Program Peer Review Summary

The U.S. Department of Energy (DOE) Hydrogen Program Fiscal Year 2022 Annual Merit Review and Peer Evaluating Meeting (AMR) included overview presentations on the DOE Hydrogen Program (the Program), as well as oral presentations of 58 Hydrogen and Fuel Cell Technologies Office (HFTO)-funded projects and poster presentations of 137 HFTO-funded projects. Project-level presentations were provided by the Office of Fossil Energy and Carbon Management (FECM), the Office of Nuclear Energy (NE), the Office of Science (SC), the Advanced Research Projects Agency–Energy (ARPA-E), and other offices within the Office of Energy Efficiency and Renewable Energy (EERE). Of these hydrogen- and fuel-cell-related projects, 11 were presented orally and 28 were presented with posters.

While individual projects were not reviewed at the 2022 AMR, a group of reviewers was asked to provide feedback on the overall Program and HFTO subprograms, taking into account both plenary and poster presentations. Panel members included experts from a variety of backgrounds related to hydrogen and fuel cells (see Appendix A). Each reviewer was screened for conflicts of interest, as prescribed by the EERE Peer Review Guide. A summary of reviewer comments and recommendations that are applicable across the entire Program is provided in the next section. Summaries of comments and recommendations that apply to specific subprograms, as well as summaries of the projects that were presented orally at the AMR, are provided in subsequent sections of this report, grouped by subprogram. The full set of Program review results, including scores, comments, and recommendations, is included in Appendix A.

Summary of Reviewer Comments

This section provides a summary of the program review comments received. The content reflects those inputs only and not the views of Program management.

Reviewers stated that, overall, the Program has a comprehensive portfolio and is well-managed. It has been very effective in driving hydrogen and fuel cell technology performance and cost improvements through research, development, and demonstration (RD&D) activities. The Program uses a well-coordinated RD&D strategy and input from multiple stakeholders to address key challenges (e.g., high costs) that prevent clean hydrogen and fuel cell technologies from being implemented comprehensively—and that restrain consumers’ acceptance of those technologies. In addition, the Program responded quickly to the Administration’s emphasis on concerns related to environmental justice, ensuring they were included in Program scope.

Even after the technology and cost goals are achieved, challenges will remain, and deploying the technologies will require broad acceptance across stakeholders: regulators, industry, and the public. Therefore, it is important to identify and address those remaining obstacles by devoting more resources to discussing barriers, assessing risks to overcome barriers, and defining and prioritizing the challenges. In addition, a clearer and more detailed breakdown of funding for different Program offices would help in understanding what RD&D priorities are being addressed.

Reviewers also noted that the Program plans for the funding provided under the Bipartisan Infrastructure Law are promising and well-formulated. The goals of these plans align well with efforts already under way, though one reviewer commented that the published expectations for the Clean Hydrogen Hubs could be made clearer, citing the well-articulated structure and goals of the Hydrogen Shot as an example. Continuity across all these efforts is key to the success. Notices of intent to issue funding opportunity announcements (FOAs) made the Program plans clearer (especially for the Clean Hydrogen Electrolysis Program and the Clean Hydrogen Manufacturing and Recycling Program) and allowed potential FOA applicants to prepare. The FOAs and the subsequent program management should be as streamlined and simple as possible, with minimal administrative burden (i.e., reporting and data collection requirements).

The Program should focus on making consistent progress and keeping a line of sight on ultimate goals, rather than trying to reach cost parity with fossil-based transportation technologies. The Program’s portfolio of projects seems appropriately balanced between near-, mid-, and long-term goals. However, the challenges and many unknowns make it difficult to determine whether decisions on the distribution of projects were truly appropriate. The Program would benefit from continued leveraging of lessons learned from past successes and evaluating what aspects and achievements have led to commercialization.

The Program's portfolio has expanded in terms of more mature technologies (i.e., those with higher technology readiness levels [TRLs] that will soon be ready to enter the commercial sphere), which were under-represented until recently. Reviewers had mixed views on the portfolio's balance. Some reviewers felt that projects working on lower-TRL technologies were less likely to meet goals and that focusing on higher-TRL activities with coordination across DOE offices would be beneficial in the near term, making hydrogen hubs and commercialization successful. Even with existing high-TRL technologies, though, some felt that the funding allocated to developing hydrogen hubs across the United States may not be adequate. Some reviewers felt that near-term research should not completely displace mid- and long-term research, noting that the lower-TRL efforts should remain an important part of a balanced portfolio.

Across the portfolio, additional testing infrastructure and increased investment in component development will be critical in the next two to four years. Furthermore, Program goals include development of a domestic supply chain, yet several projects with industry did not appear to include domestic supply chain considerations. Some reviewers suggested that "manufactured in America" should be a goal included in all subprograms. More attention should be paid to the materials infrastructure needed to enable a successful energy transition. In particular, a domestic supply of raw materials would provide cost-effectiveness, long-term jobs, and energy security. One reviewer, however, urged the Program not to overemphasize the need to improve the domestic supply chain, noting that the world's economies are integrated and allies such as Europe, the United Kingdom, Japan, and South Korea manufacture systems and components in the United States and serve as key consumers of U.S. products.

Reviewers also commended the Program's individual subprograms, describing them as extremely well-managed. Subprogram goals, milestones, and quantitative metrics are clearly articulated, providing a rational framework for coordinating complementary activities and reducing organizational redundancies. However, metrics could have been further emphasized and made clearer at the individual subprogram level. A semi-quantitative assessment of the risks remaining to overcome barriers and probability of achieving goals could also be useful. One concern is that the focus on the Hydrogen Shot and the hydrogen hubs may leave many legacy research areas somewhat "orphaned" and not as strongly tied to Program priorities. These legacy research efforts, such as HydroGEN, remain important and should continue.

The Program aligns well with industry and stakeholder needs, having extensive cooperation with a diverse range of stakeholders from the community, industry, states, international organizations, and other partners. However, to improve the probability of achieving technological breakthroughs, more industry engagement would be helpful, with industry accepting some financial risk but receiving greater rewards, such as through exclusive patents. Engaging actively with demonstrated technology disruptors and innovators at the incubator level is also a good pathway for fostering the implementation of groundbreaking technology. The Program could further enhance these engagements by providing additional guidance on a variety of avenues:

- Siting and deployment to enable technology integration into communities.
- Education and coordination to identify market opportunities related to stationary applications (combined heat and power, mission-critical facilities, microgrids, etc.); transportation applications (light- and heavy-duty vehicle fleets, materials handling, aircraft, etc.); refueling applications (in coordination with renewable feedstock producers); and utilities (electric and natural gas).
- Means of addressing concerns of distressed communities, underserved cities, and opportunity zones, consistent with both state and federal policies and goals for community investment.
- Alliance-building with local industry, supply chain partners, and community resources.
- Environmental performance, safety, and economic projection of the impact on consumer energy costs and the utility rate base.
- Coordinating with non-hydrogen stakeholders on overall integration with other technologies.
- Developing mechanisms for coordination and communication among renewable feedstock producers, energy (electric and gas) producers and grids, and energy markets for storage, transport, and dispatch of hydrogen.

In future reviews, reviewers would like to see comparisons between hydrogen and fuel cell technologies and incumbent and emerging technologies (especially batteries); such comparisons would provide useful context for assessing the future impacts and advantages/disadvantages of Program RD&D in relation to other renewable energy options.

Hydrogen Shot

The Hydrogen Shot initiative provides well-formulated, concise, and challenging goals and focus for the Program, but other notable challenges should not be de-emphasized. In working toward the Hydrogen Shot goal, progress would likely be evolutionary, so intermediate goals should be set accordingly, and progress should be quantified. To speed commercialization and reach Hydrogen Shot goals, the Program should focus on developing tools to support and enable industrial partners and stakeholders (for example, industry-vetted reference models for all promising clean hydrogen production pathways that would help determine which innovations would have the greatest impacts in terms of reaching the Hydrogen Shot goal). Also, more collaboration with the European Union, including direct partnerships on projects, could leverage knowledge and progress relating to the use of electrolyzers, strengthening efforts of the United States on the path to meeting the ambitious Hydrogen Shot goal.

Clean Hydrogen Hubs

Reviewers stated that the proposed investment in hydrogen hubs is meaningful, with potential to build confidence in the private sector and encourage investments to propel the envisioned hydrogen economy. The hubs have the potential to enable innovation in demonstrations, deployments, education, outreach, and approaches to working with states. The focus on regional markets and supply chains supports industry, perhaps encouraging the private sector to accept some initial risks. The strategy articulated by the Program will help spread hydrogen infrastructure into different regions.

The Program must focus on the long-term viability of the hubs, beyond the five-year period of the hydrogen hub investment. Projects and sites should be required to provide clear evidence of plans for commercial sustainability. In addition, Program management should think critically about the scale of hydrogen production, distribution, and use that will be supported by the Bipartisan Infrastructure Law provisions and funds, relative to the size of the overall energy market. One reviewer noted that the full cost of building out hydrogen hubs across the United States may approach $100 billion–$500 billion[1] and suggested that DOE focus the $8 billion in Bipartisan Infrastructure Law funding for maximum impact.

Furthermore, it is not clear that there is sufficient private-sector demand or market pull for the clean hydrogen that the hubs will produce. The H2 Matchmaker tool, which helps hydrogen suppliers identify hydrogen off-takers, might be of use for identifying potential off-takers.

Awarding, contracting, permitting, and building the hubs in the stated timeframe will be difficult and time-consuming. Many technical reviewers and experienced project managers will be needed. The Program should clearly detail the specific administrative, technical, or regional goals of the hydrogen hubs before releasing the FOA. Additionally, funding may not be smooth: industry and states may struggle to meet the planned 50% cost share requirement, and DOE will have to obligate funds quickly.

Clean Hydrogen Electrolysis Program

Reviewers agreed that plans for the Clean Hydrogen Electrolysis Program are well-thought-out and clearly articulated. One reviewer recommended strong continued support for advanced concepts to improve the chances of meeting the Hydrogen Shot goal; another recommended increasing the emphasis on hydrogen compression to improve system-level reliability for the electrolysis program.

Clean Hydrogen Manufacturing and Recycling Program

Reviewers expressed support for the Clean Hydrogen Manufacturing and Recycling Program. This program is perhaps less well-defined than the Clean Hydrogen Electrolysis Program, but that is to be expected, given the breadth of the manufacturing and recycling program and its early development stage. However, funding for clean

[1] E. Larson, C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, EJ Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan. "Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final Report." Princeton University, Princeton, NJ, October 29, 2021. https://netzeroamerica.princeton.edu/the-report.

manufacturing may be too low to address all the technical barriers, and so critical items should be prioritized. The proposed material recycling and end-of-life effort is a necessary and significant step toward achieving the Program's goals. One reviewer noted the importance of learning from equipment demonstrations and suggested that equipment suppliers be "required" to receive, dispose of, and learn from used equipment as a condition of receiving DOE funding. Another suggested emphasizing refurbishment of fuel cells rather than recycling, as many fuel cell components, such as advanced catalysts and bipolar plates, may be made from lower-value materials, so their value is mainly in their structure.

Consortia

The research consortia approach addresses critical challenges; it is successful, efficient, innovative, very well-organized, and a valuable catalyst to innovation and progress. One reviewer stated that "bringing multiple labs together with appropriate industrial and academic participation supercharges ideation and knowledge creation necessary to support the applications at hand." Using lab facilities and other research capabilities to support competitively selected DOE-funded projects is an effective way to accelerate learning and progress. The Program has created an effective model for integrating seedling and push projects into the larger consortium framework. However, programs involving numerous principal investigators present management challenges. The Program must avoid coordination difficulties and redundancies and ensure the lead researchers have time for research and development (R&D). Moreover, it would be helpful in future reviews to clarify differences in related consortia objectives and directions, as well as the role of Tech Teams.

The Program could enhance the visibility of the consortia by better advertising them to academia and U.S. businesses, particularly small businesses. Recommendations for improving the consortia include sharing lessons learned among the different consortia, conducting an anonymous survey of lab personnel and industry and university partners to identify best practices and areas for improvement, initiating periodic third-party reviews of the consortia to assess operation and effectiveness, and increasing the number of basic, high-risk–high-reward projects supported under the consortia.

Diversity, Equity, Workforce Development and STEM Education

The Program funds projects at universities and national laboratories, thereby playing an important role in science, technology, engineering, and mathematics (STEM) education. Reviewers were divided as to whether the Program is doing enough to advance goals for workforce development and STEM education; some stated that these activities merit increased funding because of their importance in meeting the Program's near- and long-term goals. However, all applauded the Program's efforts to ensure diversity in STEM student populations and in the workforce and the Program's collaborations with historically black colleges and universities and minority-serving institutions.

STEM education needs to span all levels of education, from elementary school to graduate programs. Needs include incorporation of hydrogen and fuel cells in standard curricula, targeted grants and scholarships for undergraduate and graduate programs, and a balanced approach that highlights both the benefits of cleaner fuels and the practical challenges to widescale adoption. Specific recommendations include:

- Promoting the teaching of life cycle analysis and the enhancement of communication skills.
- Encouraging inclusion of STEM educational activities in research proposals.
- Reaching out to state educational groups.
- Assessing the number of hydrogen-related graduate programs.
- Establishing programs to train teachers and trainers.
- Advancing internships and co-op programs for university students.
- Promoting job shadowing for high school students.

The DOE Justice 40 initiative provides a solid plan and an excellent framework for addressing critical issues associated with workforce development in disadvantaged communities and collaboration with minority-serving institutions. The talent pipeline for researchers with graduate degrees is important to the Program mission. The Program has appropriate plans to fund universities for workforce development, and Los Alamos National Laboratory's involvement of undergraduate students in its research is commendable. National laboratories could conduct further activities in workforce development:

- Increasing graduate student funding for summer fellowships at national laboratories.
- Recognizing and rewarding workforce development activities at the national laboratories.
- Developing specific resources to help scientists with workforce development, such as assisting with job searches and linking community colleges to research universities.

Outside of academia, there is a need to provide auto mechanics, utility workers, and other technicians with specialized training in hydrogen energy systems. Education and training efforts are already under way through the Hydrogen Education for a Decarbonized Global Economy (H2EDGE) project and the Center for Hydrogen Safety. Additional recommended efforts include:

- Establishing two-year training courses focused on hydrogen and fuel cell technology at community colleges.
- Developing a certification program, similar to the Electric Vehicle Infrastructure Training Program, for technicians working with hydrogen technologies.

Other support could be identified through workforce analysis, which would provide a better understanding of the demographics, geography, infrastructure needs (e.g., high-speed internet access), and training needs of the workforce and its ability to support the transition to a hydrogen economy. Universities should work with industry to ensure that workforce development results in skills valued by industry, and there is a similar need for coordination between original equipment manufacturers and institutions providing mechanic training. More workforce development efforts at the state and regional levels are encouraged, and DOE could coordinate with other agencies with specific workforce development expertise.

DOE's workforce training should address energy efficiency, system durability and lifetimes, capital expenditure evaluation, ways to decrease the cost of electricity, and energy systems integration. When creating e-learning systems for training the workforce, project developers should be included as partners to ensure that the training systems will meet their needs and that they will attract and retain a skilled workforce. One reviewer identified deficiencies in the modules available through the DOE website: they are static pages, do not necessarily interact and change with the progress of the online learner/instructor communities, may in some cases be out of date, and may in some cases require DOE employees to deliver the modules.

Intra-Agency Collaboration

DOE programs and offices have increased collaboration, which will help advance systemic approaches and favorable technology couplings. A welcome and promising evolution of a well-structured and well-managed Program, these cooperative efforts should be continued to reduce duplication, break down barriers between groups, and find solutions that help all and achieve policy goals. However, a challenge remains: stakeholders must be shown how these collaborations can lead to meaningful advancements and impacts. While overall communications between the offices are effective, offices could work together to develop a dashboard that tracks project status and strengthens information-sharing. Of less value are the numerous (time-consuming) meetings that senior researchers and program managers must attend to facilitate inter-office coordination. Perhaps an alternative approach, such as international postdoctoral fellow exchanges or rotations/details to the different offices, could reduce this burden.

The following are recommendations specific to collaborations with the various DOE offices:

- ***Basic Energy Sciences (BES) Office:*** The BES hydrogen R&D budget request has increased, emphasizing the continued need for basic, high-risk research and recognizing the Office's role in workforce development. Advances in high-strength materials, such as carbon fiber, for high-pressure tanks is important for transportation applications. A joint EERE–BES materials discovery program could move beyond current levels of incremental technology progress and help to address cost-related challenges.
- ***Office of Energy Efficiency and Renewable Energy (EERE):*** Program strengths include coordination and co-funding between HFTO and other offices in EERE, such as the Advanced Manufacturing Office's Roll-to-Roll consortium. The Program should increase support and resources for manufacturing R&D to lower technology cost for clean hydrogen technologies, thereby addressing a significant gap in high-speed, low-cost manufacturing technologies in the United States.
- ***Office of Fossil Energy and Carbon Management (FECM):*** Almost all current domestic and global hydrogen supply comes from fossil fuel sources, which may remain true beyond the next decade. Thus,

attaining Hydrogen Shot goals may require significant advances in large-scale, low-carbon hydrogen production from fossil fuels. Many approaches are predicated on the existence of a credible, commercial-scale carbon capture and storage technology, yet this technology has not yet been proven to be cost-effective at scale. FECM may require more funding to demonstrate technical feasibility to meet ambitious hydrogen cost and emissions targets and timelines. However, it is not clear whether continued research on fossil-based hydrogen production pathways is in line with stakeholder needs. One reviewer recommended that DOE assess how much fossil-based hydrogen production with carbon capture will be needed as a transition approach, and at what cost. Continued R&D on solid oxide fuel cells and hydrogen turbines is clearly needed. Also of interest is further discussion of the methods for reducing nitrogen oxide emissions from hydrogen turbines.

- ***Office of Electricity (OE):*** During the review, the Program highlighted that maximizing hydrogen's impact on the grid (e.g., through electrolysis) will require grid modernization. To this end, more emphasis should be given to engaging with OE. One area for collaboration is integration of renewable power, grid capacity, and hydrogen production at the point of use.
- ***Office of Nuclear Energy (NE):*** Collaborations between HFTO and NE are commendable, and the Program has clearly articulated the challenges and opportunities associated with integrating hydrogen production with nuclear energy. It should be noted that different rating systems may be needed for high-TRL technologies (such as alkaline electrolysis using solar power sources) vs. low-TRL technologies (such as solid oxide electrolysis cells integrated with into nuclear power plants). Integrating hydrogen production with nuclear plants may take five to ten years for permitting, testing, and training, so it would be useful to clarify how different TRLs will be treated in the Program. Another recommendation is to capture learnings as they occur for utilization in training systems.

Some of the collaborative efforts should focus on breakthrough technologies. The U.S. Department of Defense provides examples of successful approaches, such as the Navy and its science advisors through the Office of Naval Research.