Sub-Program Comments Provided by Reviewers

Hydrogen Production & Delivery Sub-Program Comments

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

- The sub-program was covered thoroughly, including hydrogen cost status and targets and the research, development, and demonstration (RD&D) strategies and framework—which addressed the leveraging of resources among stakeholders and cross-office and cross-agency collaborations. The production and delivery of hydrogen were shown to have been analyzed from a technoeconomic perspective. Several advances in research and development (R&D) were presented, e.g., a new photoelectrochemical (PEC) world record; an 875 bar hydrogen storage vessel designed to operate safely for more than 20 years and at a cost less than the target cost; and joint efforts with the Office of Science on catalysis for hydrogen production, hybrid perovskites, which are emerging as a new class of promising materials, and biomimetics for hydrogen activation. In addition, this year the price of hydrogen vis-à-vis low or high volume for early markets was thoroughly analyzed and compared with the ultimate target. In summary, the sub-program is a foundational part of H2@ Scale, which is a big national laboratory idea that will advance the U.S. Department of Energy's (DOE's) agenda toward energy security and economic growth.
- The presentation more than adequately covered the overall strategy and an overview of technical progress. This is a very well-balanced, well-thought-out sub-program that covers a very broad diversity of approaches to hydrogen production and distribution, ranging from collaborations with fundamental Basic Energy Sciences (BES) projects to foundational work done within the sub-program to applied materials and engineering work. This is a very well-integrated program, and it is apparently very well managed, as judged by outcomes.
- The overall strategy was clearly explained by the sub-program manager on slide 10. It is encouraging to see that the research is guided by the technoeconomics.
- Yes, but as in 2016, the overview presentation took too much time, making the end of the presentation challenging to follow. The presenter should focus on being concise because the individual project sessions explain all details. The real focus of this sub-program is $4–$7/gge—period. This is why the audience comes to listen to this overview.
- Yes. The sub-program was adequately covered. While Eric did a great job of explaining the department successes in the relative sub-programs, the "why" was still missing from the discussion. This has been, and remains, a challenge for the hydrogen community. While it is clear that 20 MMT hydrogen/year would be required to fuel 100 million fuel cell electric vehicles (FCEVs), an understanding and a vision for getting to 100 million FCEVs was missing. The H2@ Scale concept is helpful, but what is missing is the vision for how it functions and how we get there.
- Goals were presented, but clear, specific strategies for reaching economic goals were not described. Projects were described in generalities rather than specifics.
- Magnetic liquefaction work was not discussed.

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

- This is one of the most diverse sub-programs the reviewer has encountered within DOE. The technical and scientific range of topics is quite large and diverse, and the range of timeframes the projects span is also quite large, ranging from near-term engineering studies and laboratory-scale demonstrations to longer-term foundational materials research, such as in the area of PEC generation of hydrogen. It is a sub-program that is well balanced, with a distribution of timeframes, technical risk, and technology readiness levels (TRLs).
- The sub-program has a balanced R&D portfolio, both on hydrogen production and hydrogen delivery vis-à-vis near- and long-term objectives. In fact, the sub-program should be commended for the thoughtful distribution of resources, e.g., on electrolysis, PEC, and solar thermochemical hydrogen (STCH), as shown on slide 11 and the technoeconomics of hydrogen and delivery costs.
- One of the key aspects of the sub-program's portfolio is the very good balanced to cover near- and long-term R&D. This is demonstrated for hydrogen production with a portfolio that covers near-term technology

options focused on fossil resources, while at the same time there is also some focus on long-term options on water-splitting technologies, such as STCH and PEC hydrogen production. On the delivery pathways, this is demonstrated by near-term efforts on tube trailers and tankers, while for long-term options, there are some efforts on advanced liquid carriers.

- The Hydrogen Production & Delivery sub-program definitely has a good balance between near-term technologies such as water electrolysis and being cognizant that future advances and early-stage research could make other technologies feasible. Going forward, there will be some challenges to maintaining this balance. It will be important for the office to continue great engagement with industry (end users) to understand their needs and design appropriately balanced research portfolios. Generally speaking, the vision of rolling out 60 MMT of hydrogen per year in the next 30 years—meeting this ramp-up—will require substantial investment in demonstrations, so while many early-stage/long-term technologies could be in the pipeline, later-stage/near-term technologies of those projects can add value to society's understanding.
- The sub-program has addressed fossil, biomass, and solar as near-, mid-, and long-term paths.
- It appears to be mostly mid- and long-term focused.

3. Were important issues and challenges identified?

- "Cost" was identified as a major challenge for both the renewables pathway and for refueling stations, which are both less technically challenging and more near-term. Earlier-stage technologies also had some technical issues identified. Maintaining stable and predictable budgets was also correctly identified as a major challenge for both later-stage and early-stage R&D. While solving the technical issues is a matter of really smart scientists working on a problem, overcoming the cost challenge is more difficult. The costs for electrical energy, which is outside the scope of the hydrogen program, represent 47%, while only 34% are for the system capital expenditure, which includes many components outside the scope of the electrolyzer stack. While the Hydrogen Production & Delivery sub- scope is limited as to its impacts on these other areas, it can have some influence. The work showing electrolyzer impacts to the grid can be quantified, and the impact of hydrogen energy storage + renewables on electrical energy prices can also be evaluated. Large-scale deployments of the technology can be utilized to drive balance-of-plant (BOP) and indirect costs down through scaling.
- Without a doubt, important issues and challenges were identified. Hydrogen generation's fairly foundational science challenges have been identified, and multiple approaches are being employed. Engineering challenges in delivery and distribution have been identified, and multiple mitigation strategies are being employed to obtain enhancements in reliability or durability or reductions in process intensity and energy efficiency, all of which will eventually play key roles in delivering hydrogen to consumers at competitive costs.
- All issues across the sub-program's portfolio were addressed, and the R&D challenges and framework were thoroughly defined, as demonstrated by slide 10.
- The issues and challenges for hydrogen production and delivery, as well as the strategies to address these, were clearly explained by the sub-program manager.
- Targets were presented, and brief explanations were given. "Early Market Target" is a good addition and was clearly explained.
- Production and delivery cost reduction is the main overarching challenge. While individual projects did bring up challenges, the overview presentation does not indicate what the highest-priority issues and challenges within the sub-program are that need to be addressed to achieve such cost reduction the quickest.

4. Are plans identified for addressing issues and challenges?

- New areas of emphasis are in new initiatives, e.g., the consortium HydroGEN and H2@ Scale, both of which will drive innovations to address challenges in hydrogen production and delivery. In addition, the sub-program has put in place collaborations with other agencies to leverage their work in production and distribution, such as the National Science Foundation (NSF)/BES, the emerging energy materials networks (EMNs), to name a few, where the Fuel Cell Technologies Office and this sub-program are reaching out to find leverage to accelerate the evolution of hydrogen fueling in the consumer segment.

- The well-balanced portfolio presented by the sub-program manager on slide 11 clearly demonstrates the plan for addressing the research challenges on both hydrogen production and hydrogen delivery.
- Strategies for RD&D were stated on the Strategy (slide 10), along with the national laboratory and interagency support framework and partnerships.
- Plans for addressing technical issues are identified, but addressing the cost challenges is not clear.
- Yes. Continued R&D is needed to reduce costs.
- Plans were given, but they lacked specificity.

5. Was progress clearly benchmarked against the previous year?

- A number of advances were presented that have clearly set the new benchmarks, e.g., the appliance-type refueling station for a small number of FCEVs at 700 bar, the steel-wrap approach to the stationary storage of high-pressure hydrogen, and the new world record on PEC.
- Several accomplishments were presented, and these were very impressive, such as the novel hydrogen technology option for the Delivery portion, as well as the new PEC record and the new HydroGEN consortium recently launched in the Production area.
- Goals were given at the beginning of the presentation, and metrics were presented throughout. However, there was no clear year-over-year benchmarking toward goals using the selected metrics. Qualitatively, several technical accomplishments were shown, which illustrates the quality of the work.
- The presenter clearly delimited the progress benchmarked against 2016. Significant progress was demonstrated across many near-term, mid-term, and longer-term R&D projects within the sub-program portfolio.
- Progress was clearly benchmarked in the project presentations attended but not in the overview presentation.
- 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?

- The ongoing activities in the sub-program portfolio are focused on addressing the main barriers within FCTO. It is really exciting to see the new HydroGEN consortium being launched, as it will bring projects and expertise to overcome some of the main materials challenges on water-splitting technologies.
- This sub-program, with its broad diversity of technologies and science being worked against near-term to long-term targets, is tightly focused on challenges and barriers that FCTO R&D is trying to breach, and with great success.
- Yes, the sub-program's projects do address the DOE targets in a balanced way among the alternative technologies. An example is the 875 bar storage vessel that addresses the storage target at a cost even less than the target cost.
- Yes, delivered cost of hydrogen and cost-competitive hydrogen from renewables are the broad barriers.
- The portfolio approach is good and certainly needs to be continued. However, the goals of 60 MMT hydrogen per year cannot be achieved through laboratory-scale demonstrations. Industry involvement in the technology deployment to answer key questions of scale, longevity, BOP, etc. is needed in the future to solve the problems and achieve the widespread deployment.
- Generally, yes. However, research of new (but previously explored, such as metal hydride) compressor technologies does not solve compressor challenges. In addition, for compressor challenges, it is not clear what the decision-making process within FCTO is in this area.

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

- Overall, yes, but specifically, decisions on choices for R&D on specific topics should be more transparent, not a DOE FCTO "black box" approach. It is not clear whether all topics address actual industry needs and/or industry-identified challenges (instead they may address academic or [national laboratory] scientific challenges, separate from industry).

- While this broad set of technological and scientific topical areas might be difficult to manage effectively, that is not the demonstrated case here. This is a well-managed and efficient sub-program that has a history of success in challenging and breaking down technical barriers critical to FCTO Hydrogen and Fuel Cells Program needs.
- Liquid carrier work was examined early in the sub-program and specifically rejected as having little or no chance of meeting sub-program targets. It was formally written out of the delivery roadmap in 2012. It is not clear why carriers have resurfaced as a possible long-term option.
- Excellent management and an excellent support team are the main keys for the success and effectiveness of the Hydrogen Production & Delivery sub-program.
- The sub-program is well managed and focused and has many technical accomplishments across the portfolio. However, it is not clear how effective it is at addressing the key goals of sustainable hydrogen production at scale. This is principally because a vision and scale have been selected, 60 MMT H2/year, but there is no clear pathway on how to get there, and no go/no-go decisions based on drivers. (see answers to some previous review questions) In many cases, the program is tied up--doing the best that can be done with limited and uncertain budgets and DOE policy that is pushing for early stage research when the stated goal, 60 MMT/year, is a matter of scale up demonstrations with industry involvement.

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?

- A key strength is the continuous enhancement of sub-program elements; the sub-program is not static, e.g., bringing on HydroGEN and working with H2@ Scale. Another key strength is the leverage the program gains via communication and collaboration with entities such as NSF and BES, just as two examples. There are no key weaknesses.
- A key strength is the balanced portfolio on production and delivery involving short- and long-term efforts. The Sandia National Laboratories (SNL)/Pacific Northwest National Laboratory project on tribology in the presence of hydrogen is a promising approach to developing methodology and testing protocols for polymers operating in hydrogen. In addition, this year, fundamental science is addressed through joint projects with the Office of Science and NSF (slides 14 and 15).
- Strengths include an extremely well-balanced portfolio to address near- and mid-term challenges for both production and delivery, very efficient management and support, understanding of key barriers and how to address these, and external collaboration. There are no weaknesses.
- The key strengths of this sub-program are the breadth and depth of analysis that has been done on different scenarios and cost drivers for technologies, and many innovative technologies that have the potential to shift those cost drivers or modify the scenarios. The key weakness (this may sound contradictory) is the focus on technoeconomic analysis that really looks like economic analysis only. While it is good to baseline technologies and compare, technologies that are not “drop-in replacements” should not be evaluated only as such. Characteristics such as capacity factor, reliability, size, and connection to existing infrastructure (wires, gas lines, liquids pipelines and storage, water) need to be considered, as different technologies are unique and have been demonstrated at various scales. This is true of technologies within the hydrogen space, and also true of hydrogen vs. other technologies (such as hydrogen energy storage vs. battery energy storage or compressed air energy storage). The SimpleFuel demonstration and the PEC work are both very exciting and could change some of those costs/scenarios.
- The following are key strengths: most projects explore the challenges of producing and getting hydrogen as a fuel to vehicle drivers/operators, and liquefaction projects should receive increased emphasis because a pathway efficiency bottleneck exists here for which bench-scale solutions appear to hold promise. The following are key weaknesses: the sub-program has not clearly identified niche markets for hydrogen (as vehicle fuel or other use) that can help to scale up green hydrogen production (to at least thousands of kilograms per day); industry players are not sharing realistic cost numbers for delivery (assuming shorter equipment returns on investment than for existing industrial equipment in use); and long-term R&D focus is a given, but this does not do much to resolve current challenges with trying to achieve cost reduction (high-volume throughput can be calculated but has to be achieved first, which is a pipe dream if DOE does not focus on achieving this) to more acceptable levels (below $10 per kilogram dispensed).
- It is not clear that measurable performance benchmarks exist for early-scale research efforts. Even these projects need performance-based metrics for go/no-go decisions.

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

- In many of the project areas, the technical and scientific competition is intense. For example, in the PEC generation of hydrogen, the competition is at the highest level; many of the world's best teams of scientists work in this area. Therefore, to remain competitive in this rapidly evolving area of science, they must provide innovative approaches to the problems that need to be solved. The DOE Office of Energy Efficiency and Renewable Energy's projects do that and compete successfully with scientists funded through BES, NSF, and other world-leading R&D organizations. In one specific sub-program element, non-mechanical gaseous hydrogen compressors, it was good to see that two teams working on competing technologies were in fact collaborating. This is a healthy indicator of how well sub-program participants can work together. It is heartening to know that in some instances, the technical outcome is more important than personal technical success.
- The sub-program has analyzed the technoecomics of hydrogen production from sustainable resources (see slide 4) and addresses this long-term challenge through a well-coordinated strategy (see slides 13, 16) and the newly launched HydroGEN consortium (slide 23). The program is similarly well balanced in its strategies for overcoming the delivery and storage barriers.
- Great representation of innovative ways to approach these barriers are as follows: for production, the discovery of new materials for water-splitting technologies, and for delivery, the innovative station design projects.
- The reformer/electrolyzer/purifier is an innovative use of existing technology. Magnetic and vortex-assisted liquefaction are both highly innovative with potential impact.
- SimpleFuel is a nice demonstration of packaging technologies for deployment and reducing cost. PEC research can address the cost of electricity by removing electricity production from the equation and relying directly on solar radiation. However, there is always a tradeoff because in any location the solar radiation can be used only once for its highest and best purpose (if the market's invisible hand is at work).
- Many do; some are a rehash of previous efforts (e.g., metal hydride compressors).

10. Has the sub-program engaged appropriate partners?

- The presentation laid out the strategy for collaborations among a set of other world-leading organizations, so yes, the sub-program has done an excellent job of partnering around the world and of course here in the United States.
- The sub-program has really excelled at engaging partners. All sectors and industries are fairly represented and have their viewpoints heard.
- The sub-program has an impressive collaborative program among national laboratories and interagency interactions, e.g., a joint funding approach with NSF.
- There is excellent collaboration with national laboratories, academia, and technology providers.
- There is good collaboration within DOE and other government agencies. Collaboration with commercial partners is limited.
- Overall, yes. However, large industry player engagement should be pursued more strongly.

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

- Ample evidence was given in the way of progress in many areas where collaboration was key to accelerating DOE R&D, and a good example was given entailing future strategies, e.g., the EMN interactions.
- Judging from presentations reported on slides 14 (Office of Science) and 15 (NSF), the collaborations can be deemed successful and serving the goals of the sub-program.
- There is very effective collaboration with the partners.
- The sub-program is definitely collaborating with partners. There may be some opportunity to engage more with end users and thereby help the sub-program understand the drivers better.
- It appears to be the case—this is not a specific project review.
- It was not possible to assess the effectiveness of collaboration from the presentation.

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

- There are questions around liquid hydrogen tanker trailer research; it is not clear what the limits are or whether the limits for over-the-road transport can be expanded. This would contribute to reduction of cost per kilogram delivered, owing to the ability to transport larger quantities. Another gap is underground compressed and liquid hydrogen storage solutions tanks. Renewable energy availability does not equal all renewable energy available for hydrogen production. Other gaps include assessment of all current oil and chemical industrial processes to explore potential for diverting hydrogen streams for higher-value purposes (than current uses), 700 bar dispensing for heavy-duty vehicle applications, and cryocompressed dispensing for heavy-duty vehicle applications.
- In the area of non-mechanical hydrogen compressors (electrochemical, metal hydride, hybrids, etc.), earlier attention to cost analysis could be beneficial to further focus the overall research effort. In these areas, the technology is somewhat mature, and there may be some advantage to focusing more on systems models that lead to cost (capital as well as operating) models, gaining some R&D efficiency in the process.
- Thermochemical conversion of biomass or biomass-derived liquids is not addressed. These may be considered as being mature enough not to warrant consideration.
- The biggest gap in the portfolio is scale. Reaching the 60 MMT/year is going to be challenging without a mechanism for technology to cross the valley of death.

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

- The portfolio is well balanced. The addition of the HydroGEN consortium is very valuable to the sub-program.
- The development of strain-based mechanistic models of hydrogen embrittlement for specific steel microstructures (slide 19) is focused only on mechanical testing (PD-025). Although the work on mechanical testing carried out at SNL is state-of-the-art, it is not aiming at model development. Operation of metallic components for hydrogen applications require predictive models for safety and reliability, especially against fatigue.
- Yes: intermediate hydrogen production and delivery cost reduction goals at lower volumes should be addressed (the focus is on long-term goals at high volume).
- Scale of hydrogen production is not adequately addressed.
- The sub-program appears to be doing as much as it can under its limited budget.

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

- It is difficult to imagine where there is any “white space” the sub-program manager does not have covered—or if there is white space, there is a reason for it.
- Other areas include the following:
    - Liquid hydrogen tanker trailer research
    - Underground compressed and liquid hydrogen storage solutions tanks
    - Assessment of all current oil and chemical industrial processes to explore potential for diverting hydrogen streams for higher-value purposes (than current uses)
    - 700 bar dispensing for heavy-duty vehicle applications
    - Cryocompressed dispensing for heavy-duty vehicle applications
- These are a bit redundant, but if the goal is national deployment of sustainable hydrogen, there must be a DOE role in de-risking. Industry-led demonstrations with substantial support for large-scale demonstrations, which answer key questions, will be critical to rolling out this technology. Also, analysis that considers the unique benefits of hydrogen should be considered.
- Transportation of hydrogen from remote, renewable-resource-rich locations to high-demand locations does not appear to be given adequate attention.
- The sub-program should look into the state of R&D is for hydrogen compressors, an important component of refueling stations.

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

- The sub-program manager is doing an excellent job, is highly knowledgeable, and is doing an absolutely stunning job of massing his attack on the remaining barriers.
- The sub-program should focus on one (1) hydrogen production "park" located adjacent to a location with excess renewable energy (photovoltaics, wind, and/or biogas) and existing pipeline or large storage accessible for injection at any time; all projects should be located here, not spread out over the whole country at a large number of difficult-to-access national laboratories. This could also include compressor projects and over-the-road distribution options. The sub-program should assess whether the TRL rating concept transfers directly to industry; DOE may be investing in the low-cost, easy-entrance conceptual part of the technology development spectrum, of which only 1 out of 100 concepts makes it to market (venture capitalist process).
- A key issue in the area of hydrogen delivery and infrastructure (e.g., materials for compressor technology) is hydrogen-accelerated fatigue of metals and alloys. SNL is successfully driving the codes and standards efforts, but fatigue is an issue that is still unresolved. Further, there are no mitigation strategies, and fatigue could be responsible for potential failure scenarios in the future. A joint program with NSF or the DOE BES is indicated. None of the projects with the Office of Science (slide 14) and NSF (slide 15) addresses this important issue of hydrogen-accelerated fatigue and mitigation.
- Cost barriers can be addressed only by scale, either scale at the site or manufacturing scale. As a market emerges, vendors will be able to better compete to reduce cost on components further.
- Continue industry engagements with the new HydroGEN consortium should be continued.
- No.

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

- The only suggestion is to include the university community on fundamental science issues, for example, in the area of fatigue mentioned in items 13 and 15. In summary, Dr. Miller has done a very fine job in shaping the sub-program into one that steadily advances toward the targets with an optimum allocation of resources serving short- and long-term goals.
- The sub-program should add an annual showcase of tangible DOE-funded project outcomes/products to create an emotional response about outcomes.
- There is no excuse for the presenter's not covering all the material in the allotted time. The presentation should be reviewed and "dry runs" carried out with colleagues before the Annual Merit Review. The presentation should be pared down if all the material cannot be presented in the allotted time.
- No.

Hydrogen Storage Sub-Program Comments

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

- The sub-program, including the overall strategy, was covered in a very good and professional way. An overview was given, and all the different storage options were considered. The goals and targets were presented and addressed very well. The sub-program is very well balanced. Those alternatives and technologies at a lower technology readiness level (TRL) and with higher ultimate potential to meet the final targets, but too low a TRL to be taken on by the industry itself, are given a special focus and should, in the future, be given an even higher focus.
- The overall strategy was well explained, particularly the explanation of the current status of commercially available fuel cell cars and how that has adjusted a few key technical targets for hydrogen storage.
- Yes, the objectives and strategy were very clearly and effectively explained. The sub-program presentation had very good content regarding the strategy and projects. In some cases, the materials-based storage included too much detail and did not highlight the linkage to improving a specific target.
- Yes. The strategy was well described and thoughtfully considered.
- Efforts in materials and physical storage were well described.

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

- A very good balance between near-, mid- and long-term research and development (R&D) has been found, and all are addressed in high-pressure, cryocompressed, and physical storage means. Materials R&D, engineering R&D, advanced tank R&D, and analysis are covered. Concerning the final targets, only materials-based hydrogen storage has the theoretical potential to fulfill these. Especially as recently it is understood that volumetric storage density is more important than gravimetric storage density, the focus on materials-based hydrogen storage is correct. This sub-program, however, is not a continuation of old efforts in the area of hydrides but is following a new, much more knowledge-based approach by combining both experiments and computation in an unprecedented way that gives hope that researchers can either find and identify the right materials or answer why materials with high storage densities show unfavorable thermodynamic or kinetic properties at moderate temperatures and/or pressures. This approach has real chances if not taken halfheartedly. To be successful, the sub-program needs sufficient resources. With the current comparably low budget, there is the risk that the new methodologies cannot be fully exploited.
- Yes, the hydrogen storage team has a very good balance of projects associated with the near term (700 bar compressed) and the long term (cryocompressed and materials-based storage). In fact, there is an almost even split between the number of projects associated with the near term (advanced tanks, engineering, and analysis) and long term (materials), with a slight edge in funding to materials R&D, as highlighted in the presentation.
- Given the challenges entailed in reducing the costs and improving the performance of current and future hydrogen storage options, the balance across timescales is appropriate. The overall sub-program is focused on the appropriate topics as a function of timescale of the R&D vs. commercial efforts.
- Yes. It can be summarized as compressed gas in the near term and everything else as a longer-term R&D development.
- Too much is being spent on chemical and materials-based storage. This work has gone on for years, and materials-based storage is no nearer to meeting targets than it was 10 years ago. A lot of good work has been done on bad materials. It is time to cut this work significantly.

3. Were important issues and challenges identified?

- Yes, the most important issues and challenges are exceptionally well identified as costs of the fibers in high-pressure gas tanks, dormancy in cryogenic tanks, and especially the so far unsuitable combination of kinetics, thermodynamics, and capacities in case of materials-based hydrogen storage. There are many discovered metal hydrides with very nice properties at low working temperatures but with low capacities on the other side and other materials with high storage capacities but, for most applications, unsuitable slow kinetics or high working temperatures, but the reason is so far not at all understood. In the case of

materials-based hydrogen storage, the sub-program aims at a comprehensive theoretical–experimental investigation of such materials and setting up the capabilities required for this. The sub-program has high potential to bring about a breakthrough; however, the rather low total budget could stop the full exploitation of the developed methods and the harvest of novel, more suitable materials through this knowledge-based approach.

- Certainly. A clear picture of current status emerged, and based on current status and trajectories, the challenges emerged and were presented in a logical fashion.
- New targets are appropriate and appear to have been justified through interactions with original equipment manufacturers (OEMs).
- Yes, the high-level barriers were identified on the strategy slide, along with further details in physical and materials storage activity sections. In the materials storage section, additional information could have been provided to highlight the gaps with materials-based storage on a system level prior to jumping into the materials' limitations.
- Yes. Barriers are clearly defined for each technology approach.
- The addition of dormancy targets is good.

4. Are plans identified for addressing issues and challenges?

- Both the challenges and the plans for overcoming those challenges are very well identified and addressed. Since materials-based hydrogen storage is the only option to reach the ultimate targets, the sub-program aims at the development of exceptional capabilities at different institutions, mainly the national laboratories. In contrast to earlier attempts to identify novel materials, the sub-program now takes the growing available computational power much more into account and aims at a very close and comprehensive experimental–computational effort to allow us to see, more clearly and with more of a knowledge base, which are the limiting material processes hindering their application, thereby enabling the search for proper future approaches to screen and/or design materials with the desired or necessary properties for mobile and stationary energy storage.
- Plans for addressing the substantial technical barriers in hydrogen storage were well presented and easily understood. An R&D portfolio that is designed to address the challenges in the short, medium, and long terms was clearly defined.
- The Hydrogen Storage sub-program plans for addressing challenges were included in the strategy slide and inferred by the project portfolio. The summary statements at the bottom of certain slides were very helpful in identifying the key message and R&D focus for addressing a certain issue.
- Carbon fiber cost reduction work is clearly laid out.
- In general, yes, but plans are identified only at a top level.

5. Was progress clearly benchmarked against the previous year?

- With the high-risk, high-reward individual projects, the Hydrogen Materials—Advanced Research Consortium (HyMARC) and its projects become really operative. Several other projects could be successfully finished. Also, impressive first demonstrations and applications in mobile applications such as unmanned undersea vehicles and forklifts could be shown demonstrating some of the beneficial outcomes of research work done in the field of metal hydrides, in addition to the knowledge gained through this type of research, which fertilized other technologically important areas such as battery development.
- Yes, in nearly every aspect of the R&D portfolio, progress against benchmarks and toward achieving the technical targets was clearly presented.
- Dry winding work was well described, but cost benefits were not quantified. Tank balance-of-plant (BOP) work was highlighted, but advances over last year's work were not clear.
- There was clearly progress being made within the sub-program, although it was not benchmarked from last year. A progression of key areas such as cost or other parameters would be helpful in evaluating the rate of improvement.
- In general, no, but advances were noted in many cases (just without reference to the previous level of performance).

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?

- Reductions in cost and improvement in hydrogen storage capacities, energy efficiencies, durability, etc. are an important piece of the puzzle that must be assembled that will lead to cost-competitive, large-scale implementation of hydrogen-fuel-cell-powered transportation. This Hydrogen Storage sub-program in FCTO is designed and is well managed to address the remaining barriers to practical onboard hydrogen storage systems.
- Yes, all the projects deal with hydrogen storage options and challenges and thus address one of the main barriers (hydrogen storage) of fuel cell technologies.
- The sub-program seems to have appropriate projects for addressing the broad problems and barriers. Most of the barriers on the strategy slide are being addressed by the projects in the portfolio. The sub-program may want to ensure complete coverage of the barriers by mapping the projects to the barriers. A barrier not being addressed is the system (material) cost for materials-based storage systems.
- Yes. The projects are well selected.
- It appears that the "ship has already sailed" in favor of physical storage, yet the sub-program continues to expend well over half its budget on materials-based solutions.

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

- The sub-program appears very focused, well managed, and effective in addressing FCTO's needs, especially the new effort: HyMARC is going in the right direction by combining and developing key technologies to be able to bring about a significant impact. So far there has been a strong focus on automobile applications, which of course is good; however, hydrogen storage and fuel cell technologies are not limited to automobile applications. There is also a need for stationary applications, and so the planned efforts on H2@ Scale are welcome. However, the budget must be increased significantly to be able to include this new and, for the future, very important topic. The sub-program budget should be at least doubled to ensure good and recognizable activities and achievements and international visibility.
- The Hydrogen Storage sub-program has been and continues to be focused on key technology needs within the storage realm to address the barriers to cost-competitive hydrogen fuel cell transportation. The sub-program continues to be well-managed. Communication and collaboration are highly valued by the sub-program management, and this R&D environment has been effective in driving toward conquering the barriers.
- Yes, the sub-program is well managed and very focused on the FCTO needs. This sub-program has very effective and engaged DOE managers.
- Yes, the sub-program is well focused and well managed, and the presentation was delivered in a clear and effective way.
- The sub-program needs to come to grips with its failure to find adequate materials-based solutions and refocus on physical storage. It is not clear why the sub-program is working on alane for the U.S. Department of Defense.

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?

- A key strength has been in the layers of risk mitigation in the materials-based storage area. Multiple approaches that integrate experiment and computation, always with an eye to fairly stiff engineering requirements, engenders a very focused, well-balanced R&D program. A possible weakness is in the potential over-investment in the area of high-surface-area sorbents (e.g., metal–organic frameworks), where there appears to be significant overlap in several of the projects that include efforts to computationally predict hydrogen sorption isotherms to enable sifting through the now large databases of structure types. Another area that may not lead to progress toward enhancing foundational understanding of hydrogen storage is the area of binding of multiple hydrogen molecules on "naked" or coordinatively unsaturated non-transition metal cation sites. Binding of a single hydrogen molecule, much less multiple hydrogen molecules, to a "naked" Ca ion appears highly unlikely. Computational models that predict this need to be

certain to include all potential reaction channels to avoid dropping into false minima that predict finding stable configurations.

- The sub-program has a good mix of basic materials development and engineering solutions, as well as a good mix of (large) national-laboratory-based consortium efforts (HyMARC) and small company innovative projects. The development of alternate metals is not justified based solely on the cost and mass reductions possible if the project is successful (as the savings will be quite small). However, there may be other applications or other features of the metal that make it applicable to a much wider range of applications. This should be explored.
- The comprehensive approach of HyMARC, together with the individual high-risk, high-gain projects, is unprecedented and should be strengthened and expanded. The main weakness is the comparably low budget when compared to some European countries, the European Union, and East Asian countries. The budget should be increased significantly.
- The overall strength of the sub-program is associated with an appropriate balance between near- and long-term research. The overall weakness of the sub-program is inability to filter technologies or projects without a clear path to achieving the targets or providing a value proposition over the incumbent technology. HyMARC is a strength to promote fundamental research, promote national laboratory collaboration, and assist individual materials-based projects in the portfolio. The sub-program should attempt to highlight the historical progression and provide future projections toward the system targets. The projects not related to transportation stand out as a weakness in this sub-program.
- The x-ray photoelectron spectroscopy (XPS) work on slide 21 proves *nothing* except that the investigators were working with a highly oxidized sample. The absence of titanium at the surface may be due to migration of Al to the surface under the oxidation of the sample due to inadequate handling of the sample before analysis rather than real surface chemistry of the active material. It has been over 25 years since the reviewer did XPS for a living, and the reviewer would have been too embarrassed to show this slide even back then.

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

- The newly minted HyMARC consortium is one example of an innovative approach to removal of barriers, especially when coupled with the "seedling" project process. Gaining a better understanding of the foundational science involved in hydrogen storage materials is necessary to removing the few remaining barriers to practical application of materials-based hydrogen storage. Also, new organizational collaboration strategies among FCTO and parallel or similar activities at the National Science Foundation, Basic Energy Sciences (BES), the future energy materials networks, etc. represent new and novel ways to approach the problem by leveraging efforts across organizations and agencies.
- The comprehensive experimental–computational effort HyMARC, in particular, together with the individual high-risk projects, represents a novel, outstanding approach.
- Most of the projects are attempting to pursue novel approaches, although the innovation of the projects could be further highlighted if the principal investigators would identify the current state of the art and the specific innovation of their projects.
- Yes, there are numerous examples of novel materials/materials-synthesis and fabrication methods being pursued.
- Several of the projects do show novel approaches to the barriers.

10. Has the sub-program engaged appropriate partners?

- The programmatic collaborations of the FCTO effort with BES, Advanced Research Projects Agency–Energy (ARPA-E), the National Institute of Standards and Technology, the U.S. DRIVE Partnership (U.S. DRIVE) technology teams, and international activities such as the International Energy Agency's Task 32 interactions are all valuable in helping the FCTO effort to maintain its focus and its reputation as the world's leader in hydrogen storage.
- Yes, the sub-program has an excellent cross-section of industry, academic, and national laboratory partners. The relationship with the Institute for Advanced Composites Manufacturing Innovation was a great addition to the sub-program.

- The sub-program has engaged very appropriate partners. However, considering the really low budget, which is the main weakness, the sub-program should aim at strengthening international collaborations so that the United States is not falling behind Europe and East Asia.
- The sub-program needs to reengage with tank manufacturers and OEMs looking at novel storage methods such as cryocompressed.
- In general, yes.

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

- The Hydrogen Storage sub-program has a history of effective collaboration with a variety of U.S. and international organizations that engage in hydrogen storage or related research. The collaboration with the U.S. DRIVE technology team in hydrogen storage has helped keep the sub-program tightly focused on gaining outcomes that are impactful in the U.S. automotive industry. These collaborations are in part what has allowed the sub-program to maintain its reputation as the world-leading hydrogen storage program. All international activities look to the DOE sub-program as guidance for their own technical projects.
- Yes, the sub-program is collaborating with the partners effectively through various workshops, technical team meetings, and project reviews.
- It seems that there is excellent collaboration.
- Collaborations with national laboratories appear to be going well, but the effectiveness of collaboration outside DOE is questionable.
- Yes.

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

- It appears that where there might be gaps, the sub-program has effectively collaborated with other agencies to fill them. An example is the ARPA-E program in hydrogen storage in liquid carriers, e.g., ammonia, an area in which FCTO does not currently work.
- Hydrogen storage for automobile applications is very important, but automobile applications are not the only ones in which hydrogen will play a role in the future. Other mobile and stationary applications (with different targets and demands) should be considered as well.
- Storage system BOP components currently amount for a high fraction of system cost. Only the Sandia National Laboratories alternative metal project addresses this (and then only in a modestly impactful way). Additional BOP component cost-reduction or system-simplification projects should be pursued.
- The commercialization and cost analysis for materials-based storage is a gap in the portfolio. A basic understanding of selection of materials in relationship to their performance and affects on the infrastructure needs to be included in the sub-program.
- More work on physical storage is needed.

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

- The constant vetting of the sub-program, and the close collaboration with U.S. DRIVE, assists the sub-program management with maintaining an adequate portfolio that addresses the topics that can help eliminate technical barriers to practical hydrogen storage systems.
- The fundamental research in HyMARC is helpful, although the linkage to the performance and properties is not clear, so there could still be gaps associated with the system. The relationship with the infrastructure needs to be further developed to ensure the heat rejection expectations of certain materials can be supported.
- Such topics include BOP component cost reduction and system simplification.
- Physical storage and analysis are such topics.
- No.

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

- Given the relatively limited size of the sub-program, the scope of the current portfolio is adequate. The strategy of having a core group of researchers, e.g., HyMARC, that then inform sub-program management of research areas that need to be addressed helps the sub-program management make the necessary adjustments and additions to the sub-program via the "seedling" process. This appears so far to be an effective strategy to maintain an appropriate balance and focus of the R&D portfolio.
- The sub-program could consider funding additional cost reverse engineering for materials-based storage systems to assist in guiding the materials research. There could also be funding for holistic integration analysis of the storage system into the vehicle (e.g., waste heat management) or holistic solutions for infrastructure (e.g., increasing temperature limitations or optimizing heat rejection).
- So far, the targets for hydrogen storage aim at automobile applications. Other mobile and stationary applications have different demands and therefore different targets. These have to be addressed as well.
- Funds should be moved from materials-based storage efforts to analysis, engineering, and physical storage.
- No.

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

- The targets for hydrogen storage are formulated only for automobile hydrogen storage, which is only one part of the potential future application areas. The Hydrogen Storage sub-program should be set up broader to address also other mobile as well as stationary applications. In the field of hydrogen storage, more emphasis could be put also on the option to enhance volumetric storage densities of compressed gas tanks, even at much lower pressures, by developing hybrid compressed-hydride tanks. The approach of a comprehensive theoretical–experimental investigation, as in HyMARC, is very good.
- The sub-program could consider vehicle powertrain or platform variations and their effect on the system targets. For example, the sub-program could consider heavy-duty vehicles in terms of the volumetric density versus gravimetric density.
- Improvements to the vehicle (through lightweighting, aerodynamic improvement, etc.) should be considered as a way to reduce the requirement for hydrogen storage.
- There are no recommendations at this time. With the new consortium model now being productive, this should be monitored for efficacy, and perhaps adjustments could be made, but not at this time.
- No.

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

- The sub-program should examine its historical progress and be willing to make the tough choices to direct the portfolio toward the most promising solutions. There has been excellent work by many researchers over the years in this sub-program. An effort should be made to build on the past results, especially with the outcomes associated with the centers of excellence. The reverse engineering of materials targets should be utilized to a higher degree to guide and discontinue certain research. The evaluation of system parameters should be coupled with the infrastructure to provide a complete assessment of the hydrogen storage technology.
- The sub-program continues to be a well-managed and effective program, and so there are no further suggestions that would improve upon the sub-program at this time.
- The budget must be increased.
- No.

Fuel Cells Sub-Program Comments

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

- Yes.
  - The research and development (R&D) portfolio focused on polymer electrolyte membrane fuel cells (PEMFCs) but also includes longer-term technologies (e.g., anion-exchange membrane fuel cells [AEMFCs]) and higher-temperature fuel cells (e.g., molten carbonate fuel cells) for stationary applications.
  - Catalyst cost is projected to be the largest single component of the cost of a PEMFC manufactured at high volume; the strategy is to reduce platinum group metal (PGM) and improve performance.
  - Durability and cost are the primary challenges to fuel cell commercialization and must be met concurrently.
  - Brookhaven National Laboratory (BNL) demonstrated potential to develop low-cost Pt monolayer catalysts with noble metal free cores.
  - 3M perfluoroimide acid (PFIA) membranes meet most 2020 U.S. Department of Energy (DOE) targets.
  - 3M membrane electrode assembly (MEA) integration R&D leads to improved performance and decreased PGM content.
- Yes, the major goals of the sub-program area, their current status, new accomplishments, and current plans to achieve any unmet sub-program area goals were covered. Strategies for technology development were covered particularly well, especially through the consortium approaches that are now being implemented. The L'Innovator concept seemed interesting but was not exactly clear, and it seemed that a bit too much focus was placed on it. One potential change that could be recommended for the strategy is to assess whether another component or design feature could be a focus of near-term development in order to gain short-term progress toward the DOE cost targets. Platinum is projected as the long-term greatest cost contributor, and several projects are currently devoted to reducing platinum content as a means to reduce system cost. However, if another component would be a significant cost contributor at smaller production volumes, there may be a chance to impart more short-term impact by also focusing on improvements in that component or design feature now. Especially if solving the technical challenges of that component is more manageable than solving technical challenges of platinum reduction, the overall Hydrogen and Fuel Cells Program (the Program) may be missing an opportunity for at least short-term progress as a stepping stone by focusing only on the long-term problem of platinum content.
- Cost and durability are the major technical challenges. The sub-program's approach to identifying and addressing these issues is well covered and well structured, focused, and well managed. The consortia established by the Fuel Cell Consortium for Performance and Durability (FC-PAD) and Electrocat are really relevant for their potential to transform fuel cell technology.
- Yes, goals and objectives of the sub-program were adequately covered. The challenges were discussed, and the R&D portfolio identified focus areas.
  - Under focus areas, Performance and Durability – Mass Transport was identified, but the impact of catalytic activity was not identified, even though catalysts were identified under stack components. It is implied that catalytic activity is acceptable but not entirely clear.
  - Under Balance of Plant (BOP), there is no listing of critical components. This implies that all of the BOP components are a focus area.
  - Under Sensitivity Analysis, it is not clear what "Air Stoichiometry" refers to, whether air utilization, pressurization, humidification of the air, or something else. Also, if bipolar plate welding speed is important, it is not clear why bipolar plate coatings were left out. Bipolar plate coatings could be more time-intensive than bipolar plate welding.
- The presentation provided a good summary of current efforts and near-term plans. The overall strategy of the sub-program area was clearly presented and appropriate.
- Yes, the overall sub-program and strategy was clearly outlined.
- The presenter did an excellent job in covering the Fuel Cells sub-program.

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

- Yes.
  - An ultra-thin-film (UTF) PtNi catalyst with 8.1 kW/g PGM was achieved, exceeding the 2020 DOE target.
  - UTF PtNiIr meets mass activity and hydrogen–air durability targets (A. Steinbach et al., 3M).
  - A PtCo/HSC-f catalyst exceeds targets for specific power and PGM loading (A. Kongkanand et al., General Motors)
  - Porous particles show lower Pt but higher Co dissolution, leading to accelerated performance loss.
  - A rotating disk electrode (RDE) testing protocol and best practices were disseminated, enabling procedural consistency and less variability.
- There is a good balance between near-, mid-, and long-term R&D in the Fuel Cells sub-program, at least for the main focus, which concerns MEAs.
- There is excellent balance between early applied R&D all the way to BOP and testing.
- The sub-program has a little bit of work in all time scales, though there is an apparent heavier focus on mid- to long-term R&D. The short-term development effort could be increased to effect more real-world impact of the advances made through these projects. Achievement of the technical capability to produce fuel cells meeting all targets through the sub-program will require years before those accomplishments are integrated into the commercial technologies. With the current balance that appears to de-emphasize near-term projects, there could be a risk of exacerbating the time it will take to transfer these advancements to commercial and consumer products. Consideration of a little more emphasis on near-term work should be made.
- The present sub-program has a good balance between near-, mid-, and long-term R&D. Upcoming budget pressures may force a concentration on long-term research, giving up the very substantial increase in effectiveness in the near- and mid-term work that has been achieved recently through the improved interactions between the national labs and between the national labs and industry that are exemplified by FC-PAD.
- Yes, in general, the focus on PEMFCs provides the nearer-term R&D, whereas the ElectroCat and anion-exchange membrane work provide longer-term activities. However, although the stated goal is to advance fuel cell technologies for transportation, stationary, and early market applications, the sub-program is very transportation-focused.
- A pathway for potential cost reduction and the 2020 target have been identified. Some of the 2020 research objectives are very difficult, e.g., reduction of bipolar plate cost since the sub-program does not include bipolar plate stamping. If the success of the Program depends on the discovery and development of PGM-free catalysts without the development of an alkaline membrane (not on the pathway), Program success will be very difficult. The DOE has funded PGM-free catalysis off and on for the last thirty years without success, with much of the work addressing Fe-N-C systems, similar to the current approach. The data given (chart 14) suggest mass transport limitations; hence, the objective might be the development of an electrode structure suitable to optimizing the performance of the PGM-free catalyst rather than the development of a PGM-free catalyst.

3. Were important issues and challenges identified?

- Yes. This group is doing excellent work on some of the key issues that are limiting the commercialization of fuel cells for automotive, stationary, and portable power applications. Most noteworthy are the advancements in core shell catalysts, the new PFIA membrane, the low-loaded catalysts, the UTF catalyst layer, and the progress on the alloy catalysts. For example:
  - 3M developed a 10 μm supported PFIA membrane with a chemical additive that meets the resistance target at 80°C for all humidities and at 120°C for the highest humidity, and meets mechanical and chemical durability targets.
  - R. Adzic et al. at BNL developed nitriding core components that can facilitate the development of high-performance Pt-ML catalysts with low-or no-noble-metal cores.
  - Steinbach and Kongkanand present the development of several advanced catalysts that approach the DOE 2020 targets.

These are not incremental advances on the same old materials that have been proven to have limitations in the past. These are newly developed materials and processes that have already shown superior properties to previous materials and continue to show the potential for significant further improvements. While further progress is required to meet ultimate durability and cost targets concurrently, significant progress has been made, important targets have been met, or at least approached, and new avenues for further improvements have been identified. In some cases, some of these new avenues of improvement are approaching the DOE targets. While the primary focus has been on polymer electrolyte membranes, developments in molten carbonate, AEMFCs, and electrolyzers are important improvements for those technologies.

- Yes, there is a clear focus on what technology improvements need to be made in order to meet the objectives and goals within the sub-program area. The use of the manufacturing cost analysis method as a basis for determining research needs to meet the cost target in particular is a very effective method of finding and targeting the appropriate challenges.
- Cost and durability targets met concurrently with cost targets are the major challenges. To reduce cost, PGM-free catalysts appear key and are well covered with the Electrocat project. The more classical approach to reducing cost by lowering the quantity of PGM in catalysts is also well covered. However, in that case, a study should be made to determine the minimum quantity of Pt content in an MEA to achieve performance, durability, and cost targets but still be compatible with Pt recycling of the MEA. Indeed, with a given amount of Pt, either technical or economical aspects will lead to losing interest in recycling Pt.
- The important issues and challenges were identified. Some of the severe challenges in meeting the DOE bipolar plate and catalyst cost targets could have been emphasized a bit more, and a resetting of these targets to more realistic levels, with subsequent revision of DOE planning in light of these, should be considered.
- Yes, the ability to concurrently meet both durability and cost has been appropriately highlighted as the most critical challenge. The cost sensitivity analysis provides further support for key challenges. However, although air loop cost and bipolar plate cost have significant impacts, these are not currently part of the R&D portfolio (although workshops on these topics were held).
- Improvements in multiple components simultaneously are required to meet 2020 targets.
- Yes. See charts 7, 8, 10, and 11.

4. Are plans identified for addressing issues and challenges?

- In general, yes, appropriate plans are in place for polymer electrolyte membrane (PEM) catalyst and MEA performance and durability. With respect to FC-PAD, a major initiative under this sub-program, the six component and cross-cutting thrusts have been well chosen to contribute to required fuel cell MEA advancements. The focus by FC-PAD on pre-competitive-level activities is appropriate and will provide significant support to industry, whereas the competitive-level work is appropriately carried out by industry-led projects. However, while the objective of evaluating/benchmarking different materials by FC-PAD is useful and appropriate, it is important that this does not merely duplicate work done under other DOE-funded work, i.e., benchmarking of DOE-supported material development.
- Yes. In addition to the R&D that addressed cost reduction, performance and durability enhancement of stack components including catalysts, membranes and MEAs, the establishment of ElectroCat with core capabilities to expedite the development of PGM-free catalysts and electrodes, and the addition of FC-PAD demonstrate the longer-range vision to establish the infrastructure that will be necessary for ultimate success. In this consortium, the focus should be on using a low-Pt-loading anode 0.05mg/cm^2 and non-PGM cathode. The study should be conducted on the MEA with a minimum of 25 cm^2.
- Yes, several strategies for coordinated development to address challenges in meeting the sub-program's challenges are clearly presented. Some of the details of those individual coordinated projects (such as the multiple consortia) are a little less clear, especially as concerns their overarching strategy. Some of the consortia projects appear to run along more of a "try everything" strategy than the overall sub-program's targeted and informed strategical methods. Also, as noted during the plenary, one of the major challenges being faced right now is how to meet the two remaining issues, cost and durability, at the same time. The sub-program seems to address both of these but as separate issues, even though there is explicit acknowledgment that they must be met concurrently. The expected method of meeting both together is not so clear.

- Plans have been identified for meeting the challenges. They could have been more specific in the case of the bipolar plate material cost issue. Plans for non-Pt catalysts are detailed, if not necessarily very realistic.
- Yes. Many collaborations and workshops are focused on resolution of issues.
- The current portfolio of projects is addressing these three main issues and challenges.
- No stepwise list of activities to address the issues was presented. There are many questions, for example, what the plans are to meet the mass activity targets, whether the composition will be changed, whether the Pt-to-Pt spacing will be changed, and whether there is an explanation for PtNiIr meeting oxygen reduction reaction mass activity at an atomic scale. There are similar questions for all the other approaches. Chart 20 offers no detail; it only requires our faith that core capabilities and consortia of industry and university partners will solve issues. More specifics would be helpful.

5. Was progress clearly benchmarked against the previous year?

- Yes, for several of the main projects and the sub-program targets overall, the progress over the last year (and in some cases, even over previous years) has been well documented. The consistency of maintaining focus on past accomplishments and gauging pace of development is a strength of this sub-program.
- Progress against the previous year was clearly benchmarked in most areas, including cost, high-current-density performance, and non-Pt catalyst performance in MEAs.
- Yes. Progress was reported for catalysts and alkaline membranes. Standard practice protocols appear to be in place.
- Yes. For example, the catalyst specific power of fuel cells improved to 10.6 kW/g_{PGM}, a more-than-three-times improvement from the 2008 baseline of 2.8 kW/g_{PGM} and exceeding the 2020 target of 8.0 kW/g_{PGM}.
- In general, significant progress has been made, and the accomplishment is solid and well coordinated.
- Fuel cell cost status was benchmarked based on catalyst research-level improvements, with power output per gram of Pt benchmarked year-over-year. However, durability was noted based on demonstration fleet operation—which speaks more to hours of operation as opposed to year-over-year technology advancements. PGM-free performance was provided with a statement on performance improvement, but the graph showed only current status and no assessment on longer-term ability to meet the DOE transportation targets, as is required by the waterfall chart.
- 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 Fuel Cells sub-program is a core technology development program for meeting FCTO goals and objectives. The sub-program implements an impressive method for devising a research strategy specifically focused on the research needs and barriers within the sub-program, guided by quantitative analysis to build the overall strategy.
- Yes, for the most part, the projects in this technology area are well chosen with respect to the most critical challenges of PEMFCs. Performance and durability of the MEA are critical to meeting the long-term targets of fuel cell commercialization. These must be met at low cost. While the industry will focus on designing to appropriate trade-offs with cost, the FC-PAD consortium is focused on those activities that will enhance the understanding and provide the input to the industry to do so. However, the sub-program says little about stationary and early market applications and does not provide funding in the area of plates and the air loop.
- This is a well-focused and -managed sub-program that should lead to solutions to problems and barriers.
- Yes, the projects are addressing in detail the specific issues most relevant to the broad problems and barriers that FCTO is trying to solve.
- Yes, the different projects are well in line with the main barriers and challenges FCTO is trying to solve.
- Yes. However, the stepwise R&D was not fully discussed.
- Yes.

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

- The sub-program appears to be focused, well managed, and effective. The FC-PAD consortium appears to be demonstrating the effectiveness of this new relationship between national laboratories and between the national laboratories, industry, and academia through improved integration of diverse capabilities. It is not yet clear whether the ElectroCat consortium will be as successful.
- In most cases, the research topics are clearly identified. The progress indicates the projects are well focused; however, detailed approaches for future work were not presented. The progress that was made last year and over the previous years would not have been possible without a well-managed sub-program, but it would be good to see more detail in the sub-program overview.
- Yes, the sub-program appears to be focused, well-managed, and effective in addressing FCTO's needs. There are only few orphan projects (intermediate-temperature solid oxide fuel cells, direct carbon fuel cells, redox flow batteries, and regenerative fuel cells), and regarding the budget evolution, their continuation should be reconsidered.
- Absolutely. This is one of the best-managed programs in DOE.
- Yes, the sub-program is well managed and focused on the most critical aspects with respect to transportation.
- In general, yes. The consortium approach does appear to need a bit more focus on the internal strategy between consortia. They do make important progress, but as of right now, the focus seems to be lacking a strategy or particular technologies around which developments should start coalescing.
- 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 FC-PAD consortium seems to be making a step-change improvement in the targeting and coordination of national laboratory, industry, and academia efforts in improving fuel cell performance and durability. The personal fiefdoms of individual laboratories are breaking down, the complementary capabilities of the participating institutions are working together toward well-defined goals, and fuel cell developers are becoming more open about the true state of the art, allowing the DOE programs to address the true cutting edges of technology. The funding opportunity announcement (FOA) projects chosen under the consortium seem to address critical problems and finally align well with the activities of the national laboratories. The ElectroCat consortium seems less promising, though it may appear better after the projects chosen under its FOA have been announced. Restricting a consortium entitled "ElectroCat" to non-PGM catalysts seems inappropriate, given that the most promising paths to lower fuel cell cost (though perhaps not all the way to DOE's $30/kw target, which likely should be changed for planning purposes) lie with low-PGM catalysts. The large high-throughput component of the ElectroCat program seems particularly unrealistic. Non-Pt catalysts are highly dependent on processing details and less dependent on the compositional issues for which high-throughput methods are most effective. Some of the best non-Pt catalysts show no activity in RDE (and likely none in similar flow cells)—these catalysts must be evaluated in fuel cells. Scale-up of non-Pt catalysts is notoriously difficult. Synthetic efforts should therefore concentrate on fewer samples made at a scale of at least five grams so that activity, performance, and durability can be evaluated in fuel cells. With precursors being so much cheaper than for PGM catalysts, there is no need to work at the less-than-gram scale (though great attention must be paid to proper exposure of powders to gases during heat treatments).
- The projects cited in the overview show clear progress on reducing metal catalyst loading. The FC-PAD and ElectroCat consortium approach will increase coordination among national laboratories and with the FOA partners. Extensive national laboratory capabilities will be coordinated and applied in a synergistic manner toward PEM issues affecting durability and performance. The work by the national laboratories is generally conducted in a systematic manner, with extensive characterization to support hypothesis and models. The use of models is routinely used to help support understanding, and development of appropriate parameters will help others for use in industry models. The interactions with industry are expected to be positive and will help to guide the work, and will allow industry to access the very extensive national laboratory capabilities. The key progress achieved over the past several years is at the research level, and

despite many years of year-over-year progress, it is not clear how many of the advancements have made it into demonstration-phase or commercial-phase technology achievements. The sub-program office tends to support a couple of groups (industrial partners) on an ongoing basis, providing a significant advantage to those groups. On the other hand, there have been many advancements in the fuel cell industry demonstration-phase and commercial technology, so it must be assumed that the work supported by DOE is having an impact. Showing the linkages between research and technology deployment would be worthwhile, as well as showing the plans for commercialization of the technologies under development.

- The strengths are as follows:
  - The approach of coordinating the investigation of the performance and the durability of fuel cells or PGM-free catalysts through a consortium composed of the best available experts of national laboratories in a five-year project is excellent and represents the highest strength of the sub-program. This approach is allowing a deep understanding of the different mechanisms involved and the impact of novel materials or structures, and it ensures a long-term continuity of the knowledge. The addition of complementary projects with new industry and academia partners completes this approach in a very efficient way.
  - The L'Innovator approach is also a strength of this sub-program and should favor technology transfer to industry.
  - Mid- and long-term R&D on AEMFCs has to be considered a strength of the sub-program when considering the implementation of PGM-free catalysts.

  The weaknesses are as follows:
  - BOP components represent about half of the system cost, but no project is considering these components, even if air loop cost is the third most sensitive component.
  - Bipolar plates are also not really considered, although they represent about a quarter of the stack cost. Current base material appears too expensive to reach DOE cost targets. New base materials have to be considered.
- The key strengths are with the researchers conducting the individual projects. Many of the catalysts, PtNi and PtCo, have been around for many years, as evidenced in the patent literature. The strength in the catalyst research is the newer structures (morphologies) in which the catalysts are distributed.
- The Strategic Analysis, Inc., assessments of fuel cell system costs and drivers of those costs are particularly effective in having impacts sub-program-wide and ultimately on the fuel cell technologies that will, it is hoped, be in consumers' hands.
- One area of concern is slide 3 (in the 2017 presentation; slide 4 in the 2016 version), which suggests that the required development is almost done. This is wrong. Fuel cells are far from ready to challenge the internal combustion engine as the power source for automobiles. Fuel cells are marginally ready to challenge for niche markets. While the figures actually say that fuel cells nearly meet the six key targets, the gap between meeting those targets and commercial readiness needs to identified and addressed. The durability and catalyst degradation, as well as the mitigation strategy for the low Pt loading, are not solved. Non-PGMs are very far from being ready even for the accelerated stress test (AST).
- The work with 3M and General Motors (GM) stands out.

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

- Yes, the ongoing work, especially to develop new catalyst ionomers, seems to be adept at reacting appropriately to ongoing advancements within and outside of this sub-program area. The work appears to always be building on recent advancements, rather than replicating them or finding unnecessary alternatives for most of the sub-program's efforts.
- A significant number of the projects are considering novel and innovative ways and appear relevant to contributing to achieving FCTO targets.
- The current range of projects covers a wide range of novel and innovative approaches to the most critical problems facing fuel cells.
- Yes, to some extent. There should be more data presented from manufacturers of fuel cell stack and systems. It would be nice to have Nissan Japan, Toyota Motors Japan, GM, and Ballard present in one session and give their view of the state of the art and the technical priorities that need to be solved for automotive application.

- No. The projects are making incremental progress toward success: ultra-thin layers have been proposed for over 15 years, PtNi and PtCo are over 20 years old, and high-surface-area supports are well understood. The progress is in understanding how performance/durability is limited and making incremental changes to improve the fuel cell system.
- Generally, yes.
- Yes.

10. Has the sub-program engaged appropriate partners?

- The sub-program has engaged appropriate partners, and the coordination between partners has recently improved through the organization of consortia. Industrial partners now seem to be more open to sharing detailed information, allowing DOE efforts to be more precisely directed to the cutting edge of fuel cell technology.
- Yes, this sub-program appears to have reached several key stakeholders in academia and industry to achieve the technology improvements at the core of its objectives. This is one of the sub-program's strengths.
- Yes. There are many national collaborations (inter- and intra-agency efforts), consortia, and focused entities, as well as industry partnerships.
- Yes, the portfolio of partners participating in the different projects appears appropriate, with members of industry, national laboratories, and academia.
- Yes, but Ballard or someone in Europe should provide an independent evaluation of these MEAs.
- The sub-program office tends to support a couple of groups (industrial partners) on an ongoing basis, providing a significant advantage to those groups. Other partners are supported on an irregular basis.
- Yes. See charts 16 and 13.

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

- Yes, strategies for collaboration, especially within the consortia, are well defined. The only exception is the concept of the L'Innovator program, and that was only because it was not entirely clear how the program was expected to work. This is likely just because it will be a new form of collaboration, but the concept seems like it either needs more details worked out or needs those details to be communicated more effectively.
- Yes, the consortium structure seems to be effective in formalizing and improving the collaboration between partners.
- The consortium approach should facilitate the collaborations.
- Based on the progress, yes.
- Yes (two responses).

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

- There seems to be a gap in identifying methods for cost reduction and durability improvement in the short- and possibly mid-term and developing technology improvement projects to meet those more near-term possibilities. Focus on cost and durability right now appears to focus more heavily on long-term solutions, though accounting for time to transfer technology to industry, even short- and mid-term solutions could actually become long-term in the eyes of the consumers. At least an investigation should be done into whether any possible technology improvement targets exist now for more short-term improvement with less research cost and effort.
- As planned, more detailed cost studies of roll-to-roll processing, PGM catalyst synthesis costs, and bipolar plate manufacturing are needed to check the realism of ultimate targets. Increased DOE roll-to-roll prototyping capabilities should be used to make slot-die-coated MEAs from novel catalyst materials as early in the development cycle as possible to reduce the use of unreliable RDE and flow-cell methods, particularly for durability and performance measurement, and especially for non-PGM catalysts.
- While the primary focus has been on PEMs, developments in molten carbonate, AEMFCs, and electrolyzers are important improvements for those technologies. Learning from IrO_2 anodes in PEM

electrolyzers should teach how to stabilize the carbon and what the important parameters to get a stable anode are.
- The sub-program is focusing on MEAs and sub-components (except gas diffusion layers) and on their performance and durability. Some gaps may be identified: too few projects on bipolar plates, and no project on internal gaskets, which may be an issue for durability in hot and cold cycling conditions.
- Nearer-term commercial challenges, plates, and BOP components are not well represented in the portfolio.
- Nothing was given on BOP, which was identified as a focus area.

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

- For non-PGM catalysts, DOE should have an explicit sub-program to develop novel thick (100 microns or thicker) electrodes with designed distribution of porosity and/or other innovations to get improved high-current-density performance in air. Some group should be required to stick with a single reproducible catalyst and bang their heads against just electrode design to make better thicker electrodes in case no (highly unlikely) breakthrough in non-Pt active site density or activity is achieved by other groups.
- The sub-program identifies bipolar plates as the second-largest cost driver for fuel cell systems, and almost as significant as platinum cost. However, there does not appear to be very much research effort into this area, or at least not as much as catalyst and ionomer development. There was mention of an upcoming bipolar plate workshop, but it seems that significant acceleration in this area could be an effective way to ensure cost targets are more likely to be met by the time desired.
- MEA evaluation for both non-PGM and low Pt loading should be studied, as well as the mitigation strategy for degradation at the MEA level. Different process techniques for the catalyst and MEA manufacturing should be evaluated by an independent organization. An anode of 0l.3 mg/cm^2 should not be used in a study, as it does not meet DOE targets.
- BOP, gas diffusion layers, impurities, and seals are not adequately discussed.
- MEA operation in actual systems is not adequately addressed in the nanostructured thin film work.
- The investigated topics are adequately addressed.
- All topics are being addressed.

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

- Bipolar plate manufacturing and fundamental properties should be considered. With complex designs of bipolar plates that have been proposed, “thinning” of the metal will result in enhanced scrap or failure in operation. This is a fundamental problem. The flow of the metal during stamping or other processing needs to be thoroughly understood. With very thin plates, the size/depth of the welds becomes important, and there may be a fundamental limit in weld size and speed.
- Cost reduction activities outside of the catalyst area should be considered.
- More of the MEA study should be considered.
- There are no suggestions for new areas at this time.
- No.

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

- Recommendations include:
    - Identification of degradation mechanisms and quantification of degradation on aged stack components (bipolar plates, electrodes, gas diffusion layers, membranes, cells, sealings, etc.) coming from demonstration projects. We cannot look only at RDE and MEA data.
    - Development of advanced in situ and ex situ characterization techniques and AST protocols, compatible to existing test station hardware, with the identification of transfer functions of the component degradation measured in an AST to real-world behavior of that component. For PEMFC technology, finalization and validation of the new single-cell design initiated by the working group should be coordinated with someone independent of the groups that are funded.
    - Development of models related to degradation mechanisms, implementing models describing degradation mechanisms into performance models, and mitigation strategy that is demonstrated at

MEA level. Evaluation of the capability of performance/degradation models to confirm and quantify the accelerating impact by adapting some operating or load profiles should be considered.

- The ElectroCat consortium should expand to include low-Pt electrodes (or, less desirably, its name should be changed to reflect its restricted subject area).
- Other than the potential addition of exploring more short-term solutions, there are no recommendations for new approaches.
- The ways to address the barriers are well defined and well managed.
- Overall, the approaches to solving the barriers are very good.
- No.

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

- This sub-program is well managed, and the results obtained again during this Annual Merit Review demonstrate its effectiveness.
- The BOP should not be forgotten. Some stack limitations can be resolved through system solutions. The history of fuel cells is that, in many cases, system solutions overcame fundamental property limitations of the fuel cell stacks.
- More understanding is needed from manufacturers and state-of-the-art technologies. Toyota has already produced a large volume of Mirai cars. It would be good to determine what we know from them and what they are willing to share with us.
- Steps should be continued to improve coordination of projects at the national laboratories with those in academia and industry. FC-PAD is a good prototype.
- No.

Manufacturing R&D Sub-Program Comments

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

- Yes. Manufacturing research and development (R&D) is needed to reduce the cost of hydrogen and fuel cell components so that they will be competitive globally. Quality control is critical to enabling low-cost manufacturing with reduced waste; defect morphology should be correlated with loss in performance (National Renewable Energy Laboratory [NREL], Lawrence Berkeley National Laboratory). The goal is to identify key factors determining U.S. competitiveness. Additional effort is needed by the U.S. fuel cell community: to maintain its current competitive position in gas diffusion layer (GDL) and membrane manufacturing, and to increase its capabilities in bipolar plate and catalyst production.
- The sub-program is well covered, and the proposed strategy seems very well adapted to reaching the objectives. The two investigated pillars are very important in enabling the hydrogen fuel cell technologies to be competitive at high-volume production.
- The strategy for the Manufacturing R&D sub-program was clearly laid out. The two main pillars were effectively described, with examples in each category.
- Yes, the sub-program was adequately covered. It was a bit hard to understand the funding situation for the sub-program, which was admittedly complex.
- Yes, the sub-program and strategy were well described.

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

- Yes, there is a good balance. Some analyses are showing the current issues or weaknesses to overcome if the United States wants to stay in the top leading team for industrialization of hydrogen fuel cell technologies. Other analyses are investigating the impact of the future production routes. Quality control projects are providing information for near- and long-term developments. One project is investigating some new defect detection techniques and measuring their impact on the performance and the lifetime of fuel cells. One project is validating an optical technique, now with a packaging step, which may lead to mid-term application on industrial web lines.
- Manufacturing research by definition tends to be directed toward near- to mid-term R&D. Still, there is significant understanding needed for process effects and diagnostic tools that are more fundamental in nature that are being addressed. In this context, the balance between different stages of R&D is appropriate.
- To some extent. Local defects may have minimal impact on fuel cell performance initially but may have a huge impact later. NREL is developing advanced diagnostics for in-line detection of microsize manufacturing defects in fuel cell materials. But they are addressed only through defects. Novel roll-to-roll manufacturing technologies enable cost reduction, while investments in new materials and electrodes increase energy density, power density, and reliability. Regarding hydrogen delivery, a pipeline coupler that does not leak is needed.
- Yes, the balance between near-, mid-, and long-term R&D seems appropriate for a manufacturing project.
- This is a hard question to answer because this program is under-funded. Thus, achieving a proper balance is difficult, if not impossible.

3. Were important issues and challenges identified?

- Some of the most important issues and challenges, such as roll-to-roll processing and quality control therein, were identified. The project did the nation a service by identifying the United States' shortfalls in multiple areas of fuel cell manufacturing. For example, it would seem to be a national security issue that no major supplier of noble metal catalysts is now based in the United States. Perhaps too much of the sub-program has been supplier interaction meetings, which are not clearly of great value.
- Some issues and challenges have been identified:
    - The U.S. potential in stack manufacturing is broadly moderate to high, though with weaknesses in bipolar plate manufacturing and ionomers in the near term. U.S. original equipment manufacturers (OEMs) and other manufacturers need to re-start local development, as they have fallen behind Japan and Europe in bipolar plates, membranes, GDLs, and catalysts.

    - The domestic supply chain of hydrogen fuel cell components and systems should be expanded, and communication between OEMs and hydrogen and fuel cell component suppliers should increase.
- Highly important issues and challenges for manufacturing were identified, which clearly involved engagement from industry. These challenges included a range of topics from broad manufacturing capabilities and diagnostic techniques to specific critical components.
- There is very little new in either the 2016 or the 2017 presentation. Local defects have been a major concern for polymer electrolyte membranes (PEMs) for many years. There are test results using thermal imaging from about 10 years ago, both at the University of Connecticut and at the University of Central Florida. This process addresses only through failures; it will not find incipient failures, thin spots, foreign object damage, or chemical weak spots. This method has value, but only when coupled with a much more comprehensive integrated quality control (QC) process. DuPont, 3M, and many others are likely to have a much better understanding of what is needed to support a commercial effort. Very similar comments apply to roll-to-roll. Continuous processing is fundamental for meeting commercial production costs; however, successful continuous processes can be defined only after the production processes are fully defined, optimized, and fully understood. Academic studies at this level are useful only for long-range, order-of-magnitude projections that support funding decisions for development spending. They identify research needs but do not support manufacturing.
- The important issues and challenges being addressed were identified.

4. Are plans identified for addressing issues and challenges?

- There are some coordination activities planned to assist industry in supply chain considerations, and there are initiatives for laboratory collaboration. It is difficult to see how the objectives of the Manufacturing R&D sub-program will be met with no allocated budget, but that is not under the control of the team lead.
- The ongoing projects are addressing well the main points mentioned before.
- Yes, the plans are identified, but sufficient funding is not in place to properly execute them.
- The rationales behind current activities were given, but the presentation seemed not to have discussed plans for the future.
- No, this needs to be done with manufacturers.

5. Was progress clearly benchmarked against the previous year?

- Accomplishments of the past year were clearly laid out. It is difficult to say whether progress was clearly "benchmarked" without fully understanding the goals laid out for the year and metrics by which they were measured.
- Unfortunately, in some projects, it was difficult to clearly identify the progress, as many slides of this year were just a copy/paste of slides already presented last year or located in the back-up slides.
- Sufficient description was given of activities within the past year.
- Not much. Manufacturing companies could present what they had done and what their needs are.

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 projects in this technology area are still very focused on fuel cells. To the extent that that has been the focus in rolling out commercial vehicles, it is probably appropriate that this is the case. Also, while the examples and applications are fuel-cell-focused, these areas are barriers for related problems that FCTO is trying to solve as well. Tying these projects to broader applications would further increase the value and impact of the work.
- Yes, the projects are addressing the main problems and barriers. An additional topics might be to address the manufacturing of embedded tanks.
- The projects in this technology area are rationally directed toward the broad problems and barriers.
- Some of the activities, such as the supplier chain meetings, may not have been very effective in advancing the field.

- Yes.
- No.

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

- Yes. There is a significant diversity in the types of projects funded under this sub-program, but the individual projects are addressing FCTO needs.
- The sub-program is well managed within the budget limitations. To be more effective, additional engagement with industry is needed, across technology areas and the supply chain.
- The sub-program itself seems to be focused and well managed. Some of the efforts involving interactions with regional fuel cell promotion groups may not have been particularly effective.
- Yes, the sub-program is well managed and focused.
- No.

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?

- Strengths include the capability that is being developed at NREL for understanding of roll-to-roll processing considerations and in-line measurements to characterize defects. Understanding the detection limits for defect size, as well as speed, is essential in understanding the capability of the process. The global competitiveness study is also a key strength of the sub-program in assessing both where the United States needs to continue to advance technology and the overall maturity of the field.
- The following are strengths: (1) The analysis of the United States' position vs. other nations in fuel cells was very necessary, and the results should be stressed. (2) Projects that get information on roll-to-roll processing into the public domain and that provide pilot-scale roll-to-roll coating capability to developers of advanced materials will likely prove essential to advancing the field. Roll-to-roll-coated materials must be used for commercialization-relevant studies of fuel cell durability and performance. (3) The Advanced Manufacturing Office's (AMO's) roll-to-roll consortium, which this sub-program led to, could prove useful to the development of U.S. industrial installations in multiple areas of energy conversion and storage. The following are weaknesses: (1) It is not clear that the supplier chain meetings and workshops and the interactions with regional fuel cell promotion groups have provided significant benefits. (2) QC research needs to get out of the national laboratories and into real production environments to be of ensured value.
- The following are strengths: (1) different well-structured projects that are effective in reaching goals and milestones, (2) establishment of a clear supply chain for the main systems and components in hydrogen fuel cell technologies with efforts to communicate it to the hydrogen fuel cell community and with clear recommendations on the weaknesses to address, and (3) quality control of membrane electrode assemblies and identification of the impact of defects on performance and lifetime in order to avoid over quality. A weakness is the collaboration/communication between the ongoing projects, which is not very easy to see and should be improved.
- The effort to assess U.S. competitiveness in manufacturing of various fuel cell components is valuable in order to prioritize future FCTO investments. The work on the hydrogen pipeline coupler is important to ensure that the capability exists when it is needed. It is not clear how the work on QC and roll-to-roll process development will be transferred to industry. It is difficult to assess the value of the two projects related to supply chain development without some metrics related to actual matches made between suppliers and integrators (that result in actual component sales).
- These projects need to be addressed with stack and system manufacturing companies. UTC Power did the roll-to-roll process many years ago.

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

- The QC, roll-to-roll, and pipe coupler projects appear to be innovative. By their nature, the analysis and supply chain development projects are not.

- As a manufacturing program, this activity properly deals more with the selection of the best available technology rather than the development of entirely new processes or materials. Some of the quality control methods being explored are at least partly novel.
- Yes, most of these projects favor innovative approaches to enable a more efficient manufacturing of hydrogen fuel cell components.
- Yes, but the projects could be expanded beyond fuel cells.
- No.

10. Has the sub-program engaged appropriate partners?

- The sub-program has a few defined partners through the Small Business Innovation Research and Small Business Vouchers (SBV) programs. For maximum effectiveness, it would make sense to engage more industrial partners. The component survey work is heavily engaged with industry and has done a good job of obtaining relevant information. R&D engagement is not as evident, likely because of the budget constraints.
- This is difficult to assess. It appears that individual projects have the right partners, but the overall sub-program is too small to have attracted a large number of engaged partners.
- Not enough. Academia should be engaged only when the industry identifies a key fundamental challenge.
- The current partners appear quite appropriate. Nevertheless, increase of the participation of industrial partners (component suppliers, Tier 1) would be appreciated, in particular by validating the technological devices developed and the different models of cost breakdowns.
- The sub-program has engaged appropriate partners (suppliers, developers, national laboratories) plus some partners of questionable appropriateness (regional fuel cell promotion agencies).

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

- The sub-program is collaborating effectively with the partners that have already been engaged.
- The sub-program is collaborating effectively with suppliers and national laboratories.
- The sub-program is collaborating to the extent necessary for the individual projects.
- No.

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

- Intensified attention to roll-to-roll processing, as planned under the AMO consortium, would seem appropriate. A number of the specific manufacturing issues that need further study and public discussion are being examined under the cost analysis function of the FCTO.
- On-board storage tanks remain a key element for the commercialization of fuel cell vehicles. The tanks are too expensive, and innovative manufacturing processes may be investigated to address this issue.
- Yes. Manufacturing of bipolar plates, catalysts, and GDLs should be addressed, as these materials and components have been identified as areas where the United States is relatively weak.
- There could be more interaction with product developers (stacks) to ensure relevance for the roll-to-roll processing.
- There are many gaps.

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

- The impacts of fuel cell break-in procedures on costs should receive more attention. Internal combustion engines are now typically never fired up until they are in a completed vehicle. It would be useful to determine whether fuel cell materials and QC procedures can be developed to a similar level of confidence. Fuel cells have many parts working in series. This puts extreme pressures on QC that should probably receive more consideration and discussion than they have in the past.
- Most of the topics are very well addressed. Hydrogen refueling station trade flow mapping appears, however, not adequately addressed, with significant approximations to be corrected.
- Yes. Manufacturing of bipolar plates, catalysts, and GDLs should be addressed, as these materials and components have been identified as areas where the United States is relatively weak.

- Porous transport layer manufacturing is not addressed. Some QC measurements are included, but manufacturing development in the porosities and distribution needed, or how to make them, is not included.
- Yes.

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

- Components beside membrane electrode assemblies and catalyst layers are important and require additional focus somewhere in the FCTO Hydrogen and Fuel Cells Program. Manufacturing would appear to be the appropriate area. Also, some of the techniques for defect detection work for fuel cells but not other types of devices. Expanding the capability of these areas would be of benefit.
- Yes. Independent study and data from manufacturers should be considered.
- Manufacturing of on-board storage tanks may be one.

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

- Improved connections between DOE and industrial personnel developed under the FCTO and AMO consortia should be exploited to get more complete descriptions of manufacturing, cost, and performance status into the public domain to guide policy development.
- Additional SBVs and funding mechanisms would be helpful in engaging with small businesses, which may not have the capability to invest in cooperative research and development agreements but could use this capability.
- More effective engagement of ultimate manufacturers in the Manufacturing R&D projects will be critically important.
- Yes. We should learn what has been done in Japan and Europe.
- The current approaches are well defined and effective.

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

- The diligent and capable efforts of the manufacturing team should continue to facilitate a hydrogen/fuel cell option in the United States' energy future.
- Additional funding is needed to balance the portfolio. The focus should be on where the U.S. manufacturing position is weakest.
- Yes. There should be more work with manufacturers.

Technology Validation Sub-Program Comments

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

- Yes, the sub-program has a clearly outlined strategy for addressing a wide array of technology data gaps. The sub-program is broad, and it is impressive how well managed the strategy is at addressing all subjects within the sub-program.
- Yes, the strategy is simple and clear: do what is needed to deploy technologies. The first few slides made clear how that is going to happen, and the slides that followed described how this strategy was rolled out through individual projects.
- The sub-program's overall goals and objectives were clearly stated; however, it is not clear that the strategies and barriers reflected on slide 2 are really aligned/up to date with the objectives (which are related to vehicle performance/station performance/stationary fuel performance). In addition, the budget slide then shows the largest budget item being H2@ Scale (which is a good thing), which is not directly linked to the Goal statement. It would helpful to get the goals, objectives, strategies, and budget more clearly aligned. This may mean it is time to update the objectives/strategies.
- The sub-program, including goals, objectives, strategy, and barriers, was well discussed. "Lack of [fuel cell electric vehicle (FCEV)] and [fuel cell electric bus (FCEB)] performance a durability data" as a barrier was a surprise, considering the extensive data collection by the National Renewable Energy Laboratory (NREL) over the past several years. Perhaps the previous data were not valid because of design changes in vehicles.
- The sub-program was explained, and the strategy was described, but the presentation could have benefited from specific examples of the impact strategic efforts would have on fuel cell adoption.
- Yes, goals, strategy, portfolio, issues, and accomplishments were well organized and well described.
- Yes, the strategy was clearly described.

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

- Yes, as a technology validation program, the structure of the projects has been shown to be well balanced and appropriately weighted to near-term solutions. The requested budget for this sub-program is $0, and this would represent a significant loss to the momentum of efforts across the country to bring hydrogen and fuel cell technologies into the mainstream. The impact would be far-reaching and possibly cause delays of momentum for several years. The suggested elimination of the budget and elimination of the ability of any program within the Fuel Cell Technologies Office (FCTO) to focus on higher-technology-readiness-level (TRL) projects needs to be reversed. These programs will have some of the greatest impact in achieving the U.S. Department of Energy (DOE) and FCTO goals. Without them, it will be impossible to actually accomplish what has been set out in the Multi-Year Research, Development, and Demonstration Plan.
- Because of the nature of the sub-program, projects tend to be more near-term, but there are a couple of projects with longer-term implementation, such as H2@ SCALE. This balance is appropriate for the sub-program.
- At this point, it seems like it is time to reduce the effort on light-duty vehicles; they are in the market. Critical near-term goals seem like they should align with improving/facilitating infrastructure and mid- to long-term goals to H2@ Scale/Grid interaction. In general, things that were previously near-term are now commercial, and things that were previously mid-term are now near-term, etc. That said, the specific project focuses on, for example, dispenser reliability and hydrogen metering are important and well-focused on goals that were mid-term and are now near-term/urgent.
- Generally yes, with attention and appropriate flexibility to identify market changes that reflect consumer choice.
- Generally yes, although the timeline goes out only to 2020, which is not really long-term but is appropriate for the technology validation topic.
- By its nature, this sub-program focuses more on mid- and near-term work.
- Objectives only through 2020 are short-term but are well discussed. No objectives out to 2030 were recognized.

3. Were important issues and challenges identified?

- Yes, this sub-program in particular appears to be well informed by real-world experience and challenges being faced not only by companies but also by government agencies involved in hydrogen and fuel cell technology today. The Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) program is a primary example of this appropriate focus on known and important issues in today's efforts.
- Yes, goals for range, operation duration, and production with validation strategy to support data-driven decision-making is very appropriate. Issues to resolve meter accuracy, siloxanes, and metal contamination were adequately addressed.
- Yes. Both fundamental issues (hydrogen metering, cryocompressed dispensing/storage) and practical issues (dispenser reliability, mobile fuelers) are driving well-founded work that is important to drive commercialization of hydrogen.
- Three barriers were identified, namely (1) lack of FCEV and FCEB performance and durability data, (2) lack of hydrogen refueling infrastructure performance and availability data, and (3) hydrogen from renewable resources. Given the types of projects that are undertaken by the sub-program, the following barrier should be added: lack of appropriate hydrogen station components (meters, pumps).
- Yes. They are listed clearly and succinctly.
- The program has identified the major challenges.
- Barriers are identified that appear to be equivalent to challenges. Since DOE makes up the questions, if the presenters used the same terminology, it would make it easier for reviewers.

4. Are plans identified for addressing issues and challenges?

- Yes, the sub-program exhibits a wide array of experimental, modeling, and analysis initiatives to address the largest unknowns in implementing hydrogen and fuel cell technology in real-world settings. The approaches used are well tailored to the information needs of the challenge being addressed.
- The challenges identified are lack of data and deployment of hydrogen from renewables. Lack of data is being addressed adequately, although it seems that there is less emphasis on validating hydrogen production from renewables outside of modeling efforts. It may be that DOE feels that this area is sufficiently well covered.
- For each of the activities in the project portfolio, there is a discussion explaining "why" the work is being done. In addition, Chart 3 has an impact statement along with the strategy statement that states what is being done and why. The detailed plans for how these activities are achieved are not presented. This may not be a good question for the projects in the Technology Validation sub-program, considering the limited timing for the presentations and the large number of activities in the sub-program.
- Generally yes, with project work that includes laboratory analysis, technology integration, validation, and testing with feedback for refinement.
- Some of the individual projects (e.g., cryocompressed) need clearer deliverables/dates. Some of the others (two delivery truck range-extender projects, for example) probably need to be looked at for possible redundancy and for relevance both to the "fundamental research" direction and to the focused goals. It is not clear that integration of range extenders is fundamental to either.
- Yes. However, since the primary challenge is a lack of data, the solution is (to a large extent) just to gather data.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Yes, projects within this sub-program clearly demonstrated the progress made over the past year. Some projects that had delays were candid about as much and provided convincing plans and strategies for recovering lost time over the next year. The discussion was logical, and the honesty was appreciated.
- The presentations showed significant increases in vehicles and stations. This is the result of original equipment manufacturers' (OEMs') and California's efforts. The sub-program appears to be taking full advantage of these efforts.
- There appeared to be an appropriate continuation of previous work with consistent progress.

- No. Accomplishments were given (and are impressive), but it was not clear whether these accomplishments contained information from the previous year. A crosscheck with the 2016 presentation identified some accomplishments that appeared to carry back to 2016. Clearer delineation of 2017 and 2016 accomplishments would help.
- No. Goals are stated at a high level for this and future years, but progress to goals that may have been stated last year for this year is not obvious. The individual project summaries include many significant accomplishments, but it is not clear whether those are directly planned deliverables.
- No, it is not obvious what changes happened between 2016 and 2017 without looking at last year's slides. Some of the projects are brand new, but it is not clear from this year's presentation alone.
- In general, 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 sub-program ensure that demonstration of meeting the technology targets set out in the FCTO Hydrogen and Fuel Cells Program (the Program) are actually impactful. Validation of meeting the performance targets out in the field, and doing so with consistency and reliability, is necessary for the overall Program goals to have real-world impact. This sub-program successfully performs the work necessary for such a validation.
- Yes. This is a strong sub-program that is needed to make the transition from laboratory to prototype, leading to market transformation. Technology Validation is the sub-program, along with Market Transformation, that demonstrates that laboratory efforts can result in successful pathways to commercialization.
- In the infrastructure, H2@ Scale, and grid integration/energy storage areas, yes. In the vehicle areas, it seems like it is time to let industry integrate and commercialize; the projects in those areas seem to be working more on areas that are less fundamental. There is a caveat, however: in a couple of key areas, there is a need to execute a full-scale demonstration so that investors and stakeholders have something they can see and touch. The best examples of this are MT-008 (Large-Scale Electrolyzer for Grid Stabilization) and TV-039 (Advanced Technology Mobile Fueler). Both of these are hard to get industry to try without a full-sized demonstration.
- Yes, range, production, and durability are being addressed. Problems with meter accuracy and contaminants are appropriately targeted for action.
- The Technology Validation sub-program effort has expanded to include stationary fuel cells as well as vehicles. This is a move away from the traditional transportation focus, but it is appropriate.
- Yes, technology validation is critical to helping the industry transition out of the precompetitive stage, and DOE is well suited to performing that role.
- Yes. The projects are well selected.

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

- Yes, the sub-program maintains focus on addressing the most immediate and pressing barriers to real-world deployment and demonstration of hydrogen and fuel cell technology potential. Varied efforts seem well coordinated with one another and emerging data needs in industry and field deployment.
- The sub-program is very well managed, based on the accomplishments and successes reported. The sub-program is highly effective in demonstrating the importance of the FCTO research and development activities. Technology validation activities do not report failures, and it is not clear why. Not all projects are successful, and identifying unsuccessful activities and making decisions to stop those activities are as important as identifying success.
- Yes, the sub-program appears to be using an appropriate approach, is well managed, and is well focused.
- Yes, the sub-program is accelerating the development and adoption of sustainable transportation technologies.
- Generally yes. However, with the future budget direction, there probably needs to be some refocusing on the most critical projects.
- Yes (two 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 strength of the sub-program's projects lies squarely in their immediate usability and their ability to address problems that are being faced right now by several efforts across the country to form the first seeds of wide-ranging implementation of hydrogen and fuel cell technologies. Particular projects that stand out as strengths include the National Fuel Cell Technology Evaluation Center projects on both hydrogen station and fuel cell vehicle performance and data collection, and the H2FIRST-related activities, especially hydrogen meter benchmark testing. The ongoing work for hydrogen fuel production integration with the electrical grid also stands out as projects that are well designed and are addressing significant gaps in knowledge that is in need today.
- The hydrogen metering effort is of great importance to widespread public dispensing stations. Benchmarking actual electricity consumption at electrolyzer stations is of importance to validating the actual usage against a string of subsystem computational models (electrolyzer, compression, cooling, dispensing). The integrated grid studies are important, but it is not evident that they are appropriately part of this fuel-cell/hydrogen-centered program. Fuel cell buses and trucks will play an important role, and their study is of great importance.
- The NREL composite data products are a great resource for information on vehicles and infrastructure and should be maintained and expanded.
- Strengths include the following: the ability to collaborate with OEMs in data collection and analysis of FCEBs, FCEVs, and hydrogen stations; and access to personnel and facilities to build and test supporting technologies, including sensors (i.e., flow meters) and models (i.e., real-time simulation of electrolyzers). A weakness is that, although one of the barriers mentioned was hydrogen from renewables, the only work in this area is through models. The Technology Validation team needs to initiate collaboration with utilities to test and implement their grid simulator models.
- The sub-program has appropriate focus on commercial goals and correction/resolution of problems, which is a strength. A weakness is that the economic factors from the systems analysis (Joseck) need to be identified to better target action for the most valuable markets that are ready for commercial development.
- A strength is the focus on key near- and mid-term enablers for commercialization. A weakness is a tendency to hang on to projects too long. Some projects have to be stopped before they are finished because the landscape changes and diminishes their relevance. That is a tough call but necessary in the context of budget pressure.
- The key strengths of the projects are the collaborations, specifically NREL activities and industry contributions. The weakness of the projects is not stopping (or announcing that FCTO is stopping) projects that do not meet commercial requirements.

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

- Yes. In particular, several of the hydrogen fueling station equipment testing and characterization projects have developed entirely novel test stands and test methods that are not known to exist elsewhere. This includes several testing efforts within H2FIRST projects, as well as grid–electrolyzer interaction studies.
- The projects are novel and innovative, and the process for validation is objective and appropriate to promote commercialization and manufacture of U.S. technology, development of U.S. infrastructure, and appropriate utilization of U.S. resources.
- Yes, the sub-program is validating hydrogen station dispensing capacity by helping stations improve their performance through the flow meter, liquid pump, and component testing (contaminant evaluation) projects. The projects are actively speeding up the expansion of the industry by providing solutions to real-world problems.
- It is kind of a mixed bag—in some cases, yes (H2@ Scale, grid stabilization), and in some, no (truck range extender)—and in some cases, what is novel is that something that has been talked about for years (mobile fueler) is actually demonstrated. Some need better metrics (cryocompression) to ensure that the projects are continuing to deliver valuable results/milestones. The go/no-go structure is a good way to do this, as long as the decision criteria are clearly defined.

- The projects demonstrate that proper choice of commercial targets through collaboration of industry and the national laboratories results in incremental progress toward solving challenges and eliminating barriers, which will lead to successful results.
- The efforts are not particularly novel, but in this area, novelty is not as valuable as consistency, clarity, and comprehensive efforts.
- The approach is effective and appropriate, although not particularly novel or innovative.

10. Has the sub-program engaged appropriate partners?

- Yes. The sub-program appears particularly adept at responding to developing needs as identified by industry, government agencies, and others currently highly involved in the deployment of hydrogen and fuel cell technologies. Partnership and collaboration within this sub-program appear to be one of the major strengths.
- In general, each project lists a number of collaborators. These seem to be determined at the outset, which is fine, but it also seems like there are several projects for which it makes sense to bring in additional collaborators depending on how the project results unfold. It is not clear that the sub-program has the flexibility to do this. This may be related to how we define a "collaborator"—i.e., perhaps a collaborator has to be a contractor or provider of funds/services to a project—it is not clear.
- Yes, all listed and described partners including industry, laboratories, universities, and government are very appropriate participants. There would be value to better understanding more precisely the players, the level of participation, and the specific contributions from each of the partners.
- The Technology Validation sub-program is working with a number of commercial entities, in addition to the typical interactions with the national laboratories.
- There is appropriate collaboration by the laboratories and OEMs, but additional collaboration with utilities to vet and utilize the grid integration models is suggested.
- In general, yes.
- Yes.

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

- In general, yes. The "typical" collaborators (DOE, national laboratories, long-standing corporate participants, universities) are all very familiar with working in this environment and so respond well to structuring and working within a project framework. The sub-program might look for opportunities to draw in unconventional collaborators who might bring new perspectives.
- Yes, the transportation data collection and analysis is the best example of this collaboration. Data continue to be gathered and analyzed confidentially.
- Yes. This is a major strength of the sub-program.
- It appears so; however, more information on the level of participation and contributions from each of the partners would have been helpful.
- Yes, based on accomplishments.
- Yes (two responses).

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

- *From two respondents:* There are no obvious gaps.
- There is significant need right now to understand how to test and validate claims of hydrogen station fueling capabilities, especially claims of daily fueling capacity, back-to-back fueling capability, and simultaneous fueling capability. The Hydrogen Station Equipment Performance (HyStEP) device has been a good first step toward validating station performance with respect to codes and standards, and may be a good stepping stone for launching an effort into validating performance characteristics that are not necessarily related to a standard or a protocol.
- FCTO has been doing work in other sub-programs to understand the technoeconomic aspects of tube trailer refueling, thus avoiding on-site compression. It would be good to see this technology being validated through this sub-program.

- No, although the grouping of projects/topics is not really consistent within the presentation material (slide 4 vs. slide 20). It seems there is a need to ensure H2@ Scale, vehicles/infrastructure (with the most emphasis on Infrastructure at this point), and grid/energy storage are covered as the main groupings.
- There are no apparent gaps, but a better identification of costs and values with some information on the market potential and economic value for specific project areas would have been helpful.
- There is some uncertainty about actual hydrogen compressor efficiency. This merits further examination.

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

- No. The work that is currently ongoing seems to be overall covering a good breadth of the related issues, with their respective objectives and technical challenges being addressed.
- No, the presentation effectively addressed the main topics for stationary, motive, and hydrogen production.
- There is concern that venting losses (even at 3.6% project future levels) are too high.
- Projects that do not project commercial success should be eliminated.
- No (two responses).

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

- The area integrating stationary power with controller technology for dispatch, storage, integration of renewables, cost management, and demand response is an area that could be ripe for commercialization through competitive suppliers and/or utilities. This is an interesting focus area that should be continued.
- In response to the budget's being eliminated for the next year, all funding needs to be restored to at least the previous year's levels. Elimination of all funding for this sub-program is unacceptable.
- Emphasis should primarily be within the H2@ Scale and energy storage areas. Infrastructure reliability, energy usage, and cost also remain important.
- There are innovative hydrogen production technologies that are not included in the Program, and the Technology Validation sub-program could benefit from expanding the scope of activities.
- Validation of tube trailer dispensing should be considered.
- No (two responses).

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

- Given the budget situation, and acknowledging the development of hydrogen and fuel cell industries broadly across several states, there may be an opportunity to try to convene a states' coalition for identifying on-the-ground technology deployment issues and information needs. Perhaps efforts under such a consortium approach can help identify new opportunities for ongoing work.
- Where possible, participation and collaboration with private industry should be increased, with identification of individual contributions. Regulators should be engaged to better understand the process to integrate stationary power with controller technology for dispatch, storage, integration of renewables, cost management, and demand response for commercialization through competitive suppliers and/or utilities. Integration of technical work with economic systems analysis (Joseck) should be increased, where possible.
- The Technology Validation sub-program has the mandate to study, test, and validate actual performance of systems and components. It would be good to see a clear linkage between findings from the sub-program's efforts and the follow-on efforts to capitalize on the information. For instance, if hydrogen meters are inadequate, it would be good to know what specific research and development programs are addressing the gap. This linkage is implied, but a direct connection should be identified.
- Barriers are listed as lack of FCEV and FCEB performance and durability data, lack of hydrogen refueling infrastructure performance and availability data, and hydrogen from renewable resources. The first two are pretty well taking care of themselves. Projects supporting hydrogen from renewable resources could be a focus area to support several of the strategies.
- The sub-program could test and collect data from home/community refueling stations. There was an H2Refuel project at the poster session; the sub-program could collaborate with them to test/validate the technology's durability under different conditions.

- No, data accumulation from California and other projects should be kept up.
- No.

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

- Overall, this is a valuable and well-managed DOE sub-program. Increased private industry participation and identification of contributions, integration with economic systems analysis, and collaboration with utility regulators and competitive power suppliers would be of value. Concise white papers on sub-program accomplishments targeted for non-technical energy industry stakeholders (utilities, power suppliers, marketers), policymakers, and government officials might also be an area to show sub-program value.
- There is no excuse for the presenter's not covering all the material in the allotted time. The presentation should be reviewed and "dry runs" carried out with colleagues before the Annual Merit Review. The presentation should be pared down if all the material cannot be presented in the allotted time.
- The sub-program should try to look at which projects may need to end due to changing priorities and resources so that the remaining projects or new ones can be resourced for maximum effectiveness.
- Funding should be increased, but this does not appear to be possible with the new administration.
- There are no suggestions at this time.
- No.

Safety, Codes and Standards Sub-Program Comments

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

- The overall strategy of the Safety, Codes and Standards (SCS) sub-program is well-thought-out. The sub-program is focusing on areas that need support for enabling the deployment of hydrogen infrastructure and the further reliability aspects of it. Some examples of these are (1) the work in establishing scientific-based data for enabling the reduction of safety distances, given that footprint requirements for station deployment are currently a barrier for integrating large-capacity hydrogen fueling stations into a retail environment; and (2) the number of projects for the development of an in-line fuel quality analyzer that will enable highly reliable operation of hydrogen fueling stations.
- Yes. Mr. James provided a thorough and well-organized review of the SCS sub-program. He identified the key focal areas and barriers and the strategy for addressing challenges, and he provided a deeper look at the progress and accomplishments made over the past year. The focal areas of this sub-program are all needed for helping to accelerate the hydrogen and fuel cells market. It is also a well-balanced portfolio that addresses technical needs, outreach, and identification of future needs.
- Yes, for years, this area has had a clear overarching goal and multi-annual objectives, and these are tackled structurally and in a complete way.
- Yes, it was an excellent overview on focus areas, barriers, and objectives to address barriers.
- Goals and Strategies are stated; however, they are not referred to consistently through the first part of the presentation. Slide 2 shows Goals/Objectives in two areas, slide 3 shows budget in three different areas (maybe slide 2 is a "vertical" cut, while slide 3 is "horizontal"), and slide 5 then shows five focus areas with barriers and another set of objectives. These can be organized better so that there is a clear flow of objectives to focus areas to deliverables to resources.

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

- The balance of near- and long-term research and development (R&D) seems appropriate. For the near-term needs, the sub-program is heavily focused on station reliability by supporting several projects on the development of in-line fuel quality devices, in addition to the support of critical stakeholders on hydrogen safety best practices; whereas in the long term, the sub-program seems to be focused on liquid hydrogen and therefore larger-capacity fueling stations by supporting work that will have an impact on the required safety distances (or footprint) for the deployment of larger stations.
- Yes. The sub-program is focused on R&D and information dissemination for challenges that we face currently. It is also working on issues we anticipate becoming (and are seeing become) more prominent as the market grows. Finally, the Inter-Laboratory Research Integration Group (IRIG) was developed to identify future needs.
- Yes. Safety research is critical for enabling near-term standards and facilitating construction. Sensor research is an important medium-term effort, and materials research supporting safe/reliable/cost-effective infrastructure is a good longer-term effort.
- Yes, the sub-program covers all of what is needed for filling gaps in safety knowledge and data; it naturally integrates the underpinning scientific foundation at the service of standards and permitting tools and processes.
- Yes.

3. Were important issues and challenges identified?

- Yes. The issues being addressed under the sub-program, once solved, will help reduce space and cost challenges (e.g., separation distances, safety sensors, and fuel quality)—both currently limiting factors in hydrogen station development.
- Yes. Gaps in codes and standards (also in safety) are continuously analyzed and prioritized. The process for achieving this is based on a broad coalition of stakeholders and experts.
- Main issues and barriers were clearly identified by the sub-program manager, as presented on slide 5.
- Yes, challenges are identified for each major area of effort.

- Yes.

4. Are plans identified for addressing issues and challenges?

- Yes. The presentation focused on sharing progress within each focal area, and each focal area is designed to meet specific objectives that will address larger barriers. Future plans for each focal area were not outlined specifically; however, the progress is being demonstrated, and the path forward can be seen.
- Yes, and not only the plans—the mechanisms for their successful implementation are also properly designed on the basis of previous experiences (for example, the CSCI and the IRIG instrument).
- Slide 5 clearly identified the main objective for each of the barriers identified, and throughout the talk, the sub-program manager showed in detail the corresponding projects that will address the main barriers and how to overcome these.
- Yes. The funded projects represent well-planned efforts to address the challenges identified.
- Yes. Plans were also clarified during individual project sessions.

5. Was progress clearly benchmarked against the previous year?

- Yes, progress was clearly presented, with some of the main highlights being the techniques for understanding liquid hydrogen release behavior, the release of the Hydrogen Risk Assessment Model (HyRAM) 1.1, and the patent application for the fuel quality sensor.
- It was. Mr. James devoted a slide to outlining progress since last year. There could have been an opportunity here to highlight progress more here to underscore the value and importance of this work, for example, by showing in each focal area the status in 2016, what was achieved in 2017, and what is left to be done. That said, Mr. James still did a good job of sharing the solid progress that has been made.
- It is not clear what "benchmarking" is supposed to mean in this context. Quantitative improvement indicators are not possible for this area of the sub-program. However, certainly a multi-annual mapping of the achievements were given, allowing the assessment of the progress toward SCS gap filling. A part of the activities in this area consists of maintaining, improving, and disseminating (safety) knowledge datasets. Also, for these aspects, quantitative indicators do not exist, but there is clear evidence that improvement in respect to last year's status was achieved.
- Yes, key areas of progress for each project since the 2016 Annual Merit Review were clearly stated and summarized.
- Yes, the overview slide was a good summary of progress.

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?

- Absolutely. For example, setback distances are a persistent challenge for station development in highly populated urban areas (much of California), and bringing down the cost of safety sensors and hydrogen purity monitors will help bring down overall station costs, which will enable more infrastructure development and may help spur more private investment in the market. Additionally, safety education is still very much needed, and the safety outreach efforts are fantastic. H2Tools is an excellent resource that this reviewer values firsthand and has heard the same from many others.
- Yes. It appears evident that this area is well integrated with the rest of the FCTO Hydrogen and Fuel Cells Program and reacts well to the needs of the other areas. Examples are the focus on safety in tunnels to answer urgent needs for the deployment of the technology in the Northeast, and the need for fundamental understanding and facts related to liquid hydrogen (storage) behavior to address one of the most critical enablers for full-scale deployment.
- Yes, given that the speed of acceptance and implementation of infrastructure is being hindered by lack of clear codes, familiarity, and understanding of hydrogen properties and rules, SCS is one of the most critical areas of FCTO work. It is critical to keep an eye on how the objective of "R&D to provide critical data and information needed to define requirements..." can be very quickly brought to bear to support resolution of emerging issues such as the bridge and tunnel problems. For example, while the facilities and work at Sandia National Laboratory to quantify liquid hydrogen spill behavior are valuable long-term assets, they were not able to respond quickly enough to affect the immediate revision cycle of the National Fire Protection Association's Hydrogen Technologies Code (NFPA 2).

- Very clearly. Even with a very limited budget, the sub-program is well balanced to provide support for addressing the main barriers around safety, reliability, and code implementation.
- Yes, the projects are addressing the development of a foundation of safety knowledge and codes & standards needed and widespread sharing thereof.

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

- Very effective management has been the key for the success of the SCS sub-program. Management is always engaged with the external community and does a good job disseminating the advances of the sub-program.
- Yes, although the current projects will need to be clearly prioritized in light of the new budget and focus/ direction realities. This may mean that some projects may need to be stopped to provide resources for critical new needs that arise.
- Yes. However, it is challenging to keep up with the changing needs on a limited budget for this topic area.
- Absolutely.
- 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?

- Key strengths include the following:
    - The work on tunnel safety is very important for enabling market growth in the Northeast.
    - Reducing separation distances and costs for safety sensors could also help accelerate the market in the United States and internationally.
    - Assuring adherence to fuel quality standards is also an emerging need.
- The following are key strengths: a strong and dedicated group/network of collaborators, both national and international; alignment with industry needs; and the H2tools.org website as global resource. The following are key weaknesses: H2tools.org's dependence on U.S. Department of Energy (DOE) funding to continue operations, and the SCS sub-program's dependence on the annual budget-making process.
- Among other excellent projects, HyRAM should be mentioned as a most successful international attempt to offer to stakeholders a one-stop shop on safety design.
- One of the key strengths is that the projects have been well targeted to meet real-world immediate needs such as setback data and sensors for service facilities. It is, perhaps, a weakness that the economic objectives of all the projects are not clearly stated at the beginning. For example, after showing very promising sensing results, the principal investigator of the laser diode sensing project, when asked about cost, said in effect that the technology is extremely expensive and that it is unlikely that someone would choose to use it because of that.
- Strengths include sub-program management and significant engagement with national and international codes and standards organizations. Weaknesses include a limited budget and perhaps the lack of work on fueling protocols (this might be due to the limited budget).

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

- In some cases, yes (such as SCS-029, in which an existing instrument technology is being adapted for a new use with novel algorithms). In some cases, it is more a matter of just identifying and prioritizing the critical work that needs to be done (which is important and okay to do).
- The most characteristic and appreciated aspect of the SCS sub-program is its integrated approach to the challenges, trying to engage with all types of stakeholders and experts. This is perhaps not successful in all cases, and sometimes industry presence and input could be better, more intense and continuous, as admitted also by the sub-program manager. However, this issue is very much out of the manager's control and is a characteristic deficiency of similar international programs.
- This is clearly demonstrated by the fact that scientific-based data are used to support the proposed modifications to codes and standards.

- Yes.

10. Has the sub-program engaged appropriate partners?

- Yes. The sub-program has engaged U.S. and international partners, enabling us to leverage learnings from (and contribute to) other countries while also being grounded in specific needs for U.S. market development. Partners also exist across sectors—government, industry, academia, non-governmental organizations—and within these sectors, the sub-program has partnerships with the "right" key organizations.
- Very extensively. The continuous interactions with the codes and standards technical bodies is probably one of the main strengths of the sub-program.
- The most characteristic and appreciated aspect of the SCS sub-program is its integrated approach to the challenges, trying to engage with all types of stakeholders and experts. This is perhaps not successful in all cases, and sometimes industry presence and input could be better, more intense and continuous, as admitted also by the sub-program manager. However, this issue is very much out of the manager's control and is a characteristic deficiency of similar international programs.
- Yes, the SCS umbrella involves/requires engaging a wide array of collaborators and partners to obtain, develop, and disseminate information and data. One concern (broader than just SCS) is that DOE projects do not often bring in new partners/collaborators mid-stream through a project. It seems like cultivating the ability to do this would be very valuable, as it is often not known at the outset what direction project results are going to go.
- Yes.

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

- It appears so. The reviewer cannot speak to all collaborations, but from those organizations that the reviewer is involved with that partner with this sub-program, the answer is yes. Lines of communication are open, market needs are being identified and addressed, and the hydrogen fuel cell community is benefiting from this sub-program's projects.
- Absolutely. This in part speaks for the success of the sub-program's activities.
- Yes, although the ability to have flexible collaboration arrangements that change over the duration of the projects is needed.
- Yes, very well.
- Yes.

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

- This portfolio does a good job of addressing current key challenges to enable market expansion of hydrogen and fuel cells.
- Gaps include heavy-duty hydrogen vehicle fueling and underground hydrogen storage (direct burial) codes and standards (including setback/separation distances).
- An increase in budget will greatly help to support R&D work on fueling protocols.
- No gaps were noted.
- No.

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

- Absolutely not. However, the area of detection/sensors could profit from some clarification to avoid confusion. Under this name, a broad set of technologies is used for two very different goals. Safety hydrogen sensors are critical for the safe operation of all installations. Hydrogen impurity detection is critical to guarantee gas quality and to avoid fuel cell degradation, a very critical aspect of the whole technology chain. It is obvious that common competence in gas detection is required in both goals, but the approach to solutions is different in the two cases. This does not appears very clear from slide 5, where a general barrier typical for safety sensors is coupled to an objective specific for impurity detection, where a fully developed technology solution is not yet even available.

- For in-line hydrogen quality sensor efforts, it would be good to know what the progress is with assessing the real cost for these sensors, not just the replacement cost.
- The development of innovative fueling protocols should be taken into consideration.
- No.

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

- Other areas include heavy-duty hydrogen vehicle fueling, underground hydrogen storage tanks in hydrogen fueling station safety testing, limits for over-the-road liquid hydrogen transportation (whether limits can be expanded), and transport of liquid hydrogen by rail.
- Other needs that the sub-program could consider funding include (1) a Hydrogen Station Equipment Performance (HyStEP)-type device to enable third-party fueling protocol verification systems to be validated and 2) development of medium- and heavy-duty fueling protocols to enable acceleration of the medium- and heavy-duty fuel cell market.
- Whether the field of hydrogen impurity detection and measurement receive enough funding could be considered. This technology covers a critical role in the whole technology chain and deserves the most urgent attention. There could be also a need to join forces (resources, competences) with other sub-programs.
- In light of the fact that funding will likely not continue to be available for everything on which FCTO is currently working, it would be helpful to conduct a priority review of projects/resources underway so that critical projects can continue to be fully resourced and so that resources can be allocated if/when new critical priorities arise.

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

- There is a very small suggestion for improvement in the specific area of safety sensors as a key technology for preventing/mitigating measures. It is still not possible to offer a simple and cheap methodology for the proper installation of detecting devices in complex/difficult spaces, so the work initiated in 2017 on dispersion and detection in an electrolyzer container will not be enough to answer this question in a general sense, to determine what industry would like to have. There are algorithms and novel approaches to this, which should use three-dimensional computational fluid dynamics only in the validation phase, and later on offer easier and cheaper methods to be applied, as already adopted for other gas industry areas.
- It would be very impactful if our outreach/education projects can create opportunities for stakeholders/ students to visit existing hydrogen facilities to see firsthand what safety systems are in place, how codes are applied, and how safety systems (passive and active) work. This would increase the already very helpful momentum that has been achieved in meetings, seminars/class sessions, and webinars. Likewise, perhaps some of the web content could provide suggested facilities/contacts for viewers to consider visiting facilities that showcase examples of the material being studied.
- This sub-program could be integrated with the DOE Office of Fossil Energy safety area (if there is such a thing).

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

- It would be very impactful if our outreach/education projects can create opportunities for stakeholders/ students to visit existing hydrogen facilities to see firsthand what safety systems are in place, how codes are applied, and how safety systems (passive and active) work. This would increase the already very helpful momentum that has been achieved in meetings, seminars/class sessions, and webinars. Likewise, perhaps some of the web content could provide suggested facilities/contacts for viewers to consider visiting facilities that showcase examples of the material being studied.
- Particularly in light of the recent budget cut announcements, it seems that working more with industry to both ensure research is actually filling key needs and information gaps and to encourage/leverage private investment is now more important than ever.
- The work should be kept up, whether under DOE FCTO or elsewhere.
- The budget should be increased.
- No.

Market Transformation Sub-Program Comments

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

- *From two respondents:* The sub-program, including the overall strategy, was adequately covered.
- The sub-program was discussed in great detail, and good progress was being made in the acceleration of technology for hydrogen fuel cell systems. The success generated by the prior efforts on materials handling with the continued sales of forklift trucks without the federal subsidy validates the efforts of the Fuel Cell Technologies Office. The strategy was not specifically identified, and since this question always gets asked, a chart with "strategy" would be helpful. The objectives appear to define the strategy and are consistent with meeting the Market Transformation sub-program goals.
- Yes, markets, demonstrations, and targets were well organized and accurately presented. There is good leadership with thoughtful management.
- Although the reviewer was not able to attend the presentation in person, a review of the slides presents a very firm picture of the efforts and overall strategy for the Market Transformation sub-program.

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

- Yes, sub-program objectives to investigate use of fuel cells for stationary and motive power with baseload, back-up, and supplemental use (range extension) for practical and affordable market transformation are being objectively demonstrated for short- and long-term development.
- The balance between near-, mid-, and long-term research and development is very reasonable, considering the mission of the Market Transformation sub-program.
- There is an appropriate balance between near-, mid-, and long-term research and development.
- There is an appropriate balance in the two areas, but the funding is not sufficient to accomplish as much as is needed in both areas.
- No specific timeline for the projects was presented. Some projects were established in separate phases (Project Scope), and progress was demonstrated on all projects. However, the presentation did not allow for a determination as to whether the project(s) were on schedule. Some delays were identified, e.g., the marine project, but not necessarily because of poor technology—more because of permitting issues.

3. Were important issues and challenges identified?

- Operation, durability, and applications are being identified and tested. Performance and other issues are being identified appropriately for correction.
- Important issues and challenges were discussed adequately in spite of the limited time allocated to the presenter, although the time constraint meant that reviewers should be somewhat familiar with the sub-program's technologies and markets.
- Important issues and challenges were identified.
- Under challenges, four specific projects were listed. The challenges chart did not identify any specific details for each project. Later in the presentation, some targets were given, e.g., the availability of airport cargo tow tractors and drivetrain specifications for battery-electric-vehicle–fuel-cell parcel delivery trucks.
- Whether major issues or challenges were encountered could not be detected from the slides.

4. Are plans identified for addressing issues and challenges?

- Yes, plans are identified where applicable. For example, the transport refrigeration unit (TRU) and auxiliary power unit slide shows the next step: integration of the inverter and TRU.
- Plans for addressing issues were not specifically discussed. Project highlights and accomplishments were given. The Project Scope slide identified project activities but not specific issues the activities were resolving.
- The research process appears to be adequate to identify issues and challenges for correction.
- Yes, plans have been identified for addressing issues and challenges.

5. Was progress clearly benchmarked against the previous year?

- Yes, the movement in the forklift and back-up power segments were quite impressive.
- Progress appears to be consistent with the work plan and goals. Benchmarking to identify annual progress is adequate.
- Accomplishments and progress were clearly identified and assumed to be from this year. A cross-check with last year's presentation identified that many of project accomplishments were for this year.
- Yes, progress was clearly benchmarked against the previous year.
- Slides show new accomplishments to help the audience see progress compared to the previous 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?

- The projects clearly aim at addressing barriers to enable faster market penetration of fuel cell and hydrogen technologies in appropriate markets that benefit the broader national goals for fuel cells and hydrogen, plus battery deployment goals.
- Yes, market transformation demonstrations (lift trucks, back-up power, marine power, air transport) appear to be appropriate targets to address problems and barriers for successful commercial deployment.
- Yes. Most of the projects are demonstrating the viability and acceptance of fuel cell power in industrial and consumer applications. A few projects are just starting or have identified problems associated with permitting or acceptance of technology.
- The major hurdle for broader fuel cell introduction is the value proposition and the lack of infrastructure. More money and dedicated effort are probably required to move the needle here.
- Yes, projects in this technology area largely address the broad problems and barriers that FCTO is trying to solve.

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

- The sub-program focuses on both industry and inter-governmental needs and is well managed and effective in addressing FCTO's needs. For example, it catalyzes key program activities and partnerships and provides technical assistance to end users.
- Team leadership appears focused, with proper management of the sub-program. Sub-program outcomes will clearly address FCTO needs.
- Yes. Sub-program managers selected competent partners, and partners are moving the projects forward.
- The Market Transformation sub-program appears to be focused, well managed, and effective in addressing FCTO's needs.
- Yes, although a greater level of funding would allow more engagement.

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?

- Strengths include strong partnerships with appropriate industrial and government entities and leveraging the resources available in the private sector and agencies. There are no weaknesses.
- Strengths include appropriate targets for demonstration, good leadership, and good results. Weaknesses are as follow: (1) additional information on economic systems analysis (Joseck) would be helpful to understand costs, value, and market potential; (2) additional project reporting for non-technical stakeholders is needed; and (3) specific contributions from participants need to be identified.
- Collaboration is the strength of the sub-program. Focusing on those technologies and solutions that are near market-ready is a strong goal. The primary weakness is the inability to make broader movement on several fronts to assist market adoption. The auto industry is probably the key to making a significant dent in the infrastructure and cost challenges, and the U.S. Department of Energy/FCTO/sub-program is just not there with enough resources to help advance that consideration across the nation.

- The primary key strength is the project partners: Plug Power–FedEx, Nuvera–ThermoKing, Hawaii. A weakness is some of the project partners: US-Hybrid had a delay with a technology ownership change (UTC sold technology to US-Hybrid).
- A key strength is the creativity of the Market Transformation sub-program personnel in trying to make things happen. Weaknesses include funding and also the over-focus on funding of the laboratories, an effort that very much seems to undercut real progress toward stated FCTO goals.

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

- The projects are in themselves novel and innovative; the sub program process is well suited for project demonstration and objective technology evaluation.
- These projects are breaking ground for new polymer electrolyte membrane fuel cell applications and are demonstrating the benefits of fuel cell systems.
- The projects represent novel ways to address barriers, largely because they involve commercial or government end users with a vested interest in achieving collaborative success at minimal cost.
- No, projects do not always represent the most innovative approaches to barriers, in large part because it appears that some creative projects from industry that might offer real advances are overlooked in favor of projects from the laboratories, so one can wonder if the FCTO program is designed to focus on advancing fuel cells or keeping the labs alive. That said, the Market Transformation sub-program office seemed to do a better job than other offices, as only 2 of 6 projects presented were from labs (while 10 of 13 Technology Validation sub-program oral presentations were from labs).
- Not many novel and/or innovative ways to approach these barriers were presented.

10. Has the sub-program engaged appropriate partners?

- There is a large number of partners and collaborations, as listed in chart 15. However, the reviewer missed reporting on Proton OnSite, General Motors, and Toyota. It would be interesting to see a table with names of collaborators and an adjacent column with activities.
- Yes, all partners appear to be appropriate; however, identification of the particular roles and contributions of each partner would be helpful.
- Yes, there is a good collection of fuel cell manufacturers, hydrogen producers, and end users identified and collaborating.
- Yes, the partners are appropriate, and their cost sharing is significant.
- Yes, the sub-program engages appropriate partners.

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

- Yes, there are extremely effective collaborations with Plug Power, Hydrogenics, FedEx, Workhorse, and others.
- Yes, the use of limited funds seems very effective.
- Yes, absolutely.
- It appears that private industry is engaged. However, the specific roles and contributions should be identified.
- Yes, collaboration is effective.

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

- No significant gaps are apparent, but identification of the cash flow and economic viability for each project would be helpful.
- There are no gaps, but expanding the effort to new applications and partners would be beneficial.
- The key to broader introduction across all areas is the auto industry and adoption. If the solution comes in that industry area, then others can rapidly follow thanks to infrastructure improvements and cost reductions.
- No significant gaps exist.

- Yes, but the portfolio is budget-constrained.

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

- No, the selected topics are appropriate, but each project should be analyzed with systems analysis tools, benchmarked with comparative and/or conventional alternatives, reviewed with appropriate market information, and assessed with an economic analysis.
- The cost of the fuel cell systems for the different applications would be beneficial, specifically with comparison to U.S. Department of Energy costing analysis.
- No topics immediately come to mind.
- Yes.

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

- The topics are appropriate and justified. Additional areas of consideration might include more support for renewable hydrogen; application clusters (i.e., multiple vehicle refueling for lift, light-duty, bus, and ground support vehicles at targeted locations, e.g., the airport); and demand response with hydrogen production and storage for utility and competitive supplier applications.
- If more funds were available, it might be helpful to have more competing teams with the existing portfolio rather than looking at additional areas.
- If dollars existed, stronger play with the auto industry might be valuable.
- Yes, there are other areas, especially in hydrogen delivery.
- There are no other areas that are obvious.

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

- Partners all appear appropriate, but additional private industry involvement should be welcomed to help identify barriers and solutions. All projects should be analyzed with systems analysis tools, benchmarked with comparative and/or conventional alternatives, reviewed with appropriate market information, and assessed with an economic analysis. Each successful project should require additional reporting and outreach to present results to non-technical stakeholders, policymakers, and government regulators to help support the next steps in commercialization.
- The use of workshops to focus the discussion of challenges and identification of mitigating and solution strategies is a worthwhile process.
- No, the sub-program has a well-developed approach to the barriers.
- No, but the next round of Multi-Year Research, Development, and Demonstration Plan updates may identify new ways.
- No.

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

- The sub-program is well managed, has good leadership, and has made excellent progress, especially with lift truck commercialization. Progress and program value should be better promoted with an education initiative to industry, government regulators, and policymakers; specific participant involvement should be identified to highlight public–private partnerships and to keep private businesses engaged; and each project should be assessed with systems analysis, market benchmarking, and an economic analysis.
- Probably the important suggestion is the identification of resources to more boldly attack the challenges. Work related to unmanned aerial vehicles was mentioned on slide 5, but nothing on the slides dealt with that initiative. Also, slide 7 did not reflect the correct team participants.
- There should be more publicity regarding successes.
- The sub-program should get away from the laboratories and reach out to business more.

Systems Analysis Sub-Program Comments

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

- The Systems Analysis sub-program presentation covered annual updates on fuel cell markets, products and patents, and models that are available and are being developed. The purpose and direction of the sub-program were discussed. Most of the work being performed this year by the projects was included, although a few projects presented at the Annual Merit Review were not specifically discussed in the overview presentation.
- Yes, it is clear that this sub-program collaborates with all other areas of the Fuel Cell Technologies Office (FCTO) to ensure consistency and transparency.
- The sub-program manager clearly explained the overall strategy and the main foundation elements of it, as stated in details on slide 4.
- Yes, it was very well covered, and all relevant topics are being addressed.
- Yes (two responses).

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

- There is excellent balance on near- and long-term activities. This is clearly demonstrated, for example, on near-term activities: the assessment for hydrogen cost for low volumes for the current market; early market infrastructure analysis, where for the long term some of the relevant activities are around the support to H2@ Scale; increased focus on medium- and heavy-duty transport; and regional resources analysis.
- The H2@ Scale provides the opportunity to perform long-term research and development. Most of the other models being developed look at both near- and long-term results.
- It is clear that as long as the other FCTO programs continue to exist, there will be a need to tie together assumptions, results, goals, and technology innovation through analysis.
- The assessment of the total cost of ownership (TCO) in 2040 is appropriate, but it would be interesting to also assess the transitional stages, e.g., how the TCO will compare in 2020 and 2030.
- The sub-program addresses current and future technologies with an appropriate balance.
- Generally yes, although the studies seem to utilize long-term assumptions most dominantly, i.e., the analyses assume a 2040 analysis year with the achievement of target cost/performance.
- Yes. Analysis spans near term to long term and low to high volume.

3. Were important issues and challenges identified?

- This sub-program assesses barriers across the entire Hydrogen and Fuel Cells Program, quantifying them and directing efforts to surmount barriers.
- The focus of the Systems Analysis sub-program portfolio clearly speaks for the main challenges and how these are addressed.
- One of the areas that reviewers bring up again and again is the need to have the models validated and vetted with industry. This should be a significant component of every project within the Systems Analysis sub-program.
- Important issues were discussed, but challenges were (generally) not described in terms of target metrics.
- No, issues and challenges were not identified.
- Yes.

4. Are plans identified for addressing issues and challenges?

- Generally, yes. But given that this is systems analysis, the plans are buried as analysis assumptions. They were not openly called out as pivotal targets/metrics.
- The sub-program has a clear strategy for addressing issues.

- The very well-thought-out and diverse portfolio, the interactions with external experts, plus the models, tools, and expertise provided by the national laboratories are definitely great ways to address the critical issues.
- In one of the last slides, Fred identified upcoming activities, which include achieving sub-program targets and addressing economy-wide challenges such as energy security and sustainability metrics. Those are overarching challenges that will be tackled by the sub-program. Specific issues/challenges that will be addressed by the program were not mentioned.
- For each presentation, it would be beneficial to see how the work is different from what was done previously and how it complements other projects that are ongoing. This would help the reviewers and also the researchers themselves to articulate how their work fits into the big picture of the sub-program.
- Yes.

5. Was progress clearly benchmarked against the previous year?

- Significant accomplishments and progress presented for this year include analyses on energy security, market segmentation, resource, employment, H2@ Scale, medium- to heavy-duty, and criteria emissions, among others.
- Data were provided on the increased number of fuel cell electric vehicles (FCEVs) and refueling stations and the price of hydrogen relative to last year. It is assumed that the graphs and data presented for fiscal years 2016–2017 highlight demonstrates progress from last year.
- Analysis focus areas were identified. Benchmarking against the previous year is probably not applicable to this analysis work.
- Progress was benchmarked for only some of the projects. Other projects are too new to have a 2016 benchmark.
- 2017 accomplishments in several areas were clearly highlighted.
- In general, 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?

- The broad portfolio of models addresses most of the issues facing the Hydrogen and Fuel Cells Program. The one area that is not adequately addressed is consumer choice and behavior. This probably lies outside the expertise typically found in national laboratories. The sub-program might seek to engage original equipment manufacturers and consultants to better understand consumer choice, but often this data is tightly held.
- Yes, in fact, the sub-program helps tie together results for all pathways and technologies, adding a technoeconomic macro-level assessment of status and needs.
- Yes. This analysis is crucial in assessing the relevance of technical progress within the FCTO project portfolio.
- The sub-program has a broad portfolio of projects that clearly focus on addressing the main FCTO barriers.
- Yes, the projects are addressing the problems and barriers as specified in the Multi-Year Research, Development, and Demonstration Plan for Systems Analysis.
- Yes. The projects are well selected.

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

- The sub-program is very broad, which is understandable given that it envelops a diversity of projects that range from job creation to comparing the sustainability benefits of advanced vehicle options. Despite its breadth, it is focused, as it follows the developments and needs of other programs and provides the level of assessment needed to understand their overall impact. The sub-program is adequately managed for the reasons described above and because it has been able to incorporate relevant technical expertise from the national laboratories. As analytical issues arise, the System Analysis sub-program has been able to quickly respond with high-level assessments. A case in point is H2@ Scale, which was announced last year, and now there is a Systems Analysis project looking at market potential and economics.

- Excellent management has been the key for the excellent and valuable analysis work completed by the sub-program.
- There were no issues identified in the management and focus of the work. It is good to see the analysis being used to drive research and development in the other sub-programs.
- Yes. In additional to being well focused and well managed, the presentation was delivered in a clear and effective way.
- Yes. The sub-program has been responsive to suggestions from reviewers and other outside input.
- 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 Systems Analysis sub-program serves as the "honest broker" integrating all topics. The government team is viewed as open-minded and willing to consider new ideas. The TCO and truck investigations are particularly noteworthy.
- Strengths include the following: strong management, a well-balanced portfolio, world-class experts and tools from the national laboratories, and extensive industry engagement. Weaknesses include a limited budget.
- Strengths include strong analysis expertise and tools and dogged efforts to obtain the data needed to assemble and validate models.
- Key strengths include strong analytic capability and good support from the laboratories. Weaknesses include promotion/use of the analyses by planning agencies at the state and local levels to develop roadmaps for deployment of infrastructure and development of incentive plans. The TCO for FCEVs, battery electric vehicles (BEVs), and buses is very material at this point, given the early penetration of the technologies.
- A key strength is economic analysis that puts technical progress into context. The weakness is only that some analysis seems questionable in value (jobs impacts and county-by-county resource mapping).
- There is a concern that the jobs creation discussed as part of this sub-program is not necessarily all new jobs but, in some cases, may be just job replacement (e.g., if people are buying FCEVs, they are not buying traditional internal combustion engine vehicles). There is a need to evaluate the difference between these two.

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

- With many individual models having been developed for various purposes, it is good to see exiting models being integrated together to address larger-picture issues. This may not be extremely novel, but it is the right approach relative to developing entirely new models. The existing models have been vetted and are recognized. It would be good to see fewer models that are more versatile instead of more models.
- The assessment projects reflect innovative technologies and alternative pathways to conventional energy/ fuel/transportation pathways.
- Yes. Projects are assessing FCTO technologies from multiple vantage points such as economic viability and environmental impact. It helps to frame a complete picture of the value/endgame.
- The approach is solid, effective, and appropriate.
- Yes. Inclusion of agent-based models for consumer choice is a good example.

10. Has the sub-program engaged appropriate partners?

- Yes, this particular sub-program involves all other areas by default as it gathers information from the entire value chain to conduct analysis. Further, national laboratories and industry have been involved in conducting analyses and validating results.
- The sub-program has engaged many entities in industry to obtain information needed to construct and validate models.
- Yes, the sub-program is working with key laboratories that have constructed and operate a strong portfolio of modeling tools.

- One of the strengths of the sub-program is the extensive engagement and collaboration with industry.
- The collaboration with each project to assist in the development of the models and analysis seems adequate, although in some cases it is difficult to appreciate what contribution the collaborators are making.
- In general, yes.

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

- Yes, there seems to be an open line of communication, as the models are updated constantly with results from the laboratories and the other sub-programs. Further, the results also incorporate industry achievements.
- There is very effective two-way interaction with industry partners.
- Yes, modeling and analysis experts are directly engaged.
- It would be helpful to understand who is using these models outside of the U.S. Department of Energy (DOE) and whether the users found the models to be useful. Those that download the models should be periodically queried to provide feedback.
- Additional communication within FCTO would aid in project effectiveness.
- Yes.

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

- The sub-program is doing a great job with its funding level.
- Additional funding will greatly help.
- In life-cycle cost analyses, alternative fuels should be stress-tested against low petroleum prices (the Energy Information Administration's Low Oil case). While oil prices may go high at times, the actual production costs of oil-based liquid fuels are quite low.
- TCO should be compared for other vehicles; for light-duty vehicles, diesel, hybrids, and plug-in hybrids should be included. For buses, liquefied natural gas (LNG) should be included.
- One gap is greenhouse gas (GHG) targets to compare results across technologies on a GHG-abated/dollars-invested basis.
- No.

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

- It was good to see that the Systems Analysis sub-program has expanded to include buses and trucks. Work has been underway within FTCO for many years in this area. It would be better if the sub-program led out on the evaluation of new technologies or evaluated them as they are identified rather than waiting for years to include them in analyses.
- Current status in TCO assessment should be included; analysis is for the 2040 timeframe. It would be good to know where we are today and how we will get to 2040 numbers.
- TCO should be compared for other vehicles; for light-duty vehicles, diesel, hybrids, and plug-in hybrids should be included. For buses, LNG should be included.
- Consumer behavior is perhaps an example, but work such as agent-based modeling is a first step in remedying that.
- In the TCO analysis comparing BEVs and FCEVs, it is not clear that the infrastructure differences (relative pros and cons) between charging and fueling have been comprehended. These could be factored in as generalized cost attributes, or they could also be used to restrict the addressable market in some cases.
- No.

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

- No gaps were obvious. Of course, with more funding, the sub-program could do more. The impression is that there are enough valuable projects on hold that additional funding could be quickly deployed effectively.

- The current set of projects seems adequate. H2@ Scale analysis (planned for 2018) will be important.
- The sub-program's portfolio is very strong.
- Regarding energy security analysis, it would be good to know how much FCEVs are contributing given the shift in energy sources in the United States. It would also be good to know where FCEVs will make more of an impact, and what the potential is for this technology to reduce expenditures by DOE, the U.S. Department of Defense, and others.
- No.

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

- The current approach seems adequate.
- A risk analysis of not meeting DOE technical targets would be beneficial to the sub-program. This risk analysis should address which targets are most important to meeting the overall objectives of FCTO. This would be beneficial to the sub-program.
- The possibility of using hydrogen for long-distance freight transport (perhaps as a range extender), as well as using hydrogen for maritime transportation, could be assessed.
- No (two responses).

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

- Supporting H2@ Scale and the analysis for medium- and heavy-duty transport are great additions to the Systems Analysis sub-program portfolio.
- State and local city planners should be invited to provide feedback and propose new projects.
- No (three responses).