation (DOT), Federal Transit Administration, and U.S. Environmental Protection Agency (EPA), as well as with different departments within these agencies, such as the Pipeline and Hazardous Materials Safety Administration and the National Highway Traffic Safety Administration.
- Yes.

11. Is the sub-program collaborating with them effectively?

- The sub-program appears to be collaborating effectively to continue to make progress across a broad set of technical and scientific fronts.

- Yes, the sub-program appears to be collaborating with partners in an effective manner.
- It appears the sub-program is collaborating effectively.
- It appears the sub-program is collaborating effectively, but it was not clear from the presentation, because of the time limitation.
- One is not able to judge the effectiveness of the collaborations based on the presentation.

12. Are there any gaps in the portfolio for this technology area?

- At present, there are no gaps.
- There were no detectable gaps.
- One gap is mobile fueling at 700 bar (subtopic 1b was missing from the description on slide 32 about the FY 2015 funding opportunity announcement [FOA]). Also, the Hydrogen Production and Delivery sub-program applies mainly to passenger vehicles—it would be good to emphasize medium- and heavy-duty FCEVs in light of increasing market and policy interest in these applications.
- There may be more opportunities to address significant near-term challenges, such as carbon capture for natural gas reforming.

13. Are there topics that are not being adequately addressed?

- There are no detectable weaknesses in the set of topics that this sub-program has elected to support.
- At present, there are no topics being inadequately addressed.
- Topics not being adequately addressed include (1) transit fuel cell bus fueling and the cost of hydrogen in a balanced supply and demand situation, as well as fuel cost targets for this area, and (2) medium- and heavy-duty fuel cell vehicle fueling and fuel cost targets for this area.
- The LLNL thermal compression at liquid hydrogen stations project should be emphasized and given adequate funding—this technology could make the low cost of delivered liquid hydrogen even more competitive by eliminating mechanical compressors, the component with the highest capital cost and highest operations and maintenance cost.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- The sub-program appears to be addressing the barriers to hydrogen production and delivery within the bounds of its budget in a rational, well-balanced manner.
- Aside from pipeline cost, the sub-program should consider the feasibility of laying pipelines in urban areas, in light of challenges with “Not in My Back Yard” (NIMBY) and other aspects of implementation. These challenges could be so limiting that DOE should not focus on pipelines as much when determining long-term practical and realistic solutions within U.S. metropolitan regions.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The sub-program should continue on its current path. There are no recommendations that might make a substantial improvement in how the sub-program is going about its business.
- This sub-program appears to be very complete in its coverage.
- The sub-program needs to revisit the cost of liquid versus gaseous hydrogen delivery. It has been calculated that the cost of liquid hydrogen stations is less than the cost of gaseous hydrogen stations, while slide 14 from H2FIRST shows a higher cost for liquid hydrogen stations than for gaseous hydrogen stations. However, in 2013, the National Renewable Energy Laboratory (NREL) estimated that gaseous hydrogen stations cost approximately 60% more than liquid hydrogen stations ($2,190/kg/day versus $1,300/ kg/day), and NREL estimates that the all-in costs of delivered hydrogen from a central biomass plant are higher with gaseous hydrogen delivery than liquid hydrogen delivery ($5.74/kg versus $5.12/kg).[1] Most convincing,

[1] See T. Ramsden et al., *Hydrogen Pathways: Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios*, NREL/TP-6A10-60528 (Golden, CO: National Renewable Energy Laboratory, 2013), http://www.nrel.gov/docs/fy14osti/60528.pdf.

however, is the choice made by industry for the fuel cell material handling equipment (MHE) market: most are using trucked-in liquid hydrogen instead of trucked-in gaseous hydrogen. In addition, Linde has chosen liquid hydrogen delivery for five stations in California. If the LLNL thermal liquid hydrogen compressor approach works out, it will further reduce the cost of liquid hydrogen (the previously mentioned liquid hydrogen costs all assume mechanical compressors reach pressures to fill 700 bar tanks).

- The sub-program should increase its engagement with biomass/municipal solid waste (MSW) gasification technology partners—these entities will have to play an increasingly significant role to address the need for renewable content on the desired long-term scale.
- In general, DOE should put more emphasis on supporting the science that will lift all boats, versus applied engineering to bring a particular embodiment to market.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- Presently, there are no ways to improve the effectiveness of the sub-program.
- The sub-program should keep adding to the technical prowess of the management team. The management team is working to bring the right mix of skills to address the very broad set of technical, engineering, and scientific challenges of the sub-program.
- Sub-program managers should pressure principal investigators (PIs) to focus all (or nearly all) their effort on key technical challenges—the PIs should identify these challenges and do research to address them. Asking the projects to encompass everything from fundamental science to demonstration units dilutes the effort. Projects end up addressing engineering issues that, while important, are not going to make or break the technology.
- The sub-program should focus more on the solar thermal hydrogen production space. This approach is deserving of higher attention relative to PEC, particularly given the significant PEC efforts in DOE's Office of Basic Energy Sciences (BES) and at the Joint Center for Artificial Photosynthesis (JCAP).
- The sub-program should consider expanding its international partner base and funding two or three shared projects in common-interest topic areas for hydrogen production and delivery.

Hydrogen Storage Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- The presentation offered a clear overview of the sub-program strategy and a succinct snapshot of the overall portfolio and future directions.
- The strategy was clearly articulated and justified. The sub-program manager is well regarded internationally, and thus his observations on the "state of the art" are, as usual, well received.
- Yes. Clear, numeric goals were expressed. The presentation did a reasonable job of outlining how the present project mix is aimed at accomplishing the goals.
- The overall strategy—and specifically, the short-term strategy—was well covered and explained.
- Yes, the sub-program was covered very well.
- Yes, the sub-program manager did a very good job in providing an overview of the Hydrogen Storage sub-program's goals and objectives. Additional emphasis could be placed on the need to improve cost, gravimetric and volumetric capacity, with linkage to higher-level vehicle parameters (e.g., range).
- The sub-program has evolved to include an appropriate mix of near- and long-term research. It may be worthwhile to examine the longer-term areas of work (e.g., cryo-compressed, materials, sorbents, and chemical) and consider cutting efforts in areas with little chance of meeting goals and increasing efforts in more promising areas.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes. Near-term work appropriately centers on cost reductions for compressed hydrogen storage; in particular, it focuses on the cost of the reinforcing fiber either through cheaper carbon fiber or advances in new generations of fiber glass. Long-term work correctly centers on solid media. Mid-term work centers on cryogenic compressed-gas storage. When questioned whether the original equipment manufacturers (OEMs) would tolerate more operationally complex cryogenic and solid-state systems, the manager stated that vehicle range was still of paramount importance. One other important near-term activity is the use of intermetallic (heavy) hydrides for industrial forklifts.
- Yes, this balance was clearly described.
- The portfolio is well balanced. However, further clarification concerning the future of the chemical hydrogen storage activity would be helpful. Although chemical hydrogen storage is listed as a "longer term approach," it is not at all clear whether there is any interest from the DOE Hydrogen and Fuel Cells Program (the Program) in pursuing this technology in the future. A candid and straightforward statement that expresses the position of the Program on that technology would be useful for the hydrogen storage community.
- Yes, slide 3 provides a clear indication of the near- and long-term research portfolio. It may be helpful to have some simple metrics that indicate the number of projects in the portfolio that are near term versus long term.
- There seems to be good focus on near-term (e.g., compressed) and long-term (e.g., materials, sorbents, and chemicals) efforts. Cryo-compressed appears to be the only mid-term technology. Conformable compressed may also be a mid-term technology.
- The portfolio may be in transition. There is a short-term emphasis on high-pressure tanks. As high-pressure tanks are now becoming commercially available, some shifting away from R&D on carbon fiber development may be warranted because that is clearly in the domain of commercial entities. While some DOE investment is still perhaps warranted for particular aspects of removing the cost barriers, perhaps more funding emphasis could go toward medium- and long-term materials-based strategies that can be potential game changers. The longer-term portfolio is now heavily weighted toward adsorbents and complex metal hydrides. The R&D emphasis on complex metal hydrides is less well justified, because research in this class of materials seems to not be focused on achieving higher kinetics and lower temperature release. Wholly new long-term strategies should be sought, or new perspectives on complex hydrides need to be added.
- Currently, there seems to be more emphasis on meeting short-term targets (e.g., reduction of high-pressure tank cost) and tank engineering led by the Hydrogen Storage Engineering Center of Excellence (HSECoE).

3. Were important issues and challenges identified?

- Barriers and future challenges were well identified, with the current commercial availability of high-pressure tanks driving a reemphasis on higher and higher capacity materials that can meet the targets.
- Yes, important issues and challenges were identified, especially for the materials-based storage initiative.
- Both technical and economic challenges have been clearly understood and explained by the sub-program.
- Yes—cost, weight, and volume were identified, above all others.
- Yes—slide 3 ("…Strategy and Barriers") provides a good summary.
- Challenges were identified. It would have been helpful for the presenter to have shed more light on the "lessons learned" from the HSECoE; for example, the presenter could have highlighted key technology hurdles identified by the HSECoE.
- Yes, the barriers and R&D focus were identified during the presentation. There are certainly many challenges with the hydrogen storage system. In the future, it may be beneficial to highlight a prioritization of the challenges.

4. Are plans identified for addressing issues and challenges?

- Plans were presented to overcome existing challenges.
- Yes, plans were identified quite well.
- Yes, there is a good mix of projects to address the barriers. In the review of project accomplishments, it was helpful to have the summary statements at the bottom of the slides to directly identify the linkage between the projects and barriers.
- This sub-program has a long history of addressing these challenges (which have not changed over the history of the sub-program). Practical solutions have proved hard to find.
- Future approaches to "beat the tank" appear to be largely focused on incremental research on adsorbents and complex metal hydrides. Longer-term research on somewhat riskier, but high-payoff approaches could be sought.
- A plan that identifies issues and challenges was provided only in an indirect way. The presentation summarized the accomplishments, highlights, and plans of current and future projects in the portfolio. It was necessary to "read between the lines" to extract information concerning plans for a coordinated and coherent effort to address issues and challenges.
- Plans are not specifically spelled out for the identified issues; this is normal because the plans are described in the appropriate session presentations and not in this overview.

5. Was progress clearly benchmarked against the previous year?

- Yes, progress with respect to the previous year was indicated; the summary of the past six years of effort on storage by the HSECoE was good.
- The accomplishments were well characterized against prior years' accomplishments.
- Yes, the progress accomplished this year, compared to last year, was clearly communicated.
- Yes, progress was benchmarked in good detail for compressed gas storage. However, there was not much detail for progress in the other technology areas.
- The progress of compressed hydrogen system cost was clearly indicated from the previous 2013 record. It would be useful to identify other metrics to track progress, especially with the material-based storage system. Further highlights on how the DOE portfolio has made a difference in advancing hydrogen storage technology should be included. The metal hydride forklift was a great example of DOE research making a difference in a potential commercial product.
- Progress in all current projects and plans for new project work was summarized in an effective way. However, only very limited benchmarking against progress from the previous year was provided.
- Lowering the costs of carbon fiber is a challenging goal in a mature industry, but the sub-program has made significant progress in reducing costs by using novel precursors and optimizing processing variables. While the HSECoE has made significant progress in understanding the engineering demands of viable storage systems, this effort may have been premature in that as it comes to its planned completion, no workable materials have yet been identified

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, the projects are focused on (1) reducing the cost of the hydrogen storage system to lower the fuel cell vehicle cost and (2) improving storage system performance to meet the important vehicle attribute of driving range.
- Absolutely—the links between the different projects and the problems/barriers are clearly spelled out.
- Yes, the projects address the broad problems FCTO is striving to solve.
- Yes, storage (vehicle range) remains a serious remaining problem within FCTO.
- The Hydrogen Storage sub-program is and has been well focused on the broad and difficult problem of identifying viable hydrogen storage approaches that will surpass the performance of high-pressure storage tanks for onboard applications. The large Centers of Excellence or Center-like activities have led to large gains in understanding the practical limitations of various approaches, and have helped focus current and future research on addressing the remaining barriers. Hydrogen storage is a daunting problem, and the solutions, if they exist, will require a high degree of scientific and technical creativity. The current portfolio could be improved by seeking longer-term, riskier—but high-payoff—research directed by engineering assessments of what materials properties are required to meet the DOE targets.
- In general, yes—a reasonable portfolio of near- and longer-term approaches is in place. At present, there appear to be only two candidate technologies that are attractive in the short-to-mid term: (1) 700 bar compressed gas, and (2) sorbents (and, potentially, cryo-compressed). The other solutions, especially metal hydrides and chemical hydrogen storage, have serious limitations that may preclude their deployment in a practical system (unless major advances occur).
- Storage issues are central to the implementation of fuel cell vehicles. The sub-program has worked hard to find new methods of storing hydrogen. These efforts have not developed viable solutions, and the sub-program has refocused to address lowering costs for traditional high-pressure storage.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program is very well managed. The sub-program managers and staff have considerable expertise and experience in all focus areas of the sub-program, and they fully understand the benefits and limitations of specific technology areas. The sub-program effectively addresses FCTO's needs. The recognition by the DOE Hydrogen and Fuel Cells Program (the Program) that additional basic and fundamental materials work is needed represents a departure from the traditional Office of Energy Efficiency and Renewable Energy (EERE) charter. This is a very reasonable point of view, and it should be a sub-program imperative.
- This sub-program continues to be a very well-managed enterprise. The sub-program manager is a well-recognized technical expert in this area, and his reputation and expertise have helped the Hydrogen Storage sub-program. The DOE management team (based in Washington, DC, and the Golden Field Office) is excellent overall.
- Yes, the sub-program is focused on FCTO's needs: lower FCEV cost and improved driving range. The sub-program managers are very effective and focused on managing the projects. This sub-program provides high value to FCTO.
- The sub-program has done a good job of moving from its initial focus on hydrides and materials to a broader approach that includes optimization and cost reduction for compressed hydrogen.
- Yes, this sub-program is focused and well managed.
- The sub-program is well managed and focused.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The progress being made on the alane cost reduction project is noteworthy. The new project on conformable high-pressure storage (ST-126) could be a game changer for onboard 700 bar storage.
- The spider charts summarize each project's status and identify weaknesses in a concise and effective way. The incumbent technology, compressed gas, will never meet the volumetric target; sorbent technology

requires cooling and is costly. Likewise, existing sorbent systems fall short of gravimetric and volumetric capacity goals—material advances are needed. Light-metal and complex hydrides suffer from severe kinetic limitations and, in most cases, limited capacity. Chemical hydrogen storage systems are encumbered with the need for regeneration—the large overhead cost for system regeneration may eliminate this technology from future consideration unless a simple process can be identified.

- Some of the materials-based projects appear to be providing incremental advancements in knowledge of storage materials and are not well poised to create "breakout" advances. The current strength of the sub-program is the engineering assessments area, which is providing guidance to materials and systems developers. An area that has provided recent scientific advances is the area of "metal-assisted" sorption in high-surface-area adsorbents, wherein the included metals act to bind additional hydrogen molecules with somewhat higher binding energies. While this approach may not result in a technical advancement for hydrogen storage, it has shown how far one can go with this approach; from that perspective, it is a strength of the sub-program—the willingness to follow through to ensure that the science indeed is providing evidence of barriers that may not be achievable by certain approaches. Negative evidence is valuable in the daunting search for the hoped-for practical hydrogen storage system.
- Key strengths include the focus on immediate challenges with high-pressure tanks and the understanding of engineering challenges associated with materials-based storage. An area of weakness is that, although the sub-program has recently funded a few projects that address long-term materials-based storage, the attention and funds allocated to long-term materials-based solutions still seem insufficient.
- The key strength is the fact that the near-term projects on compressed hydrogen storage are relatively straightforward relative to the cost and engineering aspects of the technology needed. The inherently weaker projects are those associated with science-based solid-state storage media. The science of these materials is relatively new and requires significant breakthroughs.
- The projects in the sub-program are well balanced. There are a few projects that do not seem to be aligned with automotive applications. Also, there are some projects that have good intentions but may need some redirection to ensure the approach aligns with the most significant barrier for the technology.
- The continuing work on materials-based storage solutions (e.g., hydrides, sorption, and chemical storage) has been disappointing, given the high hopes present in the early days of the sub-program. Given the large expenditures to date and the failure of the sub-program to come up with promising materials, FCTO should consider the desirability of continuing efforts in this area.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- There are many novel and innovative projects in the sub-program. The sub-program managers are very good at selecting projects that target key barriers.
- Yes, the alane and conformable 700 bar projects both represent novel/innovative ways to approach the FCTO barriers.
- The sub-program has used novel approaches to lower costs and improve performance.
- Yes, the projects associated with solid storage media represent innovative ways to approach the barriers. The DOE projects represent a pioneering effort. Unfortunately, solid storage is a very difficult technological subject.
- The projects that compose the overall portfolio generally offer innovative approaches to address the barriers. With one or two exceptions, the new projects provide some interesting options for tackling the barriers in novel ways. The efforts of FCTO to create the Hydrogen Storage Materials – Advanced Research Consortium (HyMARC), comprised of national laboratory partners, is great. With the completion of activities in the three materials centers and with the HSECoE activities drawing to a close, there is a critical need for an overarching collaborative effort that focuses and coordinates R&D activities in hydrogen storage. Without such an entity, the sub-program simply becomes a mix of largely uncoordinated R&D and engineering efforts that lack the cohesion and cooperation that a Center provides.
- In general, the projects present innovative ways to approach the barriers. However, the uniqueness of some of the recently funded projects is unclear.
- While detailed information on several new projects is still to come, from the brief descriptions, these projects would appear to not be particularly innovative, but rather incremental in nature.

10. Has the sub-program engaged appropriate partners?

- The sub-program features good work on leveraging carbon fiber work being supported by other DOE programs, such as the Advanced Manufacturing and Vehicle Technologies Offices, and takes advantage of existing Oak Ridge National Laboratory (ORNL) facilities. Input from OEMs on the U.S. DRIVE Partnership Technical Teams has been valuable in formulating and guiding hydrogen storage projects toward practical goals.
- Yes, the sub-program has engaged a very impressive spectrum of participants: universities, national laboratories, consulting scientists and engineers, industry, OEMs, etc.
- Yes, the sub-program has done an excellent job in engaging partners. In particular, the DOE materials-based hydrogen storage summit was very useful in bringing the experts together.
- The sub-program has continued to be one that attempts to collaborate with other R&D entities.
- The sub-program has indeed engaged the appropriate national laboratory and private partners.
- The sub-program brings together highly competent partners.
- The projects in the current portfolio are highly relevant to the overall goals of the DOE Hydrogen Storage sub-program. However, a formal framework that initiates and sustains collaborations is not currently in place; i.e., cooperation and multigroup interactions are encouraged, but they are only informal. The new HyMARC program could go a long way to formalize fruitful collaborations among national laboratories and industry and academic partners.

11. Is the sub-program collaborating with them effectively?

- There are strong, beneficial connections and collaborations between the sub-program and all existing projects.
- Yes, the sub-program is collaborating with partners very effectively. The communications among the many partners is extraordinary.
- Yes, the sub-program has connections with the industry experts and seeks their input regarding the research.
- The sub-program appears to be collaborating with partners in an effective manner.
- Yes, the collaboration between the sub-program and partners is visible.
- This sub-program, like so many other applied sub-programs, has difficulty crossing the boundaries to the Office of Basic Energy Sciences (BES) “silo” to engage in collaborative longer-term, riskier, but high-payoff R&D in the chemistry and materials studies relevant to hydrogen storage.

12. Are there any gaps in the portfolio for this technology area?

- This technology area is adequately covering the problem areas with the current portfolio of projects.
- There are not really any gaps within the known and likely technology. However, any hints of possible new technologies showing any theoretical promise should be carefully considered for the portfolio.
- The sub-program appears to be covering most of the promising technologies in hydrogen storage with few gaps.
- The sub-program managers have acknowledged the critical need for more robust basic/fundamental research activities to address the critical challenges faced by hydrogen storage materials. With the completion of the materials centers, there has been only a very limited opportunity to explore important thermodynamic and kinetic obstacles. The new HyMARC program is a good first step toward providing a framework for obtaining deeper fundamental understanding. It will be essential for DOE to strengthen cooperation across Program offices (e.g., EERE, BES, and the Advanced Research Project Agency – Energy [ARPA-E]) and with other agencies (e.g., the National Science Foundation) to ensure that critical research issues are addressed in the most efficient and effective way.
- The lack of highly innovative longer-term strategies for onboard hydrogen storage is a significant weakness and detracts from the overall effectiveness of the sub-program. There seems to have been a downward trend in the fraction of longer-term R&D in this portfolio in the last several years. However, there appears to be a desire to add more materials R&D back into the sub-program; if more materials R&D projects are selected, there may be a reversal in this trend.

- It appears that cryo-compressed, cold gas, or adsorbents have the potential to be a near-term alternative to compressed hydrogen. Therefore, the development of robust advanced insulation of these systems would be useful.
- More emphasis is needed on long-term materials-based solutions.

13. Are there topics that are not being adequately addressed?

- All topics are being adequately addressed, at least within the spectrum of known technology. New ideas and rational theoretical analyses are needed.
- The development of innovative materials-based long-term solutions is not being adequately addressed.
- At present, all topics are being adequately addressed.
- The boundary conditions on materials that can meet the targets are now better understood and are very constraining. The solutions to these conditions will require new, "out-of-the-box," and perhaps risky R&D. The sub-program is encouraged to find ways to encourage those not entrenched in the "business as usual" approaches to storage, and to attempt wholly new approaches to the storage of hydrogen in a manner that has a chance of meeting the targets.
- The Program is encouraged to make a more definitive and straightforward statement to the research community about its future plans for chemical hydrogen storage.
- In projects that include a significant amount of modeling, validation of or reference to the model assumptions would be useful for observers to gain confidence in the project teams' predictions.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- At present, there are no other areas the sub-program should consider funding to meet overall programmatic goals.
- No additional noteworthy areas are recommended for funding.
- There are two possibilities, both of which were briefly considered for the storage problem decades ago:
    - (1) Rechargeable Liquid Organics – Catalytically decompose onboard, then pump out the H-depleted compound(s) for off-board regeneration. Perhaps a new generation of organic chemists can come up with new theoretical possibilities.
    - (2) Liquid Anhydrous Ammonia (17.7 wt.% H) – The direct burning of NH_3 was demonstrated in internal combustion engines at least a half century ago. Perhaps NH_3 can be made cheaply and cracked, and then the hydrogen could be purified to the level needed for it to be used in a fuel cell.
- The complex metal hydrides area is largely populated by materials scientists, who are taking a materials science approach to improving the materials. Perhaps adding co-researchers to these teams that have a better understanding of the covalent chemistry of this class of materials would enable different approaches to be utilized to overcome some of the kinetics issues with hydrogen release and uptake, as well as provide a "fresh set of eyes" on the problem. Looking at other covalent X-H compounds may be profitable.
- Efforts could be included to reduce the complexity and cost of the balance of plant (BOP) in all the storage systems. The HSECoE provided a good understanding of the BOP schematics and content. The next step would be to develop opportunities to reduce the number of items and confirm new designs with a complete BOP demonstration.
- Areas that the sub-program could fund include innovative materials-based solutions that are theoretically capable of meeting the DOE targets (as estimated using HSECoE generated models).

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The efforts to establish and fund the HyMARC activity are great. The consortium will provide a solid foundation for conducting collaborative research on important problems. DOE should move to rapidly include academic and industry participation in the consortium.
- Over the past few years, the sub-program has produced modeling tools that allow the researchers to (1) determine upfront whether the materials they propose are at least theoretically capable of meeting the DOE targets and (2) identify the challenges that need to be addressed. That said, if DOE decides to place more

emphasis on long-term materials-based R&D, the researchers should be asked to justify the viability of their concepts using these tools.

- There are a few compounds or classes of compounds that have some promise, but they release hydrogen at too high of a temperature, or too slowly, or both. This may represent an opportunity to better understand catalysis in these condensed phases, which is difficult. Assembling materials development teams that include catalysis and more chemical science-oriented researchers may provide ideas to address the kinetics limitations of certain classes of materials.
- The safety considerations of every new storage technology should be clearly identified and considered both in a normal situation and a failure situation. Projects should make statements about their safety consideration of the technology and attempt to connect with safety organizations.
- The continuing work on materials-based storage solutions (e.g., hydrides, sorption, and chemical storage) has been disappointing, given the high hopes present in the early days of the sub-program. With the large expenditures to date and the failure of the sub-program to come up with promising materials, FCTO should consider the desirability of continuing efforts in this area. It is not clear what the new materials consortium will do that has not been done in the last 10 years.
- At present, there are no recommendations.
- At the moment, there are no recommendations.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The Hydrogen Storage Summit held last January was successful. It provided a forum for researchers to discuss new R&D needs and express their candid opinions about current Hydrogen Storage sub-program directions. A similar summit should be convened every 2–3 years.
- In addition to this written evaluation, DOE should try a short (two hours), open brainstorming workshop at the Hydrogen and Fuel Cells Program Annual Merit Review (AMR). Of course, participants would not likely disclose any new specific ideas of potential patent value, but a discussion of the pros and cons of new scientific and technological areas might be useful to general DOE thinking and also stimulating to the participants.
- The challenges with hydrogen storage systems are daunting, and while high-pressure tanks are important for initial market penetration, long-term solutions need to be developed. Therefore, one suggestion would be to have more frequent workshops or ways to bring together researchers and engineers to discuss these issues and make recommendations to DOE.
- It would be helpful to have “guesstimates” on the anticipated “time-to-market” of the various alternative material storage projects that are being funded, as well as some indicator of the expected impact.
- A red team approach to sorption might be useful. It is not clear whether the existing approaches can really get anywhere. A very hard, critical look at this area may help improve the overall effectiveness of these sorption projects.
- All projects should have a connection to an industry partner, either as a partner or a consultant, to ensure the research is on a path to commercialization.

Fuel Cells Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- The highlights from the Fuel Cells sub-program-funded projects were well covered. The overall strategy was also presented well.
- The sub-program covered cost reduction, durability strategies, and projects with various collaborators very effectively.
- Yes, the sub-program covered the fuel cell activities well.
- Yes, the sub-program was sufficiently covered, including the detailed overall strategy.
- Goal and gap analysis was pursued, and focus areas are identified properly. However, information on the approach and how to fill the gaps is not clearly identified. Each Funding Opportunity Announcement (FOA) seems to be ad hoc. A consistent strategic plan was not presented. The sub-program should show its desired research portfolio (what should be) and the gap from the current research portfolio. Future FOAs should be developed to fill the portfolio gap. A review of results from the recent Fuel Cell Technologies Office request for information (RFI) and workshop, which asked for feedback on necessary R&D areas, would have been helpful. It is also important to show the benchmark analysis of foreign governments' funding programs to allow for comparison with the DOE research portfolio. The European Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and Japanese New Energy and Industrial Technology Development Organization (NEDO) projects have comparable funding levels and should be benchmarked.
- Yes—this is clearly a large and diverse sub-program, and the topics that were the focus of the past year were presented well. Additional information on topics within the sub-program that were not a focus in this past year could have been covered a little more thoroughly, such as by acknowledging and describing their role in the multiyear effort.
- The sub-program was represented well. While it is clear that automotive targets are well established, the technical targets for non-automotive applications are not provided in detail.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes. A lot of this work will take time to achieve success and implementation, but there is an appropriate degree of urgency to the work in order to ultimately facilitate successful commercial introduction of these technologies.
- The balance appears appropriate, even though long-term research only concerns catalysts and membranes for low-temperature PEM fuel cells. Materials for medium- or high-temperature PEM fuel cells or materials and coating for bipolar plates (BPs) may also be included. Because fuel cell cost projections unfortunately remain almost stable since 2011, projects with a high potential of achieving a technological breakthrough—even if they are high risk—might be initiated.
- Yes, the R&D portfolio is adequately balanced between near-term and longer-term impact items. The majority of the funding is focused on longer-term cost-reduction activities and in the pre-integration activities. Technology development and scale-up of the latest generation catalysts, to move these from Technology Readiness Level (TRL) <3 to >5, might be considered medium-term activities.
- The emphasis on cost reduction and performance, based on catalyst and membranes, was well documented in the presentation. It would have been nice to get some information on BP development, because BPs are the next highest cost contributor after catalysts and catalyst application.
- The presentation did not discuss the balance among the different time frames (i.e., near, mid, and long terms). However, research in this area is in the precompetitive phase and is basically mid- or long-term research.
- Yes. *(2 responses)*

3. Were important issues and challenges identified?

- Yes, the sub-program is clearly driven by attainment of the market-driven targets, and the barriers to achieving those targets were presented well.
- Proper gap analysis was done with the U.S. DRIVE Fuel Cell Tech Team. Important issues and challenges were identified.

- Yes, the challenges and issues were identified, and the key focus areas were addressed clearly.
- Yes. Challenges and strategies to address them were well identified.
- Yes, challenges are clearly identified.
- The main challenges remain cost and durability, which are well identified and addressed. The following challenge will be manufacturing with cost and quality targets, and this is addressed in the Manufacturing sub-program. The 70% system efficiency target appears to be a concern. Indeed, taking a 10% parasitic loss leads to an average cell voltage of 1 V, and even taking 0% of parasitic loss leads to an average cell voltage of 0.88 V. Today these values appear to be unrealistic while looking for lower Pt loadings and increased durability. Announcing this kind of over-aggressive target does not contribute to the scientific credibility of the sub-program. Increasing the power density is an important item that was identified—several projects on catalyst, membrane, and membrane electrode assembly (MEA) address it. BP and stack designs also have a big impact on power density, but since they are not addressed in the sub-program it appears that BP and stack design are internal OEM tasks. Therefore, stack data with MEAs developed within the sub-program should be provided by OEMs to better quantify the current situation. Another option might be to use an "open" BP design representative of automotive applications.
- Yes.

4. Are plans identified for addressing issues and challenges?

- Yes; the sub-program seems to go to great pains to assess multiple potential paths to success, which is necessary and should continue to be reinforced for the heavily R&D-focused work that is included within the sub-program.
- The FCTO Multi-Year Research, Development, and Demonstration Plan (MYRDDP) is well structured, with clear targets and items to be addressed. The cost drivers to achieve the $40/kW target have been identified, and the funded projects align with this target.
- Yes, high-level plans for gap closure have been identified.
- Yes. *(4 responses)*

5. Was progress clearly benchmarked against the previous year?

- Progress has been presented during this AMR (e.g., platinum group metal [PGM] and non-PGM catalyst performance improvement). The impact of these improvements is still unclear because the fuel cell cost projections have remained almost stable since 2011. Ionomer mapping achievements appear to be a highlight of this year, and ionomer mapping will definitively contribute to improving short-term MEA performance and durability.
- Yes, the progress was clear, and major achievements were comprehensively described.
- Progress over the years was presented; however, a direct comparison between this year and the previous year was not explicitly provided. The one exception seemed to be the work on PtNi nanoframe catalysts.
- No, just the latest highlighted accomplishments are presented. It is a recommended point to track the progress of focus areas, rather than highlight accomplishments ad hoc.
- Yes. *(2 responses)*

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes. FCTO projects are addressing a broad scope of problems that are the highest-cost elements in a fuel cell system.
- Yes, the work appears to be driven primarily by cost and durability targets, which directly address FCTO's work to achieve commercially viable fuel cell systems.
- The projects cover the main barriers. Nevertheless, taking into account the cost drivers to reach the 2020 target, it appears that some key elements (e.g., air compressor/expander module – $5/kW, BP – $2/kW) are only addressed through one project. At least a second project may be initiated to avoid relying on a single potential solution.

- There was not a clear connection between focus areas and the current or future research portfolio. It is very important to make visible how the research portfolio is related to the focus areas (e.g., problems and barriers).
- Yes. *(2 responses)*

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program appears to be well structured and well-focused.
- Yes, the sub-program was focused and well managed.
- The sub-program seems to be connected to the U.S. DRIVE Fuel Cell Tech Team well. However, the sub-program seems to be managed without a proper research portfolio or strategic plan.
- Yes, the sub-program appears to be focused and well-managed, especially considering there are so many directions for projects to cover within the sub-program's objectives. However, the presentation of the budget and expenditures did not clearly present how project priorities shift from year to year; an alternative method of presenting this information should be developed and pursued in the future.
- Yes. *(3 responses)*

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The projects in the sub-program are well balanced and cover most of the important aspects for FCEV commercialization, which include increasing low PGM utilization; transport issues; low-cost, high-performance membranes, etc. The direct imaging of three-dimensional morphology on Nafion in the catalyst layer stands out among the projects from this year.
- The projects in this sub-program were thoughtfully organized and managed effectively, and they featured extensive collaboration efforts.
- The sub-program's key strengths are the (1) multi-annual working plan with quantitative targets for each component and subsystem, (2) well-balanced academic and industrial partnerships, and (3) ongoing projects on mechanism comprehension and material characterization. The sub-program's weaknesses are (1) basing the fuel cell cost projection on the modeling of a system design that does not exist and therefore has no real validation, and (2) limited experimental validation on even a short-stack level of all the great developments performed on a 50 cm^2 single cell. This validation may be carried out by OEMs, but releasing such results would increase the sub-program's impact.
- The key strengths are the technical rigor and the ability of the sub-program to develop some breakthrough technologies and tools. FC Application Package for Open-source Long-Life Operation (FC-APOLLO), in particular, seems like a project that will have a lasting impact and the potential to drive much future research. One weakness may be that projects are not benchmarked against each other. For example, the sub-program pursues multiple paths to achieving catalyst activity and performance targets, but there was not a clear presentation of these projects' roles within the whole of the sub-program's activities. It would be helpful to have an evaluation of the projects' status, demonstrated potential, and perhaps theoretical potential. If these data were provided for all projects side by side on a consistent basis, the sub-program may be able to gain a more complete view of the projects' effectiveness compared to one another.
- A strength is the sub-program's strong technical capabilities to advance technologies at the research organizations (e.g., national laboratories, universities, and industry). The sub-program features good connections with OEMs via discussions among the U.S. DRIVE Fuel Cell Tech Team. An area of weakness is the sub-program's ability to manage the research portfolio or communicate a strategic plan to fix the research portfolio. For example, the gap analysis showed the total cost is highly sensitive to area-specific power density (performance at the high current density). However, no research projects were funded in this area (mass transport).
- Projects related to reducing the cost of catalyst were very well documented, and various partners were involved. The development of non-PGM catalyst is very promising. Even though the objectives mentioned distributed generation and a micro-combined-heat-and-power fuel cell system (5 kW), there was nothing in the presentation to shed light in that area.

- The key strength of most projects is the ability to generate novel ideas to generate excellent options for highly active catalysts. These catalysts show good promise toward cost reduction if implemented in a fuel cell stack. However, most of these materials are made in very small batches—this might be one of the biggest weaknesses.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- The ionomer distribution visualization work is very exciting and would help to solve some mysteries about degradation inside the stack. Work at both Lawrence Berkeley National Laboratory (LBNL) and ORNL in this area is very exciting.
- Yes, there is quite a lot of novel work being completed under this sub-program. Nanostructured catalysts and FC-APOLLO stand out in this regard.
- Yes. However, most of the catalyst development projects are heavily dependent on rotating disk electrode data, and MEA confirmation is of prime importance. Some efforts were made for novel catalysts to be tested in MEAs, but MEA/catalyst layer/catalyst ink optimization is a big research topic, and more efforts should be concentrated in this area for these novel shape, low-PGM catalysts.
- Some of the projects propose novel approaches, but in general, the projects have more of a continuous improvements approach.
- Yes.

10. Has the sub-program engaged appropriate partners?

- Yes, there seems to be a good deal of industry, academic, and agency involvement.
- The sub-program's collaboration is good; high-quality academic partners and national laboratories are involved in the sub-program. The collaboration with foreign partners is also appreciated because it helps to speed up FC technology development. Collaboration with the International Energy Agency (IEA) Hydrogen Implementing Agreement (HIA) was mentioned, but the one with the IEA Advanced Fuel Cells Implementing Agreement was not.
- Yes, there is strong collaboration between the various project teams. FCTO is collaborating with agencies outside the United States as well. It might be good to have reviewers from the United States attend similar peer review meetings for Japan, European Union, and other fuel cell funding agencies.
- Yes. It would have been nice to see at least some catalyst manufacturer/developer involved in developing low-cost non-platinum catalysts.
- Yes. *(2 responses)*

11. Is the sub-program collaborating with them effectively?

- Yes, some of the major accomplishments clearly were efforts coordinated effectively.
- Yes. *(5 responses)*

12. Are there any gaps in the portfolio for this technology area?

- There are no evident gaps in the portfolio.
- This sub-program focuses more on material development, but at the end of most of the projects, the researchers fail to realize the project's application in MEAs. Efforts on integrating most of the materials (e.g., low-PGM catalysts, membrane, and supports) in MEAs need to be emphasized.
- While the focus on materials and components is understandable, there does seem to be a notable lack of system-wide technology development and research.
- It did not seem that there is much being done in the area of BP development and/or cost reduction.
- No.

13. Are there topics that are not being adequately addressed?

- No; the work that was prioritized in this past year seems to be thoroughly addressed.
- The sub-program should address the scale-up of highly active catalyst so MEA tests can be completed.

- No. *(2 responses)*

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- It was mentioned in the discussion that solid oxide fuel cells (SOFCs) fall under the purview of the Office of Fossil Energy, but the system analysis of SOFC developments from that Office could be conducted in this sub-program. This seems like an area that could use increased attention because the momentum of developments for the technology seems to have slowed in recent years. This sub-program may be able to help return some focus to the technology.
- The sub-program should consider funding MEA integration of all the promising novel catalysts and MEA optimization approaches.
- MEA and BP sealing appears to not be a problem—it is unclear whether that is the case.
- No.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- Research portfolio—goal and gap analysis was pursued, and focus areas are identified properly. However, information on the approach and how to fill the gap in the focus area is not clearly identified. Each Funding Opportunity Announcement (FOA) seems to be ad hoc. A consistent strategic plan was not presented. The sub-program should show its desired research portfolio (what should be) and the gap from the current research portfolio. Future FOAs should be developed to fill the portfolio gap.
- Regarding benchmarking foreign governments' programs, it is also important to show the benchmark analysis of foreign governments' funding programs to allow comparison with the DOE research portfolio. European FCH JU and Japanese NEDO projects have comparable funding levels and should be benchmarked.
- Regarding fixing the research portfolio, the sub-program should better manage the research portfolio and communicate a strategic plan to fix the research portfolio. For example, the gap analysis showed total cost is highly sensitive to area-specific power density (performance at the high current density). However, no research projects were funded in this area (mass transport).
- This sub-program should summarize and benchmark the status of the materials developed with DOE funding against materials developed by projects not funded by DOE. Many U.S. and international research groups keep publishing results showing high-activity of catalysts; these results need to be summarized to see where the projects under this sub-program stand in comparison.
- At this time, there are no recommendations.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The sub-program's impact may be enhanced by a systematic validation of material (e.g., catalyst, membrane, and BP) and component (e.g., MEA and BOP) developments in a stack or even in a system. This will help fine-tune the R&D activities. Air contamination is considered in this sub-program, whereas hydrogen contaminants are considered to be in the Safety, Codes and Standards (SCS) sub-program. There should be a good link between these efforts in order to collect all the results for stack and system component developments and modeling. It was not clear from the AMR whether such a link exists.
- At this time, there are no suggestions.
- No.

Manufacturing R&D Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- Yes, the strategy targets identification of the cost drivers in the manufacturing process, with a specific focus on decreasing process steps, increasing automation, decreasing waste, increasing yield, and facilitating scale-up of laboratory advances. These strategies are appropriate for this sub-program.
- Yes, the sub-program was defined clearly, and the overall strategy for the objectives was covered in detail.
- Yes, the overview gave a clear picture of the action(s) that address each barrier.
- Yes.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes, the sub-program targets integration of advanced manufacturing techniques to existing membrane electrode assembly (MEA) technologies, as well as forward-looking approaches, to speed the development of high-volume production of emerging MEAs, cell components, and delivery infrastructure.
- The sub-program was balanced relatively well between near- and mid-term R&D.
- There is less long-term emphasis. However, this is understandable because this is a crucial time and immediate issues must be resolved to facilitate market penetration and commercialization.
- In general, there does seem to be a good balance; however, it seems like the timeline for how soon some of these developments and capabilities will be necessary is a little bit longer than industry stakeholders may consider. There may be a need to provide additional funding to accelerate some of the near- and mid-term projects.

3. Were important issues and challenges identified?

- Key challenges were highlighted, including the lack of high-volume manufacturing processes, the low levels of quality control, and a lack of standard BOP components.
- Yes, key issues and challenges were clearly identified.
- Yes, key issues and challenges were identified, although there seems to be a very narrow focus on MEAs. Expanding the sub-program to work on more components simultaneously will help broaden the impact and possibly help avoid a potential delay in achieving the sub-program goals, in case projects in the highly focused areas encounter unanticipated obstacles.
- Yes.

4. Are plans identified for addressing issues and challenges?

- Yes, the sub-program targets the development of in-line, real-time tools for diagnosing quality control in MEA production. The sub-program also targets expansion of the domestic supply chain for fuel cell components.
- Yes, the presentation highlighted an extensive amount of recently commenced work that will address the sub-program goals, especially concerning supply chain issues.
- The future plan was clear and focused.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Yes, the efforts related to manufacturing and quality control of MEAs and components showed progress. The new collaboration effort with industry supply chains and the global competitiveness assessment seemed to be important achievements.
- The presentation was not strong in this regard. Some major accomplishments were announced and thoroughly discussed, but the timelines of the projects were not clearly presented. It was not clear how much of the total work was completed in the past year.

- No. A number of initiatives were outlined, but there was no clear delineation of what was accomplished in the prior year, relative to what is being proposed for the following year.
- Yes.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, high-volume manufacturing, quality control, and reliability are the key drivers for market penetration of fuel cell technologies, and this sub-program targets advancements in all of these areas.
- Yes, cost and supply chain issues remain high-priority issues in FCTO, and this sub-program addresses them well.
- Yes. *(2 responses)*

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The sub-program is well managed and broadly focused. The limited budget restricts the use of multiple approaches.
- Yes, the sub-program was thoughtfully planned and well managed.
- Yes. The targets and initiatives are not overly ambitious and are well matched to the needs of the industry sector.
- Overall, the projects do seem well managed and focused. However, they are only now commencing, and there was not a strong sense of DOE oversight and guidance for the more outreach-based projects (i.e., the Opportunity Center and the Regional Technical Exchange Centers). There very well may be detailed plans and processes for how the contracted entities will carry out these projects and coordinate with third parties while coordinating with DOE, but this was not thoroughly presented.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The extensive collaboration efforts are the key strength of this sub-program. The projects for supply chain development and competitiveness analysis appear to be nicely and thoughtfully planned.
- The projects focusing on technical capabilities are rather excellent and were clearly presented. The amount of detailed work provided confidence in the significance and utility of the developments. A key strength is the development of efficient large-area tools for assessing quality control in real time by infrared (IR) spectroscopy. The key weakness is the lack of focus on what manufacturing techniques will remain constant as the MEA technologies change. A key concern is that the efforts toward additive manufacturing or accelerating scale-up will need to be revisited as the underlying catalysts and materials are further developed. Some analysis of what will remain constant and what will change will allow this sub-program to better direct its resources.
- A weakness in the manufacturing defects projects is that the researchers do not seem to establish the character (i.e., size) of the defects that compromise performance and/or durability.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes, the projects represent novel and/or innovative ways to approach the barriers, especially in the outreach and supply chain-based projects. This type of coordinated effort is necessary and has probably been necessary for some time now. The new projects seem to address the gap that had existed.
- Yes. The projects bring together advanced spectroscopy, additive manufacturing techniques, and robust modeling to address these challenges.
- Yes. *(2 responses)*

10. Has the sub-program engaged appropriate partners?

- Yes. The sub-program has forged relationships with industrial OEM manufacturers and national laboratory partners to develop new technologies and gather data on real-world problems along the supply chain.
- Yes—the partners include market experts, manufacturers, and developers.
- Yes, the sub-program has strong engagements with regional, national, and industry partners.
- For the most part, yes, the sub-program has engaged appropriate partners. In terms of developing new knowledge, and to address most of the need to disseminate that knowledge, the sub-program has formed the appropriate collaborations. The only addition that could be suggested is to increase dissemination of the information to agencies at the state and local levels, and then to use these voices to help determine additional sub-program goals. As presented, the collaborations did not have a strong government coordination aspect.

11. Is the sub-program collaborating with them effectively?

- Yes. Through integrated regional technology exchange centers, the sub-program is able to leverage data from OEMs, connect OEMs with suppliers, and exchange information in working groups to address key challenges.
- Yes, the sub-program appears to be collaborating effectively.
- Yes. *(2 responses)*

12. Are there any gaps in the portfolio for this technology area?

- Work on compressors for infrastructure remains a very high-priority need for the near-term market. It is good to see work on making longer-term solutions such as pipelines potentially viable in the near term, but the compressor reliability issue should probably be a higher priority. Right now, it does not seem to be mentioned in the planned projects.
- The principal gap is the lack of an assessment of what manufacturing advances will be insensitive to changes in the underlying technology (e.g., changes in catalyst composition, supports, or membranes).
- One gap is the lack of quantification of the effect of defects on cell performance and life.
- No.

13. Are there topics that are not being adequately addressed?

- The ongoing work seems to be rather thorough and complete.
- No.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- It may not exactly fit the goals of the sub-program, but research into reducing infrastructure build/installation complexity may be a useful avenue to explore. More pre-fab, standardized, modular designs and ideas specifically assembled for ease and efficiency of construction could go a long way in helping to roll out the fueling infrastructure at a faster pace and support accelerated vehicle deployment.
- No.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- No; the sub-program has a fairly complete set of strategies that appear to be working well.
- The sub-program should assess which steps in the manufacturing process are most likely to benefit from economies of scale. This will allow the sub-program to better allocate resources.
- The sub-program should continue with more emphasis on actual manufacturing hardware and less emphasis on studies.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The sub-program needs to reach out to state agencies to get a better sense of the urgency behind all the project goals and to help manage the priorities and focus of the sub-program's efforts.

Technology Validation Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- Yes, the objectives, metrics, and technology areas were clearly stated. The overall status of the technology was compared against the DOE targets, and future plans were addressed.
- Yes, the overall strategy was clear, and this important sub-program was sufficiently covered.
- Yes, the sub-program and strategy were adequately presented.
- The sub-program was adequately covered. The 80,000 hour target has only been reached by phosphoric acid fuel cell (PAFC) technology and, it was mentioned by the project's Principal Investigator that UTC degraded the performance of the 200 kW fuel cell to 175 kW in order to reach that level. The issue of fuel cell performance degradation in reaching durability targets should be covered in the setting of targets. In addition, the 80,000 hour target was reached with an "old" PAFC design, and there is no indication the new PAFC design will reach 80,000 hours. Other technologies have not shown that level of operation without stack replacement. The commercial power goal may be very difficult to reach.
- At a high level, the strategy discussed provided more of an overview of how the Technology Validation (TV) sub-program fits in with the other sub-programs. The presentation did not, however, really discuss the strategies used within the sub-program in terms of general project types and specifications to meet the goals. These strategies became clearer during the individual project presentations, but the high-level overview could have been more thoroughly presented.
- Yes.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes. The sub-program clearly has an emphasis toward the near term, but there are some longer-term projects that are highly valuable.
- Yes; however, it did seem that some of the near-term goals relate to aspects of FCEVs that are near commercial realization.
- The feedback loops provide pathways to communicate identified technical problems back to R&D efforts; however, this was not explained well, and it was not clear how information from the sub-program would get back to the R&D activities. Perhaps there are review committees to evaluate TV sub-program operations and provide feedback, or perhaps this is internal to the projects and therefore was not discussed in the presentation.
- It is clear what the sub-program intends to accomplish in the near future. The sub-program goals and activities up to 2017 were defined, but there was no mention of activities beyond that period of time. It was mentioned that the sub-program will address heavier vehicle classes in the future, but that was the only reference to long-term research. It is unclear what the sub-program intends to accomplish in the long term.
- Yes. *(2 responses)*

3. Were important issues and challenges identified?

- Yes, performance, durability, availability, and operational characteristics were all identified.
- Yes, the key issues and challenges were clearly identified.
- The discussion of the sub-program's accomplishments did not explicitly define the issues and challenges that were being addressed. The work is related to the issues and challenges outlined in the DOE Hydrogen and Fuel Cell Program's research, development, and demonstration (RD&D), but this overview did not explicitly tie the project accomplishments to those issues and challenges.
- No, issues, challenges, and barriers were not identified during the presentation. The presentation focused mainly on accomplishments.
- There was not any statement of challenges. The presentation reported accomplishments.
- Yes.

4. Are plans identified for addressing issues and challenges?

- There did appear to be adequate internal control to manage change. This control will be necessary as certain technologies move forward with commercialization.
- Yes, plans were identified, although it is not clear how large-scale grid energy storage will be accomplished.
- Overall, the projects seem to address the challenges, but a more explicit presentation should be provided.
- The presentation focused on near-term strategies and accomplishments, but it did not describe what issues/challenges are being addressed with the current projects.
- Slide 22 states that the sub-program is "Developing new targets." The presentation did not give any indication of how those new targets (challenges) would be met. Perhaps the planned RFI is the mechanism for achieving new targets.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- In the existing focus areas (e.g., FCEVs and stations), yes, progress was clearly benchmarked.
- Progress was identified.
- The accomplishments are outstanding, and the progress made in all areas in exceeding, meeting, and approaching targets demonstrates a successful sub-program. It did not appear that incremental benchmarking from the previous year was emphasized.
- Much more emphasis was placed simply on the current status and data collection/evaluation over the life of the sub-program projects. There did not seem to be a clear indication of how much more data was collected in the past year or how the status of technologies changed in the past year.
- The current status and goals were clearly defined, but there was no mention of how much the projects in this sub-program have advanced compared to the previous year.
- Yes.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes; in particular, there is a widespread lack of information, and the projects of this sub-program are providing a valuable resource for that information.
- Yes, the projects were well selected and represented technologies that required validation.
- The projects are definitely making a contribution to FCTO by validating advances in vehicle range, fuel cell system durability, hydrogen dispensing capacity, and storage using actual numbers instead of engineering calculations. However, fuel cell cost and public acceptance are also listed as challenges in the sub-program, and it is unclear how those challenges are being addressed. Very little cost data was presented, and there was not a clear link between the projects and consumer acceptance (perhaps that is one of the objectives of the [Station Operational Status System (SOSS)] project).
- This presentation is extremely valuable for showing that laboratory R&D can be moved to the demonstration state, and it validates the R&D. This should have been explicitly pointed out in the presentation.
- Yes. *(2 responses)*

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- The accomplishments in the TV sub-program clearly demonstrate that it is well-managed and is addressing the necessary issues for moving fuel cell technology to the marketplace. This is a critical sub-program that justifies the approaches taken by FCTO for many applications. It is not clear how the more fundamental FCTO activities, such as catalyst development, help the sub-program. Good performance of fuel cell applications can be achieved with high catalyst loadings or expensive bipolar plates, etc. It is not clear how the R&D achievements help the TV sub-program—perhaps they help through fuel cell buses or forklifts.

- The sub-program was well managed, and meaningful progress was achieved, addressing the important needs of FCTO.
- Yes; the amount of coordination required for the large amount of data that is handled is accomplished very well.
- Yes, the team was thoughtful, focused, and well managed.
- It is hard to assess whether the sub-programs are well managed. That is a question for the people involved in the actual projects. However, it is clear the projects are yielding results, and that the results are moving in the right direction to accelerate the introduction of FCEVs and refueling infrastructure, tackling major challenges such as fuel cell durability, performance of light- and medium-duty vehicles, dispensing, storage, and data collection.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The key strength of this sub-program is the thoughtfully organized validation and demonstration cross-collaboration involving important partners in various scopes.
- The data handling, aggregation, dissemination, and assurance of confidentiality are all particularly well handled in this sub-program. The one apparent weakness from the presentation was the robustness of information for the stationary fuel cell applications and the presentation of the data. The difference in counting methods for units delivered between fuel cell and combustion products was not clearly explained or was otherwise convoluted. Additionally, it seems like there should be much more information and learnings available from stationary applications, based on observations of the current marketplace and the number of commercial products being delivered.
- The key strength of the projects is the teams that have been put together, which feature a combination of industry and national laboratory stakeholders. The fuel cell bus activity stands out for surpassing the 2016 target. The forklift truck project also stands out, but it is not clear how much penetration into the market fuel cell forklifts have made. With the identified benefits of the fuel cell forklift truck, it is not clear why the market penetration is below 5%.
- Key performance metrics and representative projects were clearly identified as a project strength. Comparative analysis with conventional technologies, evolving commercial performance, and new market entries will need to be updated as these technologies advance.
- The fuel cell material handling equipment (MHE) and standby fuel cell power activities are real winners because they have entered the commercial mainstream, which is great. It is not clear how DOE can play a role in the grid storage area; for example, it seems that resources much greater than the DOE R&D budget would be required for a major fuel cell grid storage demonstration.
- One weakness is that it is unclear whether the sub-program is addressing fuel cell cost challenges or consumer acceptance. Strengths include that the accomplishments presented tackle important issues that the industry has been grappling with in terms of demonstrating technology and collecting actual performance data from real systems. There is good collaboration with industrial partners.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes, these projects represent novel and/or innovative ways to approach these barriers, especially the project to investigate electrolyzers supporting the grid.
- Yes, objective technical validation is very important and useful. The representative projects, performance characteristics, and goals all appear to be appropriate.
- It is not clear whether the projects represent novel and/or innovative ways to approach these barriers.
- Innovation is not the key to this sub-program; more than that, the sub-program is testing vehicles and infrastructure that have been developed by others. The technology being tested is innovative in many cases, but the role of the sub-program is not to innovate, but to test the contribution of these novel technologies to reaching FCTO targets. In that respect, the sub-program is doing a good job.
- TV sub-program projects tend to be incremental activities and demonstrations. It is not clear what is novel about the sub-program projects, other than they offer demonstrations. No cost numbers are available, so

one cannot judge whether these projects have "novel technology" or represent "brute force" technology at a high cost.
- Yes.

10. Has the sub-program engaged appropriate partners?

- Yes, the amount of collaboration and partnerships is very extensive and seems to cover all necessary sectors.
- Yes, the partnerships are well structured and productive.
- Yes—OEMs and supply chain and institutional partners have been identified. Increased engagement with supply chain partners—directly or through OEMs—might be a step forward for comprehensive validation to increase opportunities for commercialization.
- Yes, industrial partners and national laboratories are being engaged. Perhaps the sub-program would benefit from engaging the public as well to increase consumer acceptance.
- Yes. *(2 responses)*

11. Is the sub-program collaborating with them effectively?

- High levels of collaboration must be occurring for the reported success to be possible.
- The sub-program appears to be collaborating effectively.
- Yes, it appears to be collaborating effectively.
- Yes, it is collaborating effectively, but there will be opportunities to increase collaboration with supply chain partners, OEMs, and stakeholders.
- It is hard for someone not directly involved in the projects to answer that question. It seems that the collaborations are effective, given that the results are positive; fuel cell durability and fuel economy are improving, more work on the road testing is being performed, additional collaborations are occurring, and future plans include the right stakeholders. Further, data collection and publication are crucial to the success of the FCTO projects; it is great to see that so many partners are on board to provide data and that the Gas Technology Institute and the NREL data center have been effective at consolidating the information in a way that is useful to stakeholders.
- Yes.

12. Are there any gaps in the portfolio for this technology area?

- No, the portfolio is well representative of industry and the technology. Note that both industry and the technology will evolve, making collaboration and technology validation an ongoing and changing process.
- There do not appear to be any gaps at this time.
- There is little cost data coming out of the sub-program. Also, it is not clear how consumer acceptance is being addressed. It is not clear whether the results are being integrated into other FCTO sub-programs, or whether there are feedback mechanisms in place to ensure the appropriate bottleneck components are being tested.
- There is a gap related to identifying the cost of the technology validation demonstration of fuel cell systems. It is not clear whether these systems are on a pathway to meet the costs.
- Grid storage and stabilization seem beyond the scope of the DOE Hydrogen and Fuel Cells Program.
- No.

13. Are there topics that are not being adequately addressed?

- The technology and industry are nicely covered. Some suggestions for consideration include the following:
    - Developing some type of simple, consumer-oriented FCEV validation label (similar to the ENERGY STAR label) for range and efficiency.
    - Addressing and contrasting potential voltage drop (or lack of voltage drop) for MHE.
    - Conducting a simple comparative analysis of selected technologies with conventional technologies.
    - Increasing engagement with supply chain stakeholders, either directly or indirectly through OEMs.

- Stationary fuel cell studies do not seem to receive as much emphasis as one would expect. Additionally, the online station status project may soon need to expand to look at other options and methods beyond SOSS. Individual station developers may soon be deploying their own systems for providing consumers with similar information, and the sub-program should look into comparisons among these systems, especially concerning cost, accuracy, and response time.
- Fuel cell cost and consumer acceptance are not being adequately addressed.
- The topic of technology/system cost is not being adequately addressed.
- No.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- The technology may not yet be ready, but given other sub-program overviews and individual projects presented at this year's AMR, it is likely this sub-program will need to incorporate hydrogen pipeline studies within a short time.
- The sub-program should consider funding DOE certification for performance (similar to the ENERGY STAR program).
- Funding could be directed toward testing tube trailer deliveries as a precompression step to reduce storage and compression at the terminal.
- There is no explanation of how the technology will leave the funding of FCTO and become driven and funded by industry.
- No.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- Some type of simple, consumer-oriented FCEV validation label for range and efficiency should be developed. A simple comparative analysis of selected technologies with conventional technologies should be conducted.
- The sub-program should approach major utility companies (e.g., Pacific Gas and Electric Company and Xcel Energy) to initiate a major grid storage project. Xcel has been working on renewable electricity projects and might be motivated to pursue energy storage to enable more renewables.
- The sub-program should report the cost of the technologies being tested. It should also test tube trailer deliveries as a pre-compression step. It should test 500 bar refueling systems, including measuring performance and refueling time, comparing the results against 700 bar systems, and calculating e the cost differences.
- The sub-program should reduce funding and determine whether industry is ready to commit to moving forward without RD&D funds. Cutting subsidies is not recommended.
- There are no suggestions.
- No.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- Overall, this is a good sub-program that will need to evolve as technology evolves.
- The release and explanation of composite data products should be more widely publicized and receive more attention. It has been difficult to keep up with the update schedule and to stay informed of the developing data interpretations.
- The sub-program should build review teams to make lessons learned available to the general public.

Safety, Codes and Standards Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- The presentation gave an exhaustive overview of the activities and their link to the overall strategy. This "horizontal" or "crosscutting" sub-program is essential, and its link to the FCTO Multi-Year Research, Development, and Demonstration Plan (MYRDDP) is clear. The identified priorities are all tackled in a consistent and coordinated way.
- The sub-program's strategy has been clearly stated. It takes the right approach by starting with fundamental science and engineering in order to develop models and tools (e.g., the Hydrogen Risk Assessment Models [HyRAM]) and disseminating these to end users, both local and internationally.
- Yes, there was a very thorough description of the actions the sub-program takes in order to address its goals and how achievement of a goal affects other goals.
- Yes, the sub-program, including the overall strategy, was adequately covered.
- The sub-program was adequately covered, and within the assigned time available.
- The overall sub-program is covered both nationally and internationally. There is a good focus on the codes and obtaining data. The standards projects need data to provide support for revising standards. There is also good support for participants to participate in the code and standards activities; however, the actual support for the standards development organizations (SDOs) and the work on the SDO/code development organization (CDO) side to support the revision/development of the documents is missing. The work should have some support (cost shared with industry and SDOs/CDOs).
- Yes, the presentation provided a good overview of the sub-program. The presentation could provide a slide that shows all of the existing projects and where they fall in the broader categories. As an alternative, the sub-program could provide this detailed information in each category of the project. This could involve two broad categories—Codes and Standards Objectives and Hydrogen Safety Objectives—that waterfall into three areas: R&D, Codes and Standards support, and Outreach. From the existing presentation, it is quite difficult to tell which specific project example fits in which category, as well as how much of the funding is dedicated to which category, how that changed from previous years, and why that changed compared to previous years (responding to trends, cyclic nature of codes and standards, etc.).

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes; in particular, codes, standards, and field validation (especially for infrastructure technologies) are major areas of need for the current industry, and this sub-program appropriately prioritizes this near-term need.
- Yes, there is a proper balance between near-, mid-, and long-term R&D.
- Yes, there is an appropriate balance, although the presentation does not specifically address the timing of sub-program activities as "near term" or "long term"—the sub-program outlines a cyclical process that includes a very good explanation of research to outreach, as well as continuous improvement. This project appears to have transitioned from a research and document development effort into a more balanced and comprehensive approach to outreach; regulations, codes, and standards improvement; and targeted research.
- At this stage, considerable parts of the codes and standards domain, including safety, have already been covered by previous efforts. Considering the work already done in this area, and the already available sub-program framework, the present strategy is well adapted to the new challenges. On one side, there is the continuous improvement cycle of the sub-program framework, and on the other side, there are more ambitious and more long-term goals, such as the integrated tool and its probabilistic approach.
- Although the presentation did not clearly distinguish between near-, mid-, and long-term R&D, it did show an ongoing effort and emphasis on critical areas that will enable hydrogen to be used as an alternative fuel for transportation. These areas cover, most importantly, safety (e.g., HyRAM), performance, and reliability (e.g., fuel quality/contamination and subcomponent testing).
- It is not completely clear what distinguishes the near, mid, and long terms, but all topics in this topic area are meant for long-term application (but work must begin in the short term).
- Yes.

3. Were important issues and challenges identified?

- All of the issues and challenges associated with safety, codes, and standards were clearly identified and defined throughout all the material presented by the sub-program.
- Yes, important issues and challenges were identified. Collecting hydrogen safety data remains a challenge for all stakeholders.
- Yes, the presentation accurately reflected the need for data to support codes and standards.
- Yes, the description of advantages and challenges at various project scales was particularly well developed.
- Yes; however, the presentation did not address this topic directly. The overall barriers to be addressed were not explicitly described.
- Yes. *(2 responses)*

4. Are plans identified for addressing issues and challenges?

- It is very clear that the sub-program is very aware of the issues and challenges, and the established plan seems very adequate to overcome these issues and challenges. The resources used by the sub-program to execute the R&D really leverages world experts and top facilities.
- The implementation plan embraces two traditionally non-communicating levels of the normative spectrum: (1) the research community and (2) the standardization framework, which is traditionally led by industry. This sub-program is able to align well-identified R&D work—which is needed to deliver science-based evidence supporting continuous development in safety, codes, and standards—with ongoing efforts in regulatory and standardization bodies.
- Yes, it appears that plans are identified.
- Generally, yes, plans are identified.
- Yes, the sub-program identifies a clear plan for addressing challenges; however, it assumes the objectives are solutions to challenges the audience already understands. It might be best to revisit the challenges and issues, particularly to highlight the new challenges faced. This would allow the sub-program to address the dynamic changes the sub-program manager is implementing as part of the management strategy.
- The general strategy for addressing the remaining issues and challenges was identified. However, there was not a lot of specific detail provided in terms of future work to address the challenges. Much more effort appeared to be put toward describing the recent accomplishments. It may be that this work is still ongoing, but it was not explicitly clear how the accomplishments tied into future plans.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Yes, for the new H2FIRST projects, several reports were issued, including a DOE record that demonstrated a 50% reduction in separation distances, shorter response times for the hydrogen quality analyzer, and a commercially ready hydrogen sensor.
- Yes, this project has shown significant results, with great progress in outreach and developing tools such as HyRAM.
- Yes, the progress was clearly benchmarked against the previous year.
- The major accomplishments of 2015 have been clearly and convincingly presented. In general, the multi-year progress is evident. There is only one improvement to make. The sub-program covers a broad range of activities, and it cannot be expected that every single area of progress would be mentioned in a general presentation. For improving future presentations, keep in mind that it is difficult to identify year-to-year progress and realignment of the plans by looking only at the lists of “emphasis” for 2014 and 2015.
- Yes, it was clearly benchmarked, assuming the “progress” and “accomplishments” listed in the project reports are in addition to achievements made during the previous year.
- The progress in projects was specifically discussed in terms of the past year, although there was not a clear indication of how this compared to work done in the previous year.
- Yes.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, the projects in this technology area are definitely addressing the broad problems and barriers FCTO is trying to solve.
- Yes, these projects are providing important advancements in the ability to rapidly deploy hydrogen fueling infrastructure and fuel cell technologies.
- Yes, the projects are definitively addressing the broad problems and barriers.
- The projects and activities being managed by the sub-program address the main areas of enabling hydrogen fuel cell technologies. One suggestion would be to fund some R&D work and eventually some demonstrations on hydrogen mass flow metering to improve the accuracy levels of existing metering devices. This is a key area that still needs improvement for current technology and one that will be a significant enabler of hydrogen infrastructure technologies.
- The overall sub-program is addressing both national and international market issues. There is a good focus on the codes and obtaining data. There is also good support for participation to support the code and standards activities; however, the actual support for the SDOs and the work to revise/develop the documents is missing. The roles of national laboratories and private-sector companies that have comparable capabilities need to be better defined. There are real cases where the national laboratories are competing with private industry, and it appears the money being spent to add capabilities duplicates what exists in the private sector.
- The projects are addressing the broad problems to some extent. There are significant concerns regarding the efficacy of the research at NREL, specifically the ongoing testing of pressure relief valves. That work seems highly inconsistent with the work products from materials testing or reference stations where the outcomes have targeted a large impact on the broader community. The outcome and impact of the effort to test pressure relief valves has not been defined, despite several years of review. This reflects negatively on the efficiency and management of the sub-program and the FCTO objectives as a whole.
- Yes.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- Yes, this sub-program is very effective. The evolution of outreach information is a tremendous step forward for the support needed for FCEVs. This sub-program also seems very capable of making timely changes in its activities. The rollout of the new safety tools website is extremely timely and a good indicator of a well-managed sub-program.
- It is clear this sub-program effectively coordinates and leverages the resources and players to address the overarching needs and challenges. Coordination is traditionally difficult in this area, due to the necessity to steer research centers, conduct (pre-)normative activities, and interface with standardization bodies (and specifically their industrial components). One would also expect a certain amount of resistance to this approach by some industrial stakeholders that assume they should be the only players in this space. Despite the possible resistance and management difficulties, the sub-program is well managed and succeeds in achieving its goals.
- Yes, there is a very clear structure to the sub-program's approach to addressing challenges and barriers. The management of the sub-program appears to be well developed, especially considering the multitude of approaches utilized to address the sub-program's goals.
- It is very impressive to see how well the sub-program is currently managed and its collaboration with local and international bodies and institutes in the safety, codes, and standards areas.
- Yes, the sub-program appears to be focused, well managed, and effective in addressing FCTO's needs and goals.
- Yes. *(2 responses)*

8. What are the key strengths and weaknesses of the projects in this sub-program area? Do any of the projects stand out on either end of the spectrum?

- The strength of the projects is their ability to address real-world, current issues with high priority in a timely manner. DOE's partnerships with varied stakeholders and agencies through this sub-program are helping to accelerate timeliness and ensure that focus and attention remains on the most critical issues. The work on hydrogen behavior and risk assessment appears, in particular, to feature a well-developed and confidence-building methodology that will hopefully have a significant impact on industry-wide work, like National Fire Protection Association (NFPA) 55/2.
- Overall, the deliverables of projects in this sub-program represent key strengths. There are no major weaknesses in any of the projects in this sub-program.
- Many of the projects in this area are excellent and strive to achieve science-based evidence and to interface with industrial stakeholders. The achievements in this area show the importance—or better, the essential role—of government and public institutions in shaping the development and deployment of a new, disruptive technology. There were not any weaknesses. However, one would expect a certain grade of competition among the national research centers in terms of covering the major share of the sub-program activities. Slide 6 claims there is a clear and strategic distribution of tasks between Sandia National Laboratories (SNL) and NREL. The slide does not show, however, how the distribution was determined. There was probably something similar to a strengths, weaknesses, opportunities, and threats (SWOT) analysis; if so, that should have been explicitly stated, along with a definition of "subcomponent" versus "component." Otherwise, one could get the impression that NREL's choices for testing valves and SNL's choices on which materials to test are made independently. Finally, slide 11 shows a Los Alamos National Laboratory project on sensor development. This effort seems to be of lower impact in terms of the overarching goals, compared with the other projects presented. The development of a new sensor is an important achievement, but it is not exceptional if considered in the frame of the industrial development of sensors.
- Efforts involving the first responder tools/information are progressing well, and these resources are assisting in education and outreach.
- The sub-program's key strengths include that the overall effort involves all key stakeholders and disseminates the needed knowledge/lessons learned, including on an international level. A key weakness is that the statement of "35,000 first responders reached" does not include enough information to fully understand the context.
- The greatest strength of this sub-program is the role it plays in outreach and code development. One of the sub-program's weaknesses is the NREL effort on codes and standards support and component testing; it is recommended that the sub-program evaluate this effort's long-term focus.
- The actual project portfolio seems very well balanced and robust. The only recommendation is to include a flow metering project(s).

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- The most ambitious project, in term of novelty and risk, is the development of an integrated tool for safety design (HyRAM) based also on a probabilistic approach. This is something the international community is dreaming of, and it is very important to enable and facilitate market deployment of the hydrogen and fuel cell technologies. It has a high risk of not reaching the final objective—not because of the lack of scientific quality, which is very high, but because its success depends on its acceptance by a broad spectrum of end users and stakeholders that traditionally do not trust probabilistic approaches. Nevertheless, the importance of the project motivates this effort.
- The sub-program appears to make use of the latest media technology options available to disseminate information needed to the safety, codes, and standards community.
- HyRAM and the new H2 Tools information portal are very good examples of the innovation and creative aspects of this sub-program and its management.
- Yes, each project in this sub-program represents a novel or innovative way to address the hydrogen safety barriers.
- Yes, the projects in the sub-program portfolio all have a strong scientific and engineering background. To expand the innovation aspect of the portfolio, the team should consider funding a project on refueling

protocols as a long-term option to existing standards. Items to consider could include reduction of energy consumption, improvement of equipment reliability, and reduction in cost of required equipment.
- Yes; in some cases (especially the more outreach-oriented projects), the projects borrow from previous or outside work, but there is still innovation in the sub-program's implementation and presentation of that work, and in providing tools that have translated more detailed and complex technical investigations into content that is more immediately accessible to broader audiences (e.g., authorities having jurisdiction and first responders).
- Yes.

10. Has the sub-program engaged appropriate partners?

- Yes, this sub-program has developed interfaces with all the partners and stakeholders required—from end users to industries, designers to the general public, and (international) scientific communities to governmental institutions.
- The sub-program has absolutely engaged appropriate partners, including national laboratories, industry stakeholders, local partnerships, and international entities.
- Yes, the sub-program has definitely engaged appropriate partners. Each project in this sub-program seems to be well engaged with other institutions.
- Yes, the sub-program has engaged appropriate partners, including international partners.
- The sub-program has generally engaged the appropriate partners; however, the sub-program should clarify the roles of the national laboratories and private-sector companies with comparable capabilities. It is difficult to understand areas when FOAs are announced, particularly when submissions appear to be directly appropriate but are "discouraged" with little to no explanation.
- Yes, the focus on international collaboration needs to be tempered with domestic collaborations. The DOT transport issue (i.e., higher-pressure transport) and bridges/tunnels/parking are going to be ongoing issues with high priority and great importance. With limited time and budget, the sub-program should carefully consider whether the past few years have been "the lull before the storm," and while the international partnership development of the past two years lays good, long-term groundwork, sustaining this level of effort in the next few years may not be the best use of resources. This sub-program has shown good flexibility and has good advisors.
- Yes, there is a high degree of collaboration with outside partners. The only recommendation would be to strengthen the partnership with Korean automotive manufacturers and industry, as discussed in the question-and-answer period.

11. Is the sub-program collaborating with them effectively?

- Yes, the international community speaks highly of the sub-program manager, and there is much less confusion over the direction of DOE and U.S. hydrogen efforts as a whole. The outreach performed by this sub-program over the past few years has been very good.
- The sub-program is definitely collaborating effectively. This is one of the strengths of this sub-program.
- Yes, the sub-program appears to be collaborating effectively.
- The sub-program is absolutely collaborating effectively.
- Yes—the results clearly show the effective collaboration as well.
- It has yet to be determined whether the sub-program is collaborating effectively—a resolution is in progress.
- Yes.

12. Are there any gaps in the portfolio for this technology area?

- No, the sub-program's projects are quite comprehensive.
- It does not appear that there are any gaps.
- There are no technology gaps to report.
- There is an appropriate focus in the technology areas; however, the funding for revising codes and standards from the SDO/CDO side should be revisited as a cost-share activity, and the roles of the national laboratories versus the private sector need to be clarified.

- The hydrogen mass flow measurement issue is a gap.
- No.

13. Are there topics that are not being adequately addressed?

- No, all topics are being adequately addressed, especially considering the limited budget available—even though the budget is stable compared to the previous year.
- The sub-program is generally focused on industry priorities.
- There are no topics that are not being adequately addressed.
- There did not appear to be much material covered for stationary applications (although collaborations with the organizations dedicated to this area were noted) or mobile applications, besides the light-duty vehicle (LDV) and LDV fueling infrastructure topics. While these LDV topics need significant attention right now, stationary applications likely could use more attention than they are receiving, and other mobile applications will likely require attention fairly soon.
- No.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- There were no identifiable additional areas this sub-program should consider funding.
- Currently, there are no other areas the sub-program should consider funding.
- Yes, this sub-program should address the real problems faced by the industry, such as the development of engineering requirements for minimum standards. This sub-program could study the radiation effects of vent stack releases in relation to the current requirements of API 521, instead of the current path with pressure relief valve testing (it is not clear why researchers are testing the effects of an incorrect part selection).
- The sub-program should consider funding a mechanism to support the SDOs/CDOs in developing documents (in addition to data and providing experts for the work).
- The sub-program should fund an additional project on probabilistic risk assessment (PRA) using a subject-matter expert in this specialized field.
- The sub-program should fund hydrogen mass flow measurement. A recommendation for long term would include an advanced refueling protocol.
- No.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The team has demonstrated it has a well-defined approach.
- No; the sub-program implements an array of methods that appear to be working very well.
- The international collaboration framework is very vast, from IEA/HIA for the sharing and collection of R&D results, to the intergovernmental International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), up to the international standardization body the International Organization for Standardization (ISO). All these efforts are practically based on volunteering to share data individually obtained in a single country. Perhaps it would be possible to engage internationally at an operative level by defining joint RD&D programs. This is probably only possible through bilateral collaboration agreements that manage budgets and resources.
- The sub-program should explore new ways of reporting the “number of first responders trained” so DOE and stakeholders better know how and what first responders to reach, as well as what the sub-program has achieved with emergency responder outreach and what is still left to do.
- The sub-program should consider a new project on hydrogen PRA.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- This sub-program could more clearly prioritize the laboratory activities. The sub-program has established the connection between the laboratory, regulations, and outreach. It is not clear how each laboratory activity achieves a given regulatory or outreach goal, and what the anticipated impact is. It is not clear how

this sub-program determines those priorities. It is not clear whether all of the top priorities for regulations/codes and standards or outreach are addressed by the current laboratory activities. If not, perhaps a change in laboratory activities is required to address more relevant gaps. It is not clear whether the PIs have been asked to provide the impact of the research on those RCS or outreach goals.

- There is one challenging suggestion that is not easy to implement. Progress in this area cannot be simply evaluated on the basis of progress to a few quantitative targets. Some qualitative indicators are now available, such as the number of downloads of a training package, or the availability of guidelines where none previously existed. However, it is not clear how to evaluate the impact of these achievements, or how to show that specific guidelines have achieved a certain level of improvement. These questions have been partially answered in this area; for example, when showing that science-based release calculation has allowed for a safety distance reduction. Perhaps it is possible to quantify these impacts for the rest of this sub-program.
- The sub-program should consider how California stakeholders (as the first market) can help more with identifying the required target audience and phased outreach strategy.
- The sub-program should consider adding a mechanism to support the SDOs/CDOs in developing documents (in addition to data and providing experts for the work).
- At this time, there are no other suggestions.

Market Transformation Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- Yes, despite the fact that the sub-program manager was unavailable to present on the topic, the sub-program was clearly defined, both through the presentation and by the team member presenting. This indicates that not only has the sub-program manager effectively refined the purpose of the sub-program in his own mind, but the sub-program manager has also effectively communicated the sub-program goals and purpose to the team. These are the great hallmarks of a well-run sub-program.
- Overall, the sub-program description and strategy are well defined and understood. The presentation adequately discussed the goals and objectives of the Market Transformation sub-program, which include the following:
  - Deploy and demonstrate hydrogen and fuel cell solutions.
  - Catalyze the introduction and deployment of the technology.
  - Perform business case analysis and inform the broad community.
- Yes, the mechanisms by which the sub-program achieves its goals were especially well presented.
- Yes, the strategy, partnerships, and applications were presented very well.
- Yes, the sub-program was adequately covered.
- Yes.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes, for this sub-program's scope, the projects are appropriately balanced, with a heavier weight placed on near-term, pre-commercial opportunities.
- Yes; the focus is decidedly on the near-to-mid term, as it should be for market transformation.
- Yes, a good pathway is presented for testing emerging technologies and commercialization.
- Given the nature of market transformation, the balance should be more heavily in favor of high-TRL opportunities and more focused on near-term objectives (1–3 years). The list of activities underway in the sub-program brings that proper balance.
- Near- and mid-term R&D is well represented with existing projects, including the new project modeled on the French experience. Long-term R&D needs to be strengthened; the mobile refueler project, while interesting, is limited to "last-mile" infrastructure issues.

3. Were important issues and challenges identified?

- Yes, the presentation identified the selection of technologies, identified partnerships, and set framework for demonstration and analysis.
- Yes, important issues were identified.
- Yes, the important issues and challenges were identified, but not specifically. The project identifies "challenges in reducing the commercial risk to high hydrogen and system utilization and reliability under mass market penetration scenarios" and "obtain data from operating experience to develop replicable business cases." These may be the important issues, but it is not clear whether these are the challenges. The specific challenges in the near and long terms are unclear. It is not clear what is causing risk in utilization or reliability (e.g., supplier diversity, demand development, or consumer confidence). The graphics in this slide were confusing and did not relate well to the topic.
- Yes; however, the broad challenges that are addressed by the sub-program could be detailed with more specificity. As presented, they seemed to not adequately cover the broad range of challenges that the sub-program should truly address. The individual accomplishments did a better job of being specific in this regard. If the broad challenges are more specifically addressed, it will likely be easier to connect them to the specific project challenges that were addressed. In fact, it would be very helpful if the challenges at the sub-program and project levels could refer to each other more directly or be more clearly parallel in wording.
- Generally speaking, yes, the important issues and challenges were identified. The biggest challenge is to support the faster and broader introduction of hydrogen infrastructure, and that component may be slightly undervalued and under-resourced.

4. Are plans identified for addressing issues and challenges?

- Yes, plans for identification and management of issues and challenges were presented; some of these plans will require ad hoc decision making as issues and challenges are identified.
- There are good plans, but with such esoteric challenges, there is a sufficiently wide umbrella to cover any possible topic. The sub-program should identify the challenges more specifically. The sub-program could do such without identifying—and thus restricting—future opportunities.
- Yes, plans were identified, although the presentation was very broad. A bit more detail than was presented would be very helpful. For example, it would have been good if the presentation addressed what kinds of models, tools, and templates are to be developed in the coming year, what questions they will answer, and who they will be targeted to help.
- Generally speaking, yes, plans were identified.
- The plans are probably described in detail in the specific project presentations.

5. Was progress clearly benchmarked against the previous year?

- Yes, new demonstrations and expectations were presented and appear to be appropriate.
- Yes, there is a very good summary slide that is easy to compare to previous years.
- Progress was clearly benchmarked against the previous year; the only new niche to be identified is the application modeled after the French approach.
- One would expect to see this benchmarking in the specific projects being reviewed. It was not clear that the overall sub-program was benchmarked against last year. The presentation included a good highlight of how the investment in MHE and backup power has potentially served to catalyze the introduction of the technology (5–10-fold).
- This was not very clearly presented. The prior year information was really only presented in terms of appropriation and expenditure.
- No, it was not presented, other than the budgets per year.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- Yes, FCEV, hydrogen refueling, material handling, and range extender efforts were all presented and are appropriate for demonstration, and are on the path to commercialization.
- Yes, the projects are addressing the broad problems and barriers for the non-passenger-vehicle markets.
- Yes, the projects address the main issue of getting traction in visible niche markets.
- The broad FCTO goals, especially for building the market and bringing down costs, are certainly addressed by the projects. The sub-program overview also did a good job of showing metrics to success in terms of volume of units delivered pre- and post-DOE projects. However, the same was not done for costs (which is at least as critical). Additionally, some context and perspective should be supplied. For example, it was not clear whether the 5,500 backup power units purchased by industry are a significant number of units in terms of production numbers and power/energy market share.
- The projects are focused on the right type of activities, but a little more focused effort to improve hydrogen infrastructure might be called for in the next five years.
- Yes, this sub-program compensates for a defunct Technology Validation (TV) sub-program, in that it is able to identify project opportunities that would otherwise seem to be covered by the TV sub-program. The Market Transformation sub-program, which has clear leadership and has achieved success, and the issues with the TV sub-program, begs the question of why technology validation efforts are not managed by the Market Transformation sub-program.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO's needs?

- Yes, the sub-program does a good job of clearly delineating the objectives it will work to address, and it seems like most projects are on schedule.

- Yes, sub-program managers appear to be very open and thoughtful regarding moving the appropriate technologies into commercialization.
- Yes, the MT sub-program manager and team have done a very commendable job in identifying and executing projects that help with market introduction.
- Yes, this sub-program seems quite well managed.
- The sub-program is focused and well managed.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- The strength of this sub-program is the creative sense of opportunity that it uses to identify and succeed with projects in several application areas with limited funds. This creativity and continued success with strong and well-planned leadership ensures long-term success. The greatest weakness of the Market Transformation sub-program is the structural relationship it holds with technology validation. The inability of the Technology Validation sub-program to produce tangible results restricts the success of the Market Transformation sub-program.
- The MHE fuel cell projects are obviously succeeding, given the large number of industry-funded projects (12 times more industry-funded than DOE-funded fuel cell MHE). Similarly, the backup power systems are succeeding, with a 6:1 industry-funded to DOE-funded project ratio. No data was provided on the other applications. In the future, it might be useful to list the market size in these other areas; for example, the presentation could list how many ground support equipment units (GSEs); refrigerated trucks; trash trucks; and Class 1, 2, and 3 vans there are in the United States.
- The sub-program's strength is that it uses a small amount of funds to help leverage others' investment dollars and help field technology-ready solutions. The main weakness is that the small budget also constrains the number and types of projects that can be considered.
- Project selection, geographic diversity, and technology analysis are all strengths. A weakness might be the budget constraints for sub-program expansion.
- The biggest project-specific weakness seemed to be with the GSE project. The vehicles are to demonstrate real-world capability (and it was mentioned, in particular, that they will need to demonstrate compatibility with the outdoor working environment). However, the project timeline included less than a year for this demonstration and validation. This does not really seem to be an appropriate amount of time to provide a high degree of confidence in the real-world capability of this application. If possible, this evaluation period should be extended, and similar demonstrations in the future should work with a longer period, as well.
- At present, Plug Power's success in MHE (forklifts today, hopefully baggage handling tomorrow) is the only example of traction. Vision Industries' bankruptcy is a case of a fuel-cell-based company failing to achieve traction.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes, despite a small number of potential suppliers for equipment, this sub-program seems to creatively develop a project that attracts a diversity of suppliers and a tremendous diversity of project partners. It seems to appropriately leverage opportunity and market need; for instance, the auxiliary power unit for refrigerated trucks features heavy industry participation and seems very close to being a commercial product, whereas the marine generator is much more government-entity-sponsored and represents a longer-term opportunity. Nevertheless, the sub-program is able to prevent the use of a "one-size-fits-all" approach to project development, which would have prevented one of these two opportunities from being fulfilled.
- Yes, the projects appear to be both novel and innovative, and they are clearly ready for demonstration, analysis, and validation.
- Yes; the maritime application, in particular, appears to be a very novel approach. It would be interesting to see this project continue to be refined and potentially expanded for maritime applications with even more stringent operating requirements (particularly the amount of energy storage for the application).
- The funding opportunity announcement (FOA) and the mobile refueler initiative stand out as innovative initiatives.
- Yes.

10. Has the sub-program engaged appropriate partners?

- The sub-program has absolutely engaged the appropriate partners. The team has interfaced with dozens of federal, state, and local entities, along with commercial partners, over the years. This is probably one of the most collaborative sub-programs this reviewer has ever seen.
- Yes, the sub-program has engaged the appropriate public laboratories and private partners.
- Yes, there is clearly a broad spectrum of partners, especially within various industries.
- Yes, the sub-program features a diversity of project suppliers.
- Yes, the partnerships are appropriate and helpful.
- Yes.

11. Is the sub-program collaborating with them effectively?

- Yes, project managers have gone above and beyond to create effective partnerships and avenues for collaboration.
- Based on its past success and current status, this sub-program has a high likelihood of achieving successful collaborations.
- The deployment and demonstration of the project platforms seems to indicate the sub-program features a very effective collaborative environment.
- Yes, the sub-program appears to be collaborating effectively with partners.
- It is hard to tell whether the sub-programs are collaborating effectively with partners.
- Yes.

12. Are there any gaps in the portfolio for this technology area?

- There are no current gaps, but the emerging technology is subject to change as external conditions change. Sub-program managers must be constantly aware of these changing conditions, which may affect the path to commercialization.
- Stationary (non-backup) power applications appear to be receiving no continuing development or attention. While this may have been addressed in the past, the lack of accomplishment metrics (as presented for backup and forklift power applications) seems to imply that perhaps the market has not yet transformed to a sufficient degree. This area seems worthy of a second look. Additionally, ancillary considerations for hydrogen LDVs may need to become a priority for this area, especially concerning safety, codes, and standards. For example, it might be worth considering how DOE can ease the transformation of the FCEV servicing marketplace. It is not likely that the OEMs will remain the only servicers of their FCEVs, and independent businesses not involved in the business of building FCEVs likely need support in this area.
- The gap in pulling technology forward from the other sub-programs seems to be the result of a failed TV sub-program rather than this sub-program's concern. Despite this issue, there seem to be several infrastructure-related items with which this sub-program is not involved. There is a significant opportunity to develop light-duty fueling infrastructure projects, not just mobile fueling. It is not clear whether this sub-program has done the due diligence with infrastructure providers, or whether this sub-program has developed the relationships and identified opportunities.
- The main concern would be to reexamine the opportunity to catalyze the hydrogen infrastructure industry to broaden and deepen its capability to support vehicle fleets.
- It is not clear whether there are any gaps.

13. Are there topics that are not being adequately addressed?

- The topics, at this time, appear to be adequate and consistent with the budget, but that may change as conditions change.
- Applications that make use of opportunity fuels did not seem to be covered extensively in the review of recent accomplishments or the plan for the coming year. In particular, waste gas to hydrogen, trigeneration, renewable power-to-gas, and the overall intersection of the electric and natural gas grids through hydrogen need significantly more attention than they were given this year. There is a need among stakeholders (including state agencies) to understand the full potential and scalability of ideas such as these. At-scale

demonstrations are consistently called for in stakeholder meetings, although they do not appear to be a priority in this sub-program (which appears to be the most directly applicable sub-program).
- It is not clear how these specific market niche applications have been chosen - there was a systematic screening process or has DOE been opportunistic (in which case, opportunities may have been missed).
- It is not clear what happened to cell phone tower power supplies.
- The only topic not being adequately addressed is infrastructure.
- This question seems redundant with #12.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- At this time, there are no other areas the sub-program should consider funding.
- The major areas appear to be consistent with the budget and sub-program goals. Some additional attention might be beneficial regarding sensitivity to changes in external conditions and the path to commercialization, including a business case without investment tax credits (ITC), periods of low electricity and fuel costs, and reduced financial support for carbon reduction.
- Home power and the intersection of home power and LDV FCEVs seems to be an area that has "fallen off the radar" across the industry. However, there is great promise in integrated solutions that address both the home-based stationary and LDV sectors by more thoroughly demonstrating the possibilities. The number of market drivers could be doubled in DOE demonstration project(s) that provide information to the community on the viability and economic opportunity of these systems. Moreover, the home/auto combined system could help alleviate anxiety regarding the infrastructure being deployed and developed, as well as provide the automotive industry increased assurance that consumer convenience is being addressed, there is ample opportunity for consumer refueling, and there will ultimately be significant market launch volumes of home and vehicle fuel cells.
- The sub-program should consider funding infrastructure-related efforts—specifically, demonstration-scale equipment, suppliers, and support systems.
- The sub-program might want to consider fuel-cell-powered railroad locomotives (perhaps starting with switching yard engines).

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The objective to help market-ready solutions get to market through specific projects is the appropriate method for the sub-program.
- The sub-program should develop a better understanding of the existing hydrogen sources and then develop infrastructure market expansion opportunities around those sources. It should develop infrastructure market demonstration opportunities in un-involved zero emission vehicle (ZEV) and ZEV-leaning states (i.e., Oregon, Vermont, New Mexico, and Washington). It should continue to creatively use the funds available to encourage private and public partners to develop projects that provide an expansion to the established networks in California and the Northeast. It should "nibble at the edges" of the private and competitive markets in California and the Northeast. Perhaps national park destinations could represent opportunities for lower-cost, lower-size demonstration fueling facilities.
- Some current methods could be expanded, including (1) mechanisms to consider sensitivity to changed conditions (e.g., fuel costs, energy output value, ITC, and other incentive loss); (2) increased engagement with the supply chain, either directly or through OEMs, for improved reliability, inventory control, and cost reduction; (3) increased attention to potential cash flow and ability to secure commercial financing; and (4) further engagement to continue developing and maintaining community partnerships for the deployment of demonstration projects.
- No.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The sub-program should continue engaging other federal partners (e.g., the U.S. Department of Defense, Environmental Protection Agency, U.S. Department of Agriculture, and U.S. Postal Service) for more shared projects. The sub-program should perhaps consider a partnership with the U.S. Department of

Commerce and/or the U.S. Small Business Administration or others for marketing of successful demonstrations.

- Time seems to be running out; after so many years, the only area where traction is visible is the forklift MHE area (in addition, luckily the Nuvera buyout by NACCO Materials Handling Group and Toyota's commitment to supply 400 fuel cell forklifts to Osaka Airport are sustaining the "buzz" in this market). It would be interesting to see whether a solid business case can be made for fuel cells in other niche areas. It is unclear whether there has been a systematic screening of niche areas to identify other traction opportunities. Learning from the French experience is a good idea.
- The only recommendations are to slightly increase funding, if possible, and to refocus some investments on the infrastructure challenge in the next 3–5 years.
- Integrate TV into the Market Transformation sub-program to simplify the FCTO sub-program structure and centralize the point of contact between pre-commercial and commercial opportunities.
- No.

Systems Analysis Sub-Program Comments

1. Was the sub-program, including overall strategy, adequately covered?

- Yes. The goals were clearly stated at the beginning of the presentation. The Systems Analysis strategy was also clearly articulated: to develop comprehensive, consistent, and validated data; to obtain or develop models and methods with which to analyze the data; and to carry out a focused set of studies to address questions that can guide and evaluate the DOE Hydrogen and Fuel Cell Program's (the Program's) R&D efforts. Because the data and models have essentially already been developed (updating and checking is still required, of course), the work is now focusing on analysis.
- The strategy for the Systems Analysis sub-program is very robust and employs very well-known tools and models from world-class laboratories. It is also crucial for identifying opportunities for providing direction to overcome barriers and challenges in other sub-programs, such as the Hydrogen Production and Delivery sub-program. The sub-program's extensive collaboration with industry and academia adds a lot of value and robustness to the analysis work performed under the sub-program.
- Yes. The overall goals of the sub-program are well stated. Compared to the 2014 goals, the 2015 goals are more specific about quantifying benefits, such as greenhouse gas (GHG) reduction, and have expanded to cover life cycle analysis (LCA) of water use. Because the Systems Analysis sub-program is relevant to other activities within DOE, coordination was properly mentioned as a challenge/goal (e.g., connecting to the Vehicle Technologies Office models for fuel cell vehicles). The overall strategy and modeling scope was well covered in slides 3–6.
- The sub-program was described very well and seemed to have a good balance of technology analysis, infrastructure analysis, and high-level implementation and market analysis. One area of the strategy that was mentioned as an objective but not discussed was risk analysis and risk mitigation strategies. It was not clear what risks were identified as a result of the analysis and what additional work should be performed to mitigate these risks. High hydrogen utilization and low pressures will reduce cost, but it is unclear what should be done about this because we are headed toward low hydrogen utilization and higher pressures.
- Yes, the objectives, challenges, and strategy were covered adequately.
- Yes.

2. Is there an appropriate balance between near-, mid-, and long-term research and development?

- Yes. There is recognition throughout the Systems Analysis sub-program that the near-term launch of hydrogen technologies has a different set of issues than long-term development of low-net-carbon hydrogen pathways. There are elements of both near- and long-term analysis. Near-term analysis is appropriately claiming significant attention as fuel cell systems become commercial and fuel cell vehicle rollouts begin. This year, the sub-program established an interim (near-term) delivered hydrogen cost target of $7/kg and a long-term target of $4/kg (for automotive fuel). These were revised from previous targets. In the near term early market analysis for FCEVs, especially analysis enabling the commercialization of FCEVs, is stated as an important focus of the Systems Analysis sub-program. Many projects focus on near-term issues, such as infrastructure analysis and financial analysis of hydrogen stations. Long-term issues are also addressed for example, analyzing renewable sources of hydrogen production and advanced technologies (a project in this area analyzed advanced production methods).
- Yes, there is a reasonable balance between the time frames. Projects such as the Hydrogen Financial Analysis Scenario Tool (H2FAST) are useful to activities going on now and in the near future, namely assisting with the deployment of the earliest infrastructure for hydrogen vehicles. Other projects assist in defining targets for 2020 and beyond, while still others assess the long-term potential and conditions for market acceptance, future GHG emissions under different pathways, and so on.
- There is a nice balance between the near-term R&D, such as the efforts to develop an interim hydrogen cost target, and the longer-term R&D, such as the analysis to evaluate the benefits of increased fuel cell efficiency on the storage system and fuel cell. It is good to recognize the benefits of FCTO funding, as was done in the correlation between annual jobs and FCTO funding.
- The sub-program has an appropriate balance: it performs analysis on current hydrogen pathways and early market vehicle penetration while also providing a lot of analytical information to identify the main barriers

to future hydrogen pathways and FCEV penetration and how to overcome these barriers through DOE's R&D efforts.
- Yes, now that the sub-program is incorporating early market analysis, it is more balanced than before.
- Yes.

3. Were important issues and challenges identified?

- Yes. The Systems Analysis sub-program has highlighted the importance of hydrogen delivery and compression, storage and dispensing (CSD), in addition to production and end use. Initially, the importance of CSD to the economics of hydrogen and fuel cell vehicles was not fully appreciated. Analyses by the sub-program have shown how important it is and should help refocus R&D resources toward this critical area. The sub-program has also made an important contribution by highlighting the importance of reducing the costs of low-C hydrogen production. The sub-program recognizes the importance of the transition to hydrogen and fuel cell vehicles, but more needs to be done in this area.
- The sub-program is definitely focused on the main challenges associated with the hydrogen infrastructure development, and this was clearly demonstrated during the presentation.
- Yes, the emphasis is well stated on slides 2, 3, and 9, as well as on the slides for individual projects.
- The issues and challenges for the System Analysis sub-program are laid out in the presentation: market complexities, availability of data, and coordination of analysis. It may be useful to identify the issues and challenges that are identified as a result of the analyses that were performed and to identify approaches the other sub-programs could take to address these challenges.
- Yes, but one of the challenges is understanding market transitions, particularly because consumer behavior is difficult to model.
- Yes.

4. Are plans identified for addressing issues and challenges?

- Yes. Most plans involve model development and adding to model capabilities (see the list of FY 2015–2017 recent and upcoming activities from slide 20, copied below.)
    - "Diverse portfolio and expanded capability of models developed by the Systems Analysis sub-program are enabling analysts to address barriers to technology development and commercialization.
    - Emphasis on early market and infrastructure analysis. (Comprehensive approach to evaluate portfolio of fuel cell applications for light duty transportation, stationary generation, back-up power, material handling equipment, and the electric sector to realize economic, environmental and societal benefits.)
    - Continue life-cycle analyses of cost, greenhouse gas emissions, petroleum use and criteria emissions, and impacts on water use.
    - Continue to enhance existing models and expand analyses.
    - Assess programmatic impacts on market penetration, job creation, return on investment, and opportunities for fuel cell applications in the near term."
- Yes, by looking at the portfolio, it is very clear that the sub-program has a well-thought-out plan for conducting the proper analysis work, which will provide guidance to DOE's R&D work on hydrogen and fuel cells.
- Yes, the current and planned projects address the challenges identified.
- Yes. However, the Program should pay greater attention to the process of transitioning from petroleum to hydrogen. This is a particularly difficult problem and one that has not been extensively studied in industry, government, or academia. It poses special problems from economic, technological, and public policy perspectives. There are real and large barriers; strong positive feedbacks, including network externalities; and deep uncertainties. There are many important issues about which little is known. It could be argued that because the Program's primary responsibility is R&D, transition issues, especially public policy issues, are someone else's responsibility. Unfortunately, few are taking up that challenge, with the possible exception of the state of California.

- One area of concern is the validation of models. The H2FAST model was impressive. It would be beneficial to now document the validation of this model with available data from hydrogen refueling stations.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Several analyses on hydrogen station costs clearly identified opportunities and options for reducing the costs of dispensed hydrogen. The development and dissemination of H2FAST will be a key enabler to the development of hydrogen infrastructure.
- Yes, progress in understanding impacts on water use, employment, and much more was clearly presented.
- Yes, progress was benchmarked, although the degree of benchmarking shown varied. Progress was clearly indicated for these ongoing projects: Life Cycle Analysis of Water Use for Light Duty Vehicle Pathways, financial analysis for stations, and H2FAST, (Component and Infrastructure Assessment) Station Cost Analysis for Capacity and Fueling Pressure. Also, the following new projects showed results: Hydrogen from Methanol Reforming, Component and Vehicle Assessment, Impact of Fuel Cell System Peak Efficiency, Fuel Consumption, and Cost.
- The status for most of the accomplishments outlined in the presentation was not shown, compared to the previous year, but this is not absolutely necessary, given that the slides show work in 2014/2015.
- There was nothing in the presentation that clearly described how the work performed this year tied back to the work performed last year. This would be valuable to help one appreciate the progress that was made and how work in FY 2015 built on the results of FY 2014. Based on a review of the FY 2014 presentation, there are many areas that did build on previous efforts.
- No, progress was not clearly benchmarked, although there were graphs showing reduction in costs, etc.

6. Are the projects in this technology area addressing the broad problems and barriers that the Fuel Cell Technologies Office (FCTO) is trying to solve?

- The ultimate target of FCTO is meeting cost and performance targets. The sub-program is helping stakeholders understand how far different pathways are from meeting these targets and what barriers/challenges need to be addressed. The Systems Analysis sub-program works with the other sub-programs within FCTO to continuously update assumptions and pathways, and it integrates input from industry. Yes, the sub-program is addressing FCTO's challenges.
- Yes—one project looked specifically at targets for cost and performance, and what they might mean for FCTO goals. A project also looked at job creation associated with hydrogen infrastructure development.
- Yes—the sub-program is definitely in line with DOE's ultimate hydrogen cost targets, and the analysis work is providing significant data and guidance in order to achieve these targets.
- Yes, but the problems are numerous and difficult. The sub-program has done excellent work in benchmarking and analyzing hydrogen production pathways and their costs and benefits, including employment, water, and GHG impacts. The unique and novel problems posed by a major energy transition for the public good need special attention. Hydrogen and fuel cell use by heavy vehicles also deserves increased attention. Some of this is handled by the Market Transformation sub-program, but there are likely important possibilities beyond transit buses, namely medium and heavy duty trucks, that should become a core part of the sub-program's research and analysis.
- It appears the accomplishments from this sub-program address concerns, at least in some degree, for all of the other FCTO sub-programs: Hydrogen Production and Delivery, Storage, Fuel Cells, Market Transformation, etc. Some analysis was done both for stationary and mobile applications. Nothing was presented on the MYRDDP milestone "Complete analysis of the impact of hydrogen quality on the hydrogen production cost and the fuel cell performance for the long range technologies and technology readiness (2Q, 2015)."
- Yes.

7. Does the sub-program appear to be focused, well-managed, and effective in addressing FCTO' needs?

- Yes. Systems analysis of hydrogen and fuel cells has proven to be very complex. The sub-program has done an impressive job of building expertise, an information base, models, and analytical tools. Numerous important issues have already been addressed, yielding valuable insights and guidance.
- One of the main reasons this sub-program consistently meets its goals and objectives is the effectiveness of how it has been managed. This particular aspect is very impressive, given the significant number of stakeholders involved in this sub-program.
- Yes. The individual projects addressed important questions. There was good analysis of the impact of the Program on reducing costs for fuel cell backup units and forklifts, and on job creation.
- The Sub-Program Manager presented a set of very clear goals, progress to date, and results for each of the projects funded. It is clear the sub-program has been integrating external input from industry and others, such as the National Academies.
- Because the sub-program has such a wide breadth of areas of interest and such a wide range of time frames, it is difficult to see it as well focused. In general, it appears to be a wide range of disparate projects. It is not clear whether it is possible to tie them together in terms of time frame and model/tool hierarchy.
- Yes.

8. What are the key strengths and weaknesses of the projects in this sub-program? Do any of the projects stand out on either end of the spectrum?

- One strength is the breadth of issues that the sub-program seeks to address. Another strength is the way the sub-program models draw on and synthesize knowledge across DOE labs and modeling activities. The sub-program tries to make its models as consistent and well verified as possible, which is not an easy task. Collaboration and outreach to stakeholders through model development and workshops are other strong points. Sometimes the sub-program seems spread thin. It would be good to see connections with energy/economic models such as NEMS or others that include multiple sectors of the economy. Particularly excellent projects include the following:
    - The H2FAST project seems very valuable and stands out as useful for near-term studies of a station "business case."
    - The LCA of water use is of increasing interest.
    - There is nice use of the ORNL Market Acceptance of Advanced Automotive Technologies (MA3T) model to assess the impact of cost reductions in storage and fuel cell cost on market penetration.
- The main strengths of this sub-program are probably the models and tools being used to carry out the analysis work. One area in which the sub-program demonstrates its strength is in the understanding of hydrogen refueling station costs and identification of designs and configurations that provide options to reduce costs. There are probably no weak areas, but the sub-program should receive more funding.
- There is a good team of analysts working on these issues to develop things like spreadsheet tools, etc.
- Methanol is an innovative approach to hydrogen delivery. It would be good to have a full cost analysis and engineering assessment of this option, and not just the GHG analysis, to really understand whether it makes sense. Water usage compared to a variety of renewables is a nice addition to the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, although water consumption could be tied to the economics of the approach. The H2FAST model, and its potential utility to determine the economics of hydrogen refueling stations, is impressive. It is good that the analysis of fuel cell efficiency is being tied to fuel cell and storage system cost. However, it does not make sense to tie it to a particular time frame. It highlights the importance of improved fuel cell performance. The vehicle penetration analysis results could be clarified to provide solid conclusions and recommendations that drive some future work.
- Strengths include the expertise and human resources built up, especially at the national laboratories (e.g., NREL, ORNL, Argonne National Laboratory, SNL, and LBNL), but also at universities, especially the University of California, Davis, and the University of California, Irvine. The resources developed by the sub-program like ; the Hydrogen Analysis (H2A) model; and numerous models such as GREET, the Hydrogen Delivery Scenario Analysis Model (HDSAM), the MA3T, other market models, Autonomie,

H2FAST, and more give the sub-program powerful analytical capabilities. The Macro-System model has been developed into a useful tool for linking models together. Strengths also include the contacts and collaboration with industry. Particularly in the area of market models—that include representations of consumers' choices of vehicles,—there appears to be a need to better articulate the purposes of the different models and to understand their particular strengths and limitations. There are many unknown elements, including the following: (1) which models predict initial demand for hydrogen fuel cell vehicles to assist in the deployment of early infrastructure; (2) which models are designed to analyze the co-evolution of the market for vehicles, hydrogen supply, and refueling infrastructure to assess benefits, costs, and policy issues; and (3) which models are for evaluating sub-program goals and assessing costs and benefits.

- Key strengths include the very strong technical expertise, good models, involvement of the right stakeholders, and clear goals. A key weakness is that some of the models are set up to assume that DOE targets are met and only consider high volumes of production for key technical components and high market penetration, which generates unrealistic results. These models need to be coupled with early market assumptions such as low utilization rates and high cost of technology.

9. Do these projects represent novel and/or innovative ways to approach these barriers as appropriate?

- Yes. For example, the addition of H2FAST this year should be helpful to states developing and executing plans for deploying hydrogen infrastructure. It should help in developing policies and evaluating proposals. It is also likely to be useful to early infrastructure providers. Good progress has also been made in the analysis of water impacts and life cycle cost analysis of hydrogen pathways. This work is likely to increase in importance.
- New technology pathways are constantly being integrated into the models. For example, the LCA models now include 700 bar for refueling, and an effort to include 500 bar is on the way; merging hydrogen production technologies are being analyzed; and additional onboard hydrogen storage technologies are being considered. Continuous communication with the U.S. DRIVE Technical Teams, which represent different stages of the value chain, ensures that the latest technologies are being considered.
- Yes, there are projects that represent novel ways to address the key analysis questions. The sub-program manages a number of innovative and useful models that can be used to address questions posed in slides 2 and 3.

10. Has the sub-program engaged appropriate partners?

- Yes. There is good involvement from industry, academia, consultants, and the national laboratories. The sub-program has strong partnerships with industry, which enables valuable input from industry to inform and help target analysis. The national laboratories play a key role as valuable and reliable reservoirs of knowledge and expertise. A sub-program such as the Systems Analysis sub-program cannot function effectively without an array of experts to draw on. Most of these experts reside at the national laboratories. Academia and industry also play a critical role, but the national laboratories perform a core function as the place where expertise can be created and sustained.
- Yes, the sub-program is very engaged with major stakeholders in industry and government, including the national laboratories. The workshops are an effective way to bring stakeholders together around hydrogen issues of interest.
- The sub-program features successful collaborations with partners that provide very valuable feedback to the portfolio of projects under this sub-program.
- The sub-program appears to have engaged a variety of partners that will assist in developing and validating the results. The level of engagement is difficult to determine based on the presentation; however, the multinational workshops with a wide range of industries and laboratories in attendance suggest a strong interested in gathering a wide range of opinions and ideas.
- Yes, industry and national laboratories are involved.
- Yes.

11. Is the sub-program collaborating with them effectively?

- Yes, the sub-program appears to be collaborating effectively. This is not easy, given the rapid growth of activity in the hydrogen and fuel cells space.
- Yes, and this collaboration is clearly demonstrated by the numerous accomplishments and successes achieved.
- It appears that the sub-program is collaborating with partners effectively.
- Yes, the collaborations are effective.
- Yes. It was not possible to determine whether H2USA is making effective use of the capabilities of the sub-program. The presentation was expected to include more details about these interactions.

12. Are there any gaps in the portfolio for this technology area?

- There are no gaps, but there are areas that should probably be given greater attention, such as understanding the transition process. The sub-program has made important contributions by doing analysis and developing resources for early infrastructure deployment, and the sub-program appropriately considers this an area of emphasis. It also emphasizes the interaction between hydrogen supply and vehicle demand. However, the transition includes more than just these issues. There are many unknown aspects of the transition or the conditions for success and the threats. In addition, greater emphasis should be given to heavy-duty vehicles. Heavy-duty vehicles are a diverse segment, and it is not at all clear that in the long run hydrogen and fuel cells could not play a major role as a primary power source for these vehicles.
- No, there are no gaps, but the water consumption numbers need to be scrubbed and compared with the literature on two fronts:
    - Water consumed to make the biomass: One paper estimates that it requires on the order of 3,200 gallons of water per kilogram of hydrogen produced from biomass, assuming a biomass production energy ratio of 0.737.[2]
    - Wind electrolysis: NREL has previously estimated very high water consumption (294 gallons/kg of hydrogen) is needed to cool the electrolyzer.[3]
- In a way, hydrogen FCEVs are similar to compressed natural gas (CNG) vehicles. CNG vehicles have not had significant market penetration in the United States, and they face challenges similar to those of FCEVs. It would be interesting to assess lessons learned from the CNG vehicle industry and understand how they can be leveraged to advance FCEV market penetration. A number of LCAs have been done for GHGs, cost, energy, petroleum use, and water. It would be useful to incorporate criteria air pollutants and show the results of all these parameters for different vehicle technologies for early market and developed markets with the same assumptions in one presentation.
- There are two areas discussed in the MYRDDP that were not addressed in the portfolio: risk mitigation and policy analysis. It would be useful to evaluate what research needs to be done to mitigate particular risks identified with the analyses. It would also be useful to better understand how possible changes in government incentives and regulations could impact the business case for hydrogen, infrastructure development, or fuel cell use.
- There is a need for more transition analysis. Given recent results from the National Academies report on light-duty transitions and others, it appears the benefits of hydrogen outweigh the costs. A better understanding of this issue for different applications would be useful. The sub-program appears to be going in this direction, which is good. It is good to see interest in looking at roles for hydrogen in non-LDV transportation. As scenarios for a low-carbon transportation future are developed, it is important to keep the sub-program closely coupled with activities in other parts of DOE.
- More funding is needed.

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[2] See P.W. Gerbens-Leenes, "The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply," *Ecological Economics* 68, no. 4 (2009): 1052–1060, http://www.sciencedirect.com/science/article/pii/S092180090800339X.

[3] Mark Ruth et al., *Hydrogen Pathways: Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Seven Hydrogen Production, Delivery, and Distribution Scenarios*, NREL/TP-6A1-46612 (Golden, CO: National Renewable Energy Laboratory, 2009), http://www.nrel.gov/docs/fy10osti/46612.pdf.

13. Are there topics that are not being adequately addressed?

- The sub-program's portfolio seems well balanced, and it covers the main areas to address the top barriers and challenges currently facing the hydrogen industry.
- Overall, the sub-program is doing a very good job.
- The fuel economy of FCEVs needs to be updated. For example, the national laboratories measured an average fuel economy of 68.3 miles/kg of hydrogen for the Toyota Highlander sport utility vehicle FCEV. As fuel cell technology is migrated into mid-size passenger vehicles with lower cross-sectional area, lower aerodynamic drag, and lower mass, the fuel economy will increase. The following are some examples of increased fuel economy, assuming that the decade-old Highlander fuel cell was packaged into a Prius-like sedan: reducing the test mass from 1880 kg for the Highlander to 1679 kg for a Prius FCEV increases the fuel economy to 76.8 miles/kg, reducing the cross-sectional area from 33 sq. ft. to 28 sq. ft. increases the fuel economy to 77.2 miles/kg, and reducing the drag coefficient from .326 for the Highlander to 0.25 for the Prius body increases the fuel economy to 85.4 miles/kg. Note that this assumes no increase in fuel cell efficiency after 10 more years of development and no increase in specific power of the fuel cell, both of which will increase fuel economy even more. For example, the Toyota Mirai has a reported range of 650 km on 4.3 kg of hydrogen, or a fuel economy of 93.9 miles/kg of hydrogen, indicating that Toyota has improved fuel cell efficiency and specific power since it built and tested the Highlander FCEV more than a decade ago. Thus, the fuel economy numbers that DOE is using for the FCEV (i.e., 50, 55.3, and 68) are way too low and are short-changing the benefits of FCEVs.
- The sub-program is quite comprehensive and addresses a wide range of important issues. It might be useful to develop a clear plan for market modeling, especially models involving vehicle choice. Several models are receiving support, and different scales and scopes need to be modeled using different approaches. However, the presentation did not provide a clear sense of which models address which issues.
- Some of the assumptions in the models are too optimistic:
    - Models that assume that DOE targets are met.
    - Assuming high market penetration.
    - Assuming technology is produced "at volume."
    - All ranges of the spectrum should be considered.

14. Are there other areas that this sub-program should consider funding to meet overall programmatic goals?

- It appears to be a well-balanced portfolio of near- and long-term analyses for the wide range of topics applicable to hydrogen and fuel cells.
- The sub-program should formulate a research agenda for transition analysis. In a way, this is overdue because vehicles are already being manufactured and leased. On the other hand, the transition will take decades, even if it is very successful.
- The sub-program should consider funding projects related to LCA of criteria air pollutants, understanding potential displacement of CNG technologies using fuel cells, and integration of fuel cells to renewable energy sources to address intermittency issues.
- The sub-program should coordinate with the Market Transformation sub-program to document progress as fuel cell and hydrogen technologies are rolled out.
- The sub-program could further fund and perform analysis work on advanced hydrogen technologies in FCEVs, including how these will impact the hydrogen delivery pathways.

15. Can you recommend new ways to approach the barriers addressed by this sub-program?

- The current approach has been demonstrated to be successful over the years.
- Future market behavior is a central issue for the sub-program. Of course, this depends on issues such as the price of oil and how consumers evaluate fuel costs versus vehicle purchase prices in their car-buying decisions. However, it also depends on issues that are mostly unknown, such as the following: (1) the number of early adopters and how willing they are to pay for the first thousands of novel fuel cell vehicles; (2) the risk aversion level of the majority of consumers, and how quickly it can be overcome, (3) the perceived cost of limited fuel availability; and (4) the value of a diverse set of vehicle choices. On the fuel

supply side, it is unclear how important the cost of hydrogen will be to customer satisfaction. It is also unclear what will happen in California if there is no effort to control the price of hydrogen to early vehicle purchasers, or how public policies and business models can be structured to ensure a satisfactory supply of hydrogen at a cost that encourages adoption of fuel cell vehicles. It can be argued that these issues are outside of the sub-program's scope (and budget). However, it is not clear who will do the necessary research and analysis.

- Yes, there are two recommendations for new ways to approach the sub-program's barriers:
    - For barrier "Stove-piped/Siloed Analytical Capability," it may be useful to more strongly encourage activities in other sub-programs to integrate the use of the resources and models that have been developed in this subprogram, especially if the activities are being conducted by different organizations.
    - For barrier "Inconsistent Data, Assumptions and Guidelines," the research organizations associated with the Program should be encouraged to use the information developed by this sub-program as part of Funding Opportunity Announcements or Annual Operating Plans.
- There is a growing focus on understanding consumer decisions and choices around advanced vehicles. The sub-program should encourage continued discussion of these topics with stakeholders.

16. Are there any other suggestions to improve the effectiveness of this sub-program?

- The Systems Analysis sub-program is making important contributions to guiding DOE's R&D decisions and evaluating the most important costs and benefits of hydrogen and fuel cell vehicles and other applications. The entire Program budget should be increased and, when that happens, the sub-program budget should be increased as well. There is a lot to be done. Recognizing that DOE actively participates in the IPHE, keeping close track of technological progress, policies, and implementation around the globe should probably be a core function of the sub-program effort. There is no doubt this is being done to some degree, but the presentation did not provide much information. Perhaps the United States can learn from what is happening in Germany, the rest of the European Union, Japan, Korea, and China.
- This sub-program is very effective in conducting useful analyses of hydrogen and fuel cell systems. To the extent possible, it should facilitate transfer of the latest knowledge about hydrogen and fuel cells to other groups within DOE and to agencies that model energy systems and futures.
- The only suggestion is to update the fuel economy of FCEVs for passenger sedans, which will improve the benefits of FCEVs compared to other vehicles.
- There are no additional suggestions to make.