Analysis, Codes and Standards – 2023

Analysis, Codes and Standards Subprogram Overview

Introduction

The Analysis, Codes and Standards subprogram aligns with priorities in the *U.S. National Clean Hydrogen Strategy and Roadmap* and performs enabling activities to inform research, development, demonstration, and deployment (RDD&D). The subprogram comprises two activity areas: Systems Analysis and Safety, Codes and Standards (SCS). The Systems Analysis activity area identifies priority markets for hydrogen technologies and assesses impacts. The SCS activity area informs safe design and operation of technologies and addresses regulatory and permitting challenges.

The Systems Analysis activity area funds crosscutting analyses to identify technology pathways that can facilitate large-scale use of clean hydrogen to enable decarbonization, advance environmental justice, and enhance energy system flexibility and resilience. To perform these foundational analyses, the subprogram relies on a diverse portfolio of both focused and integrated models that characterize technology costs, performance, impacts, and cross-sector market potential. These tools and capabilities are continuously updated and enhanced. New tools are also developed as needed.

Crosscutting analyses are conducted in collaboration with a range of entities:

- Other Hydrogen and Fuel Cell Technologies Office (HFTO) subprograms
- Various U.S. Department of Energy (DOE) offices: Strategic Analysis Team, Vehicle Technologies Office, Bioenergy Technologies Office, Office of Fossil Energy and Carbon Management, Office of Nuclear Energy, Wind Energy Technologies Office, Solar Energy Technologies Office, Advanced Materials and Manufacturing Technologies Office, Industrial Efficiency and Decarbonization Office, Office of Clean Energy Demonstrations, and others
- State and local government organizations
- Other federal agencies (e.g., the U.S. Environmental Protection Agency)
- Private sector companies
- International organizations.

In Fiscal Year (FY) 2023, the Systems Analysis activity area focused on user-friendly tools to characterize cost and emissions of real-world deployments, analyze cost and emissions of additional hydrogen production technologies, and incorporate hydrogen into energy market models to include hydrogen demand scenarios in strategic sectors to enable net-zero by 2050.

The SCS activity area supports research, development, and demonstration (RD&D) to improve the fundamental understanding of the relevant physics and provide the critical data and safety information needed to develop and revise technically sound and defensible codes and standards. These codes and standards provide the technical basis to facilitate and enable the safe and consistent deployment and commercialization of hydrogen and fuel cell technologies in multiple applications. SCS activities include identifying and evaluating safety and risk management measures that are used to define requirements and close the knowledge gaps in codes and standards in a timely manner. SCS activities also focus on promoting best safety practices and developing information resources.

In FY 2023, the SCS activity area focused on approaches to streamline permitting, resources on current codes and standards and safety best practices, and safety component research and development (R&D) (e.g., release behavior, sensors).

These crosscutting efforts support technology development and scale-up of hydrogen activities across the entire hydrogen value chain (production, delivery, storage, and end use), as well as across multiple industry sectors (transportation, grid integration and power generation, industrial and chemical industries, etc.).

Goals

The Systems Analysis activity area supports HFTO's decision-making and prioritization process by evaluating technologies and energy pathways, identifying gaps and synergies, and providing insights into future benefits, impacts, and risks.

The overarching goal of the SCS activity area is to enable the safe deployment and use of hydrogen and fuel cell technologies and ensure that key stakeholders have confidence in that safety. This goal is pursued by:

- Facilitating the creation, adoption, and harmonization of regulations, codes, and standards (RCS) for hydrogen and fuel cell technologies.
- Conducting research to generate the valid scientific bases needed to define requirements in developing RCS.
- Performing RD&D to inform deployment and enable compliance with RCS.
- Developing and enabling widespread dissemination of safety-related information resources and lessons learned.
- Ensuring that best safety practices are followed in activities sponsored by the Hydrogen Program; to that end, soliciting and reviewing project safety plans and directing project teams to safety-related resources.

Key Milestones

The key milestones of the Systems Analysis activity area are as follows:

- Develop models and analyses to support the implementation of the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Law) and the Inflation Reduction Act. **(2023–2027)**
- Conduct state-of-the-art assessments of technology cost, performance, and value proposition to help guide the RDD&D portfolio. **(2023–2027)**
- Validate and refine models and tools to enable large-scale market growth, inform multisector coupling, and realize emissions reductions and jobs potential. **(2027–2035)**
- Characterize market barriers and opportunities for supply chain expansion and high-volume manufacturing. **(2027–2035)**
- Assess RDD&D and market transformation processes, policies, and progress across applications and sectors to enable system resilience, emissions reduction, and sustainability; and assess job potential, including impacts on disadvantaged communities. **(2035–2050)**

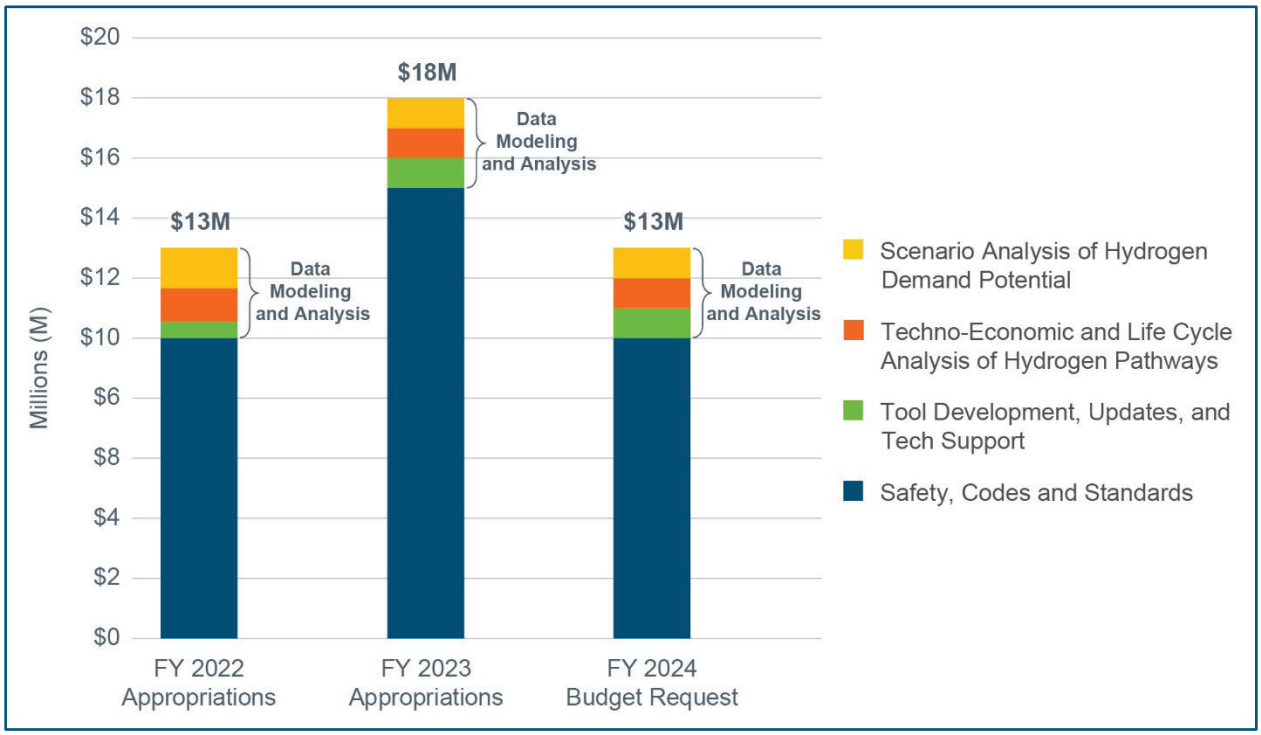
The key milestones of the SCS activity area are as follows:

- Identify ways to reduce the siting burdens that prohibit expansion of hydrogen fueling stations by using hydrogen R&D to enable a 40% reduction in station footprint, as compared to the 2016 baseline of 18,000 square feet, by 2022.
- Develop a compendium of gaps and priorities requiring harmonization for global codes and standards for hydrogen infrastructure and mobility technologies.
- Initiate at least three new non-automotive-related applied risk assessment and modeling efforts pertaining to large-scale hydrogen deployment applications.
- Ensure monitoring systems and data collection are in place for potential hydrogen and other emissions/ releases and validate hydrogen sensor technology capable of parts-per-billion sensitivity, detection speeds of less than one minute, and <$1,000 annual operating cost.

Budget

The FY 2023 appropriation for the Analysis, Codes and Standards subprogram was $18 million. The budget for the Systems Analysis activity area is $3 million per year. The budget for the SCS activity area grew from $10 million in FY 2022 to $15 million in FY 2023, with new funding to support approaches to streamlining permitting for hydrogen deployments.

The FY 2024 budget request of $13 million includes $3 million for Systems Analysis activities and $10 million for SCS activities.



Annual Merit Review Results

During the FY 2023 Annual Merit Review, 23 projects funded by the Analysis, Codes and Standards subprogram were presented, and 16 were reviewed (a breakdown by budget category is shown on the right). The reviewed projects received scores ranging from 3.1 to 3.7, with an average score of 3.4. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

Following are reports for the 16 reviewed projects. Each report contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

Number of Projects Reviewed by Budget Category	
Tool Development, Updates, and Tech Support	3
Techno-Economic and Life Cycle Analysis of Hydrogen Pathways	1
Safety, Codes and Standards	
Codes and Standards Harmonization	3
Component R&D	3
Hydrogen Behavior and Risk R&D	3
Materials Compatibility R&D	1
Safety Resources and Support	2

Project #SA-174: Life Cycle Analysis of Hydrogen Pathways

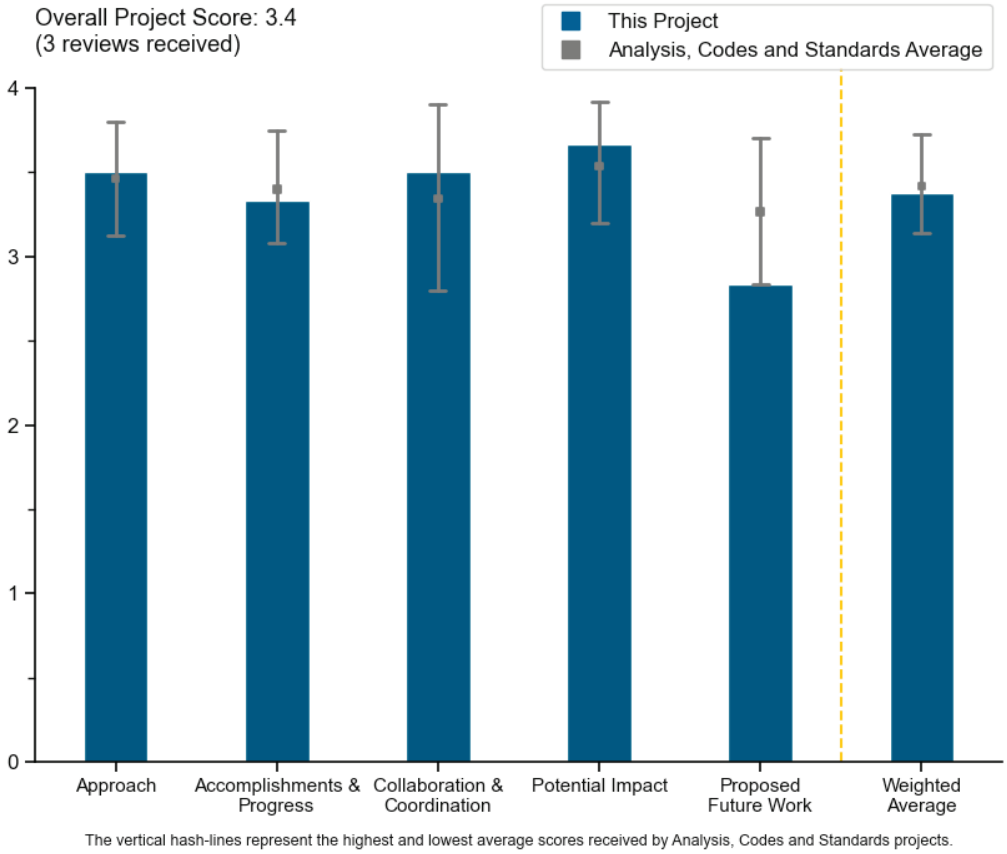
Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	WBS 5.1.0.6
Start and End Dates	10/1/2019
Partners/Collaborators	National Energy Technology Laboratory, National Renewable Energy Laboratory
Barriers Addressed	• Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools • Stovepiped/siloed analytical capability for evaluating sustainability

Project Goal and Brief Summary

Hydrogen is being considered for new markets, including as a means of producing synthetic fuel and of manufacturing steel from iron ore using hydrogen to reduce iron oxides. This project aims to evaluate the environmental implications of hydrogen production technologies. Argonne National Laboratory is collaborating on this project with the DOE Strategic Analysis Office, DOE Advanced Manufacturing Office, National Renewable Energy Laboratory, National Energy Technology Laboratory, and University of California, Irvine.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The core of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) model incorporates all the latest science into a tool that can utilize operator-specific data to estimate emissions. The work done by Amgad Elgowainy and the project team focuses on creating modules and models that leverage the importance of the Inflation Reduction Act's 45V tax credit to the myriad of production technologies and configurations that could exist for hydrogen production. The project's work is essential and reflects why GREET was specifically included in the Inflation Reduction Act.
- The approach is in line to provide a real picture of the greenhouse gas (GHG) emissions using a unique tool and also allowing a comparable approach. To do so, the tool has to be freely available.
- GREET is a key foundational repository of emissions and energy contributions. This project is effective in building on GREET.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments achieved this year are very good, with development of an H_2 module user interface with simple process and outputs and the evaluation of electrolyzer capital expenditure (CAPEX) embodied GHG emissions. Following are a few comments on the presentation. Hydrogen produced from nuclear electricity is low-carbon but not renewable hydrogen. The CO_2 allocation method used for co-products should be clarified. In chlorine plants, there are inconsistencies regarding the use of water as input. It is surprising not seeing the impact of platinum group metals such as iridium and platinum on the GHG emissions for electrolyzers. The inclusion of H_2 in the gas global warming potential (GWP) is highly debatable. As H_2 is not a GHG, it is not to be considered as such, even if it has an indirect impact. The emissions of natural gas and methane remain the real problem. Moreover, for calculating the GWP, the latest equation adopted by the United Nations Framework Convention on Climate Change (UNFCCC) should be used, as this is now the Fifth Assessment Report (AR5) and not AR6.
- The project estimated GHG emissions for the byproduct H_2 from a chloralkali plant pathway. The project has built on past work to develop a large array of H_2 production pathways (for which energy and GHG emissions are compared). The project has also extended analysis to the autothermal reforming pathway and developed an H_2 module interface.
- The level of work is typically outstanding, but the project has opportunities to make the tool more policy-relevant.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- The simplified life cycle analysis (LCA) tool is a great way for non-regular users of GREET to understand the basics of LCA for hydrogen.
- GREET and the pathway analysis draw on a large range of domestic and international collaborators.
- Collaboration is adequate regarding the activity.

Question 4: Potential impact

This project was rated **3.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project's use of GREET will be significant, as it will impact the level of subsidies of hydrogen producers.
- Because of the large 45V tax credit, the potential impact of the project's work is almost impossible to overestimate.
- The models and pathway analysis will be widely used.

Question 5: Proposed future work

This project was rated **2.8** for effective and logical planning.

- Proposed future work is aligned with the project objectives. The project's inclusion of GWP of H_2 is highly debatable and should not be included before general consensus, based on scientific facts, is achieved. The possibility of taking CAPEX embodied emissions into account for all the pathways should be investigated. Achieving a full LCA is indeed the real approach to ensure achieving the climate targets.

Project strengths:

- The technical work and the level of detail regarding the LCA of hydrogen production technologies and potential end sources are unparalleled.
- The project has a long history, appears quite robust, and is already used by many people. The work is managed by experienced, highly skilled experts.
- GREET is foundational and a publicly available tool used by many groups for a wide range of applications.

Project weaknesses:

- There has been a good deal of debate around how to evaluate the indirect emissions from electrolytic hydrogen production, which requires accounting of a consequential-type analysis of the marginal impacts of a large electric load on a local grid. Since GREET is an attributional model, the project can utilize only defined resources (or a defined mix of resources) as emissions factors. However, depending on how eligibility is determined, there could be a good deal of variation as to what the "real" emissions impacts would be for a given project. Even a basic analysis of the impact of adding renewables based upon the project's Emissions & Generation Resource Integrated Database (eGRID) (even on an annual timescale or scaled up to an annual timescale) could have impactful policy implications for these types of projects. This is especially the case when attributing long-established low-carbon resources with little likelihood of being backfilled with commensurate generation technology (i.e., nuclear or large hydro). This is outside the traditional lines of GREET, but it could not be more important for the success of the 45V program.
- An H_2 GWP multiplier is not included in the analysis.
- There are no specific weaknesses to be reported.

Recommendations for additions/deletions to project scope:

- The project should add an H_2 GWP multiplier to the analysis. Electrolyzer embodied GHG can be presented as a combined value (stack plus balance of plant) and compared to batteries and photovoltaic panels (to put it in perspective).
- There should be some written analysis, reasoned discussion, or modeling that could attempt to address the significant potential indirect emissions impacts of 45V.
- The two main recommendations are not to include GWP of H_2 and to extend the model by including CAPEX embodied emissions for all pathways.

Project #SA-178: Cradle-to-Grave Transportation Analysis

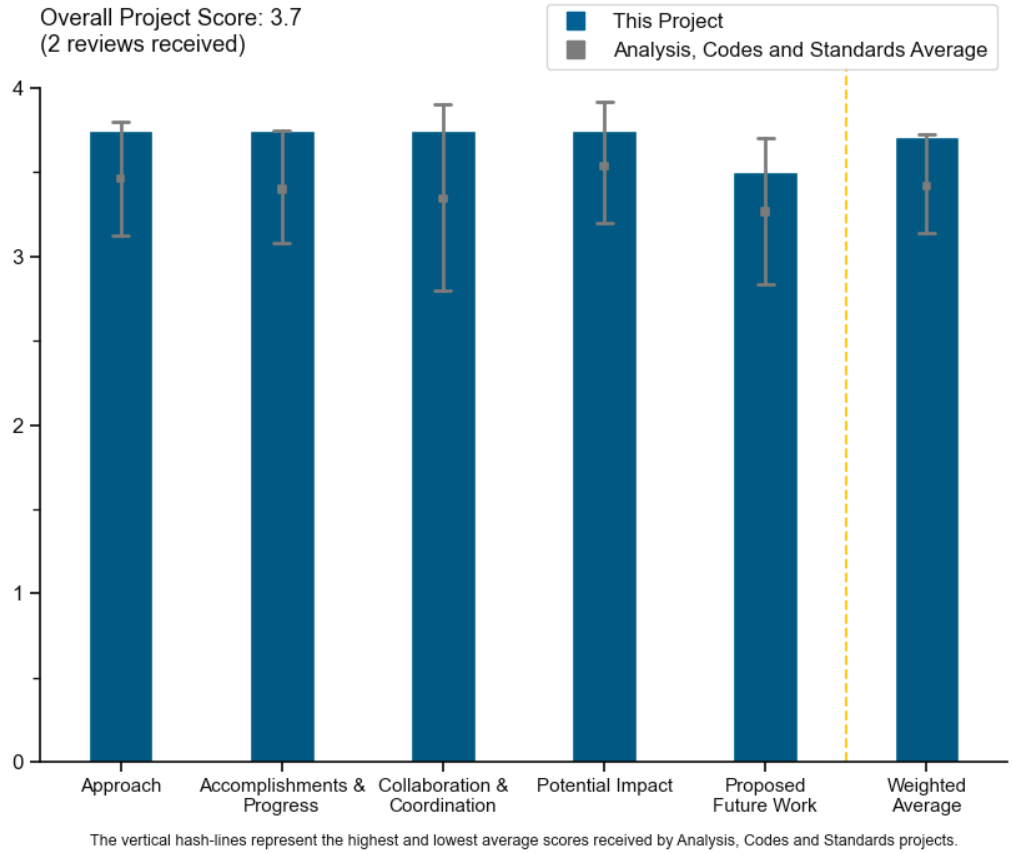
Amgad Elgowainy, Argonne National Laboratory

DOE Contract #	WBS 5.1.0.6
Start and End Dates	10/1/2021
Partners/Collaborators	U.S. DRIVE Partnership's Integrated Systems Analysis Tech Team, Strategic Analysis, Inc., Argonne National Laboratory Autonomie Team
Barriers Addressed	• Inconsistent data, assumptions, and guidelines • Insufficient suite of models and tools • Stove-piped/siloed analytical capability for evaluating sustainability

Project Goal and Brief Summary

This project will deliver information about anticipated cradle-to-grave (C2G) greenhouse gas (GHG) emissions and costs of different vehicle technology pathways. Argonne National Laboratory will employ the lab's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) and Autonomie modeling tools to evaluate C2G economic and environmental impacts of medium- and heavy-duty vehicles. The analyses will examine fuel production, vehicle operation, and vehicle manufacturing for different vehicle classes and powertrains.

Project Scoring



Because of late reviewer withdrawals and conflict of interest notifications, the minimum number of reviewers for a complete review panel (three reviewers) was not achieved for this project. The results are included here to inform future work and reviews, but the scores for this project are not included in the subprogram average.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach adopted is well aligned with the project objective to evaluate C2G economic and environmental impacts of fuel production and vehicle technology pathways.
- The level of detail provided is excellent.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments presented this year are of great interest and allow for expanding the range of vehicles considered in the GREET model. For the GHG emissions, it is not clear whether wheels and tires have been included, but they should be. It is expected to see different values of GHG emissions from tires, depending on the weight and the type of energy used.
- This project appears to bring multiple DOE goals together for a unified project, which could have very interesting future implications.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- The project is a great opportunity and example of multiple types of collaborative work between different parts of DOE. Contract management should allow these types of collaborations.
- The level of collaboration appears correct for this project.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The usage of GREET has a significant impact in the choice of transportation from an economic and environmental point of view and for the level of potential subsidies. It is thus important to develop a transparent and reliable tool.
- It may be interesting to observe how deployment and actual C2G impacts take hold as state mandates for Advanced Clean Fleet regulations are implemented.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The project should consider drayage and drayage-type trucks and how those operations, duty cycles, and configurations may be different from other Class 8 long-haul or box trucks. The project should also look at zero-emissions transportation refrigeration units and any sort of parasitic or related loads associated with transport refrigeration unit trucks, trailers, and containerized trucks.
- The future work corresponds to the need to evaluate the total cost of ownership, which is usually the main decision driver.

Project strengths:

- GREET is a tool that has been developed over many years with many users. It appears quite robust and is continuously improved upon with these kinds of projects.
- The project has a strong level of detail and consideration of the types of vehicles involved.

Project weaknesses:

- The project should consider drayage and drayage-type trucks and how those operations, duty cycles, and configurations may be different from other Class 8 long-haul or box trucks.
- There are no specific weakness to mention.

Recommendations for additions/deletions to project scope:

- Regarding fuel production, a full life cycle analysis approach, including capital expenditure embodied emissions, should be developed.

Project #SA-181: Global Change Analysis Model Expansion – Hydrogen Pathways

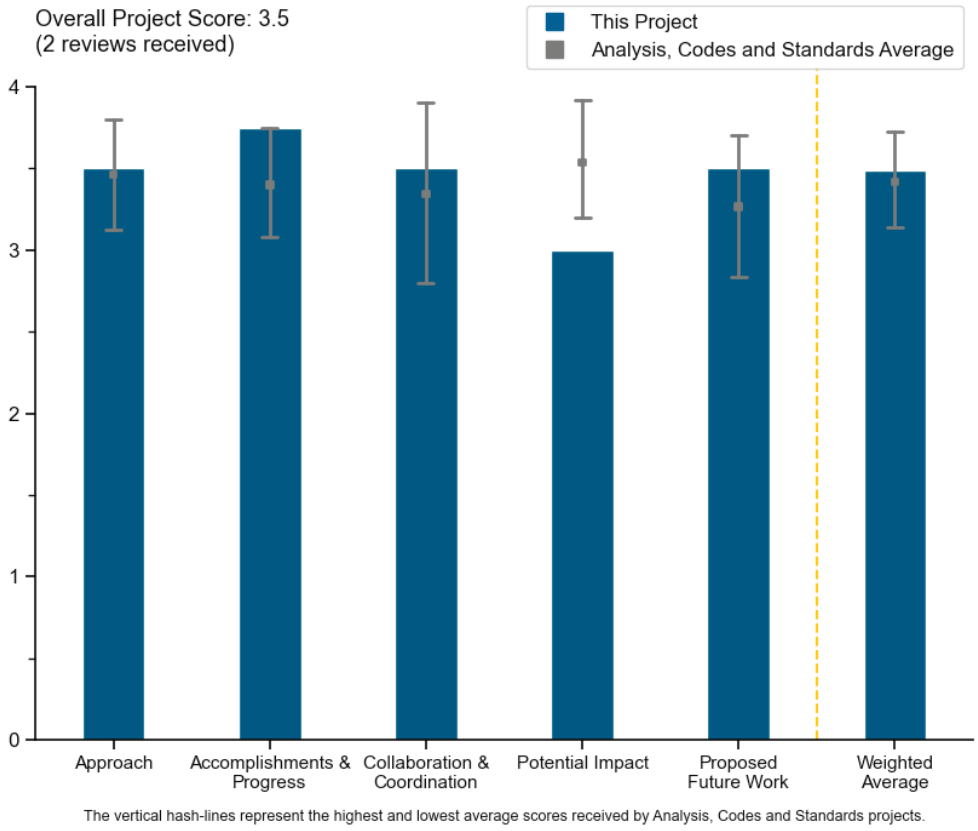
Page Kyle, Pacific Northwest National Laboratory

DOE Contract #	WBS 5.2.0.107
Start and End Dates	05/1/2021–10/31/2023
Partners/Collaborators	Argonne National Laboratory, National Renewable Energy Laboratory, University of Maryland
Barriers Addressed	• Complexity of modeling structures • Large number of assumptions to be reviewed • Consistency with ongoing Energy Efficiency and Renewable Energy research into these topics

Project Goal and Brief Summary

This project seeks to add a hydrogen module to a configuration of the Global Change Analysis Model (GCAM) in an effort to improve hydrogen representation in the tool, which allows researchers to explore the interplay of energy, agriculture, and climate systems. The work will include analyses of various hydrogen technologies to offer insight into their role and importance in facilitating system-wide emissions mitigation. By updating cost, performance, and emissions mitigation information on hydrogen production technologies, the project aims to increase hydrogen consumption in the industrial, transportation, refining, and building sectors, helping them to achieve decarbonization goals.

Project Scoring



Because of late reviewer withdrawals and conflict of interest notifications, the minimum number of reviewers for a complete review panel (three reviewers) was not achieved for this project. The results are included here to inform future work and reviews, but the scores for this project are not included in the subprogram average.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Overarching objectives and barriers are generally well defined, and the project also appears fairly feasible. Despite the complexity, model updates are straightforward in their objectives and feasibility. The one piece that seems to require further attention and clarification is the "Value of Technology" analysis of hydrogen technologies in emissions mitigation. This objective is of utmost importance and cuts to the core of the foremost challenges concerning hydrogen. It is difficult to see from the materials offered how this analysis has been conducted and how identified strengths and weaknesses were laid bare by the test case.
- The project has a good approach for updating hydrogen in GCAM, which has long been needed.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and DOE goals.

- The project update makes a significant leap in the development and contemplation of hydrogen in GCAM/MiniCAM.
- There appears to be good progress on expanding hydrogen end uses, production, and transmission and distribution (T&D) options and incorporating updates in the public model version.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- Collaboration is necessary for this type of model development, and it is great that the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) team at Argonne National Laboratory and the National Renewable Energy Laboratory were included, and hopefully a sustainable pipeline for adding updates was established for implementing technology changes.
- Collaboration lacks sufficient information to provide a fine-grained response. However, based on the list of partners, there appears to be solid collaboration and coordination with academic and other DOE labs.

Question 4: Potential impact

This project was rated **3.0** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Considering the use of GCAM in Intergovernmental Panel on Climate Change reports and high-profile climate studies, including the U.S. Long-Term Strategy, the project's effort has significant importance in bolstering the evaluation of hydrogen in supporting U.S. and global climate goals and informing the Hydrogen Program and DOE research, development, and demonstration (RD&D) goals. However, the "Value of Technology" analysis will be a key component in determining the effectiveness of this effort in supporting DOE goals to target hydrogen deployment in high-value applications where it does not compete with more efficient solutions. There is little information on this analysis as of now, which makes it challenging to evaluate the degree to which this project supports DOE hydrogen programs and goals.
- The potential impact is difficult to gauge, as GCAM is extremely complicated and there are very few consumers who understand the specific nuances within the model. Ideally, there was contemplation and clear justification for how the baseline scenario was modeled with uncertainty and to highlight what or how parameters could be changed to reflect different baselines or specific model runs.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The categories identified as future work are sensible, notably the addition of hydrogen emissions and their greenhouse gas (GHG) impacts. This is a key shortcoming in current models that may lead to major climate-damaging misfires in hydrogen deployment. That said, there appear to be two key missing categories:

  - Continuous refresh of the techno-economics of hydrogen end uses, including compared with clean energy alternatives. It is critical that GCAM remain at the frontier of hydrogen analyses by reflecting advancement in clean energy solutions to keep supporting the most cost-efficient pathways to net-zero.
  - A more fine-grained representation of hydrogen production pathways, notably various operational frameworks for electrolytic hydrogen. Those include variability of operations with renewable electricity availability and baseload, or close to baseload, operations.

  Those issues are the core of the 45V clean hydrogen debate and will remain key considerations in determining the highest-value proposition of hydrogen deployment for grid and economy-wide decarbonization.
- The proposed future work is important to capture and should be implemented soon and updated as the science of the radiative impacts of hydrogen are developed.

Project strengths:

- This is a project with utmost importance, considering the widespread use of GCAM in high-stakes climate and technology modeling, as well as the substantial interest in hydrogen as a climate solution. The expansion of hydrogen end uses and T&D technologies appears to be in the right direction, and plans to incorporate hydrogen emissions and their GHG impacts would position GCAM to be at the cutting edge of hydrogen modeling.
- The project's strengths include interaction with other DOE research, as well as updates to the model and contemplation of the modern hydrogen sector, hydrogen production types, uses, etc.

Project weaknesses:

- The "Value of Technology" analysis will be a key indicator of this project's effectiveness in supporting a fine-grained examination of hydrogen's highest value proposition for decarbonization. The project provides little information in the materials presented on this piece, which poses some difficulty in determining the project's value. Furthermore, it is key that in future work the techno-economics of hydrogen production and end-use technologies, as well as those of alternative clean energy solutions (e.g., direct electrification), be periodically updated to capture the continuously evolving nature of climate solutions. This is necessary to ensure that DOE's Hydrogen Program and RD&D programs writ large support the most cost-efficient decarbonization pathways and avoid costly detours.
- The project has no real interactions with the conventional hydrogen market of petroleum refining or chemical production, as well as the more discrete impacts on renewable diesel or electro-fuel production. There could be important impacts as these technologies develop or if there are significant differences in the crude slates, which could significantly alter conventional hydrogen demand. Also, when hydrogen is used for the vehicles distributing the hydrogen to stations should be contemplated.

Recommendations for additions/deletions to project scope:

- The project should provide a periodic update of the techno-economics of hydrogen production and end-use technologies, as well as those of alternative clean energy solutions (e.g., direct electrification), to capture the continuously evolving nature of climate solutions. The project should include a more fine-grained representation of hydrogen production pathways, notably various operational frameworks for electrolytic hydrogen. Those include variability of operations with renewable electricity availability and baseload, or close to baseload, operations. The project also has an opportunity for public comment on the upcoming paper on the value of hydrogen technology in emissions mitigation.
- The project should have better interaction for renewable diesel production, especially in fossil fuel refining, considering its outsized demand.

Project #SA-186: Updates to National Energy Modeling Systems to Include Hydrogen Module

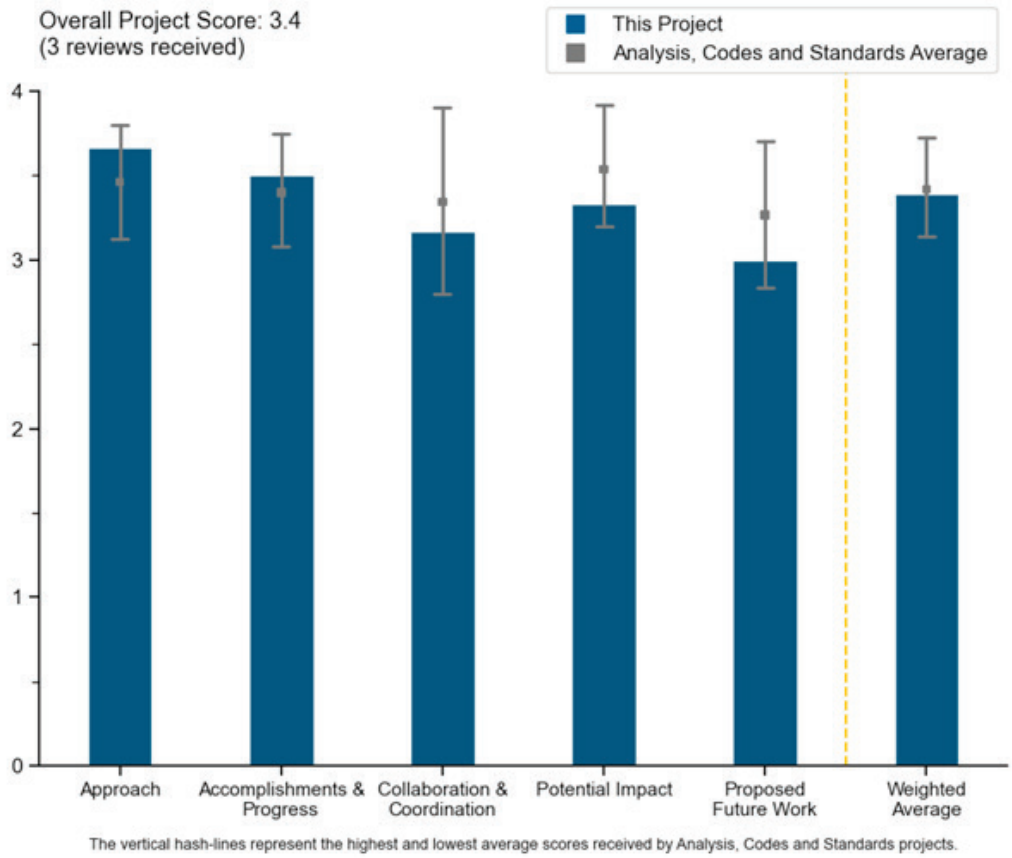
Michael Schaal, OnLocation, Inc.

DOE Contract #	38574
Start and End Dates	4/1/2022–12/31/2022
Partners/Collaborators	Office of Fossil Energy and Carbon Management, U.S. Energy Information Administration
Barriers Addressed	• Broad scope of changes needed across many sectors of the model

Project Goal and Brief Summary

This project aims to enhance the representation of hydrogen production, transportation, and storage in the National Energy Modeling System (NEMS). The project will add additional hydrogen demand representations to NEMS and increase the range of technology trade-offs available in low-carbon scenarios using NEMS. This project will review how existing U.S. Energy Information Administration (EIA) cases result in changes in the projection of future hydrogen supply and demand within an integrated area of the U.S. energy economy. The work will contribute to an understanding of which policies and technological advancements result in differing levels of hydrogen production and consumption.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The overall approach using the Advanced Interactive Multidimensional Modeling System (AIMMS) seems good. The addition of different modules for multiple uses of hydrogen is also good. However, the project may need to include some work around the hydrogen capacity expansion needed to support these industries.
- Project objectives are clearly defined. The progress on implementing a hydrogen market module and expanding the range of hydrogen end uses across sectors furthers the goal of enhancing hydrogen's representation in NEMS.
- Adding hydrogen to NEMS makes sense and could provide some interesting results or expose modeling constraints.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The project appears to contemplate the interactions of hydrogen throughout the economy and is working well to combine equities throughout DOE for examining how hydrogen can contemplate many programs.
- The project is making excellent progress toward the stated goals.
- While progress concerning incorporating a hydrogen market module (HMM) and expanding hydrogen sectoral end uses appears to be robust, it is difficult to determine how robust assumptions and model structures are from the materials offered for review. However, the categories implemented are sound and offer solid foundations for periodic improvements.

Question 3: Collaboration and coordination

This project was rated **3.2** for its engagement with and coordination of project partners and interaction with other entities.

- The project has great collaboration with national laboratories and is jointly funded by several offices. The project needs to make sure to include original equipment manufacturers for each sector that is modeled to ensure that the latest and greatest performance projections of hydrogen use are included. There are also several other significant economy-wide modeling efforts, such as from the Electric Power Research Institute (EPRI) Low-Carbon Resources Initiative expanding the EPRI Regen model, with which the project should collaborate.
- The reviewer does not have sufficient information about collaboration and coordination to provide a fine-grained response. However, based on the list of partners, there appears to be solid collaboration and coordination with federal agencies (EIA) and DOE programs. There seems to be missing collaboration with non-government entities, notably academics. DOE should encourage OnLocation to extend review and input opportunities to non-government entities, especially as NEMS is widely used by a diverse set of stakeholders, including non-governmental organizations and the private sector.
- The project is a research collaboration for many offices at DOE, and rightfully so.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward goals and objectives.

- Considering the central use of NEMS in government and non-government energy projections, in addition to its unique ability to endogenously assess the impact of various policies on hydrogen deployment trends, this effort has significant importance in bolstering the evaluation of hydrogen in supporting U.S. and global climate goals and in informing the Hydrogen Program and DOE research, development, and demonstration (RD&D) goals. However, absent thorough test cases where the model updates are demonstrated to enable an examination of the techno-economics of hydrogen relative to other clean energy solutions, it is difficult to assess the extent of the project's value. A thorough techno-economic comparison

across clean energy solutions, and an endogenous evaluation of their merits in supporting climate goals, will be critical in determining the effectiveness of this effort in supporting DOE goals to target hydrogen deployment in high-value applications where it does not compete with more efficient solutions. There is little information on those capabilities in materials offered for review, which makes it challenging to evaluate the degree to which this project supports DOE hydrogen programs and goals.

- The project is conducting highly impactful work that undergirds strategy decisions for a variety of stakeholders.
- The impact is difficult to judge because few consumers fully understand the complexity of NEMS and, in particular, specific modules. The hope is that there is enough thought into the base cases and uncertainty bounds to help more inexperienced consumers (say, at EIA) take something useful from this tool.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The plan to include granular temporal pricing in the representation of electrolysis is very sound and should be highly encouraged, as this will be a key factor in determining the economics of electrolysis and its interaction with the grid and broader economy. This issue relates to the core of the 45V clean hydrogen debate and will remain a key consideration in determining the highest-value proposition of hydrogen deployment for grid and economy-wide decarbonization. OnLocation should be encouraged to periodically update the techno-economics of hydrogen production and end-use technologies, as well as those of alternative clean energy solutions (e.g., direct electrification), to capture the continuously evolving nature of climate solutions. This is necessary to ensure that DOE's Hydrogen Program—and RD&D programs writ large—supports the most cost-efficient decarbonization pathways and avoids costly detours. OnLocation should also be encouraged to include estimates of hydrogen emissions linked to various production, transport, storage, and end-use options. The climate impact of hydrogen emissions is a key component to ensure that we do not misfire with DOE and private hydrogen investments and slow down climate progress.
- Proposed future work was not covered in the presentation; however, it seems that adding competition between sectors and the development of more modules would be future work.

Project strengths:

- NEMS brings a unique ability to endogenously examine the techno-economics of various clean energy solutions and policy impacts on technology deployment, and together with the substantial interest in hydrogen as a climate solution, that ability bolsters this project's importance and value. The HMM and added end uses appear to be in the right direction, and plans to incorporate granular temporal electricity pricing would support a fine-grained and robust evaluation of the interactions of electrolysis with the grid and broader economy. Additionally, the HMM would enable a much more robust examination of its optimal value for economy-wide decarbonization.
- The project offers explicit hydrogen supply and demand scenarios, contemplation of many hydrogen technologies, and interactions between parts of DOE to integrate complicated technologies into NEMS.
- The project has a comprehensive approach with multiple end uses.

Project weaknesses:

- Test cases assessing the ability of the enhanced model to robustly compare across clean energy solutions on the basis of techno-economics will be a key indicator of this project's effectiveness in supporting a fine-grained examination of hydrogen's highest-value proposition for decarbonization. There is little information in the materials presented on this piece, which poses some difficulty in determining the project's value. Furthermore, it is absolutely key that in future work, the techno-economics of hydrogen production and end-use technologies, as well as those of alternative clean energy solutions (e.g., direct electrification), be periodically updated to capture the continuously evolving nature of climate solutions. This is necessary to ensure that DOE's Hydrogen Program—and RD&D programs writ large—supports the most cost-efficient decarbonization pathways and avoids costly detours.

- It is not clear how much elasticity (elasticity around transient or based on delivery infrastructure) is built into the models.
- The project has no clear interaction with liquid fuel production.

Recommendations for additions/deletions to project scope:

- The project should include hydrogen emissions across the value chain and their greenhouse gas impacts. Additionally, the project has an opportunity for public comment on the representative/test results of net-zero pathways examined with the enhanced model. A periodic update of the techno-economics of hydrogen production and end-use technologies, as well as those of alternative clean energy solutions (e.g., direct electrification), is encouraged to capture the continuously evolving nature of climate solutions.
- It would be interesting to learn whether there are interactions between the hydrogen module and the liquid fuels module as, depending on the slate of crudes for petroleum or the introduction of more biofuel or electro-fuel technologies, there could be significant differences in hydrogen demand (as liquid fuel refining is the highest consumer of hydrogen).
- The project should focus more on decisions between sectors (i.e., pinch analysis of the highest value of climate-neutral carbon) and collaboration with EPRI, etc.

Project #SCS-001: Component Failure Research and Development

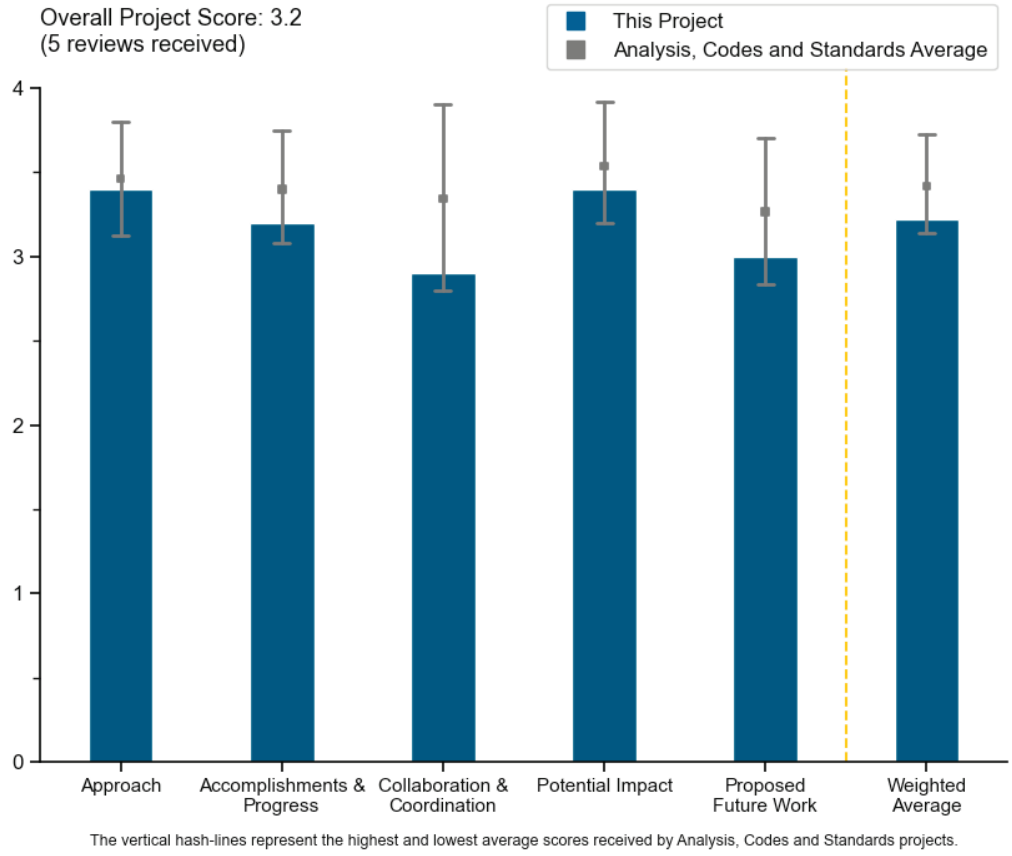
Kevin Hartmann, National Renewable Energy Laboratory

DOE Contract #	WBS 6.2.0.502
Start and End Dates	10/1/2018
Partners/Collaborators	University of Maryland, A.V. Tchouvelev & Associates Inc.
Barriers Addressed	• Safety data and information: limited access and availability • Safety not always treated as a continuous process • Insufficient technical data to revise standards

Project Goal and Brief Summary

The project aims to establish a scientific basis for risk and reliability analysis in hydrogen systems by integrating data collection, model development, and stakeholder engagement. To achieve this, the project focuses on deploying the Hydrogen Component Reliability Database (HyCReD) to track hydrogen-specific component failure rates and failure modes, understand leak behavior and size for different components and failure modes, and introduce new models and data into quantitative risk assessment (QRA) and prognostics and health management (PHM) for hydrogen systems. The project seeks to improve the reliability, safety, and cost-effectiveness of hydrogen systems through reduced downtime, enhanced understanding of hazards associated with leaks, and application of new models and data in risk assessment and system maintenance.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The stated project approach does an excellent job at laying the groundwork to achieve the project deliverables. The pathway is very reasonable and sound; it includes developing a component reliability database, developing an experimental means of quantifying typical failures modes (leaks), and then devising new models to support QRA of hydrogen systems.
- The project's approach to overcome barriers in safety data is clearly being addressed by the implemented methods. The project's collaboration with the University of Maryland seems well integrated and connects well with the DOE Hydrogen Program activities.
- The project problem and goal are clearly defined and understood. The project's tool will address critical barriers in the hydrogen industry.
- The ability to assess and capture hydrogen system component reliability is relevant, and work is advancing.
- Using modeling for QRA and PHM and using the Leak Rate Quantification Apparatus (LRQA) for leak rate and Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) to assess hazards is a good approach. However, the gaps seem to be lack of failure data.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The development of the HyCReD approach is an excellent accomplishment. The principal investigators shared subsequently that the database entry process was simplified to allow for the maximum uptake of useful information while at the same time minimizing the effort from the individuals providing the information. Given the project goals, this deliverable was critical. The use of existing failure information from H2Tools was also noted and should provide some good information for the effort.
- The HyCReD tool demonstrated significant accomplishments in this Annual Merit Review. The performance indicators are well defined and demonstrated through the examples shown.
- The team successfully compiled a database with existing information. To get more input, the user-facing interface should continue to be enhanced to allow the inputting operation to be simpler. Also, the tool should allow periodic uploads of large datasets from users.
- The HyCReD database would help with lessons learned and enhancing codes and standards. However, lack of failure incidences limits the database. More outreach is needed, and one hopes that more data will become available in the future.
- The project milestones and go/no-go decision points are not specified, so it is difficult to assess details. Qualitatively, work to date is relevant and comprises progress toward the overarching project goal.

Question 3: Collaboration and coordination

This project was rated **2.9** for its engagement with and coordination of project partners and interaction with other entities.

- There is good collaboration within the project team, which includes a well-rounded group of experts from the national laboratories and subject matter experts A.V. Tchouvelev & Associates Inc., and a call was made to support the failure incident database (HyCReD), but perhaps more coordination is necessary with groups such as the Center for Hydrogen Safety and the Hydrogen Safety Panel (HSP). Perhaps a presentation to the HSP is in order for the next meeting (which is in the October timeframe in Washington, DC).
- The project has great collaboration with a university, a private institution, and a government entity (National Renewable Energy Laboratory [NREL]).
- Collaboration between NREL and the University of Maryland is noted and productive. There are some concerns about industry engagement to populate the incidents going forward that might require different collaborations for project success.

- Further coordination and collaboration are needed with hydrogen facilities and the HSP. The incidents on components could also be included in the H2Tools database so all the information is available in one place.
- The project's tool needs significantly more partner engagement and input from operating companies to be successful.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project targets a strong need within industry to support QRA, given the lack of available (credible) leak data to support such risk assessments. The project provides an excellent use case, showing how the deliverables could support the safe implementation of hydrogen enclosures. Such enclosures could be relevant beyond stationary applications and could be relevant for mobile (tube trailers and fueling stations) and onboard vehicle systems (and rail, marine, and aviation applications where enclosures may be employed).
- Much of the existing hydrogen equipment is used near the maximum limits of its design. High pressures, pressure cycling, and temperature cycling of components is a difficult use case that causes significant reliability challenges in hydrogen equipment. This issue is problematic for hydrogen station operators and for the consumer who is affected by the poor reliability of stations. The project's database has the potential to highlight challenges that are faced by many organizations in the hydrogen industry.
- The impact of the project is demonstrated through identifying failure incidents and improving safety, codes and standards to prevent the events from occurring in the future. The project's model was done for compressed natural gas (CNG) vehicles through the Clean Vehicle Education Foundation, initially, and is now maintained by NGVAmerica. The project's database has been a good resource for safety standards development for CNG vehicles.
- This project has great potential to advance progress in obtaining very important data to greater reliability and in meeting DOE goals.
- The work is relevant and can help address DOE objectives. Solving the external engagement challenge will be critical to scaling up real-world impact.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- Collaboration with HSP, NREL, and hydrogen facilities to validate HyCReD and determine leak hazards is important. Also, quantification of the effects of hydrogen leaks within enclosures would be good for standards development. U.S. regulations on this matter may also need to be considered (https://www.reginfo.gov/public/do/eAgendaViewRule?pubId=202304&RIN=2127-AM40).
- Making the database able to be used by all is a critical next step for the project and seems feasible.
- The plan for future work is logical and relevant. More future focus on external stakeholders would be an important addition.
- The stated proposed future work activities present no issues.
- The project has no clear path forward to gather operational information. The project could engage industry organizations to introduce the tool and gain buy-in from the management of operating companies. Also, equipment standards organizations (such as the CSA Group) may be interested in supporting a tool that monitors performance of components during operation.

Project strengths:

- The project is well stocked with subject matter experts and is well organized in its approach to achieving the mission. The development of the HyCReD database is well executed, and the ensuing utility will support industry objectives.
- Hydrogen equipment has significant reliability challenges. The project's database will be a valuable tool for combining the influence of the entire industry to identify weaknesses in equipment reliability and performance and will encourage improvements in design.

- Validated tools such as HyRAM+ are already available for evaluating hazards from component failure. HyCReD could be a repository of component failure incidents that could help manufacturers and improvements to safety standards.
- The project uses a scientific basis for risk and reliability analysis that will significantly improve safety data.
- Viability of the concept has been validated. Good collaboration exists between partners.

Project weaknesses:

- The project has no major weaknesses. The project could engage more with industry and other organizations (CSA Group, HSP, etc.) to support HyCReD.
- Data of this kind is hard to find and clearly document. Although the project is making a great effort to do this work, it may be data-limited.
- There needs to be more coordination with hydrogen facilities and other hydrogen research communities to get component failure incidences in the field. Also, the project needs to coordinate with H2Tools to include HyCReD information so that all failure incidents are available in one place.
- The project's major weakness is the lack of industry involvement. There are several potential incentives that could be utilized for contributing to this tool, and the tool could also be mandated as a part of funding opportunities. Industry involvement is key for success of the tool.
- The potential for limited impact at scale without more effective modes of incident input should be considered and addressed.

Recommendations for additions/deletions to project scope:

- The project proponents are strongly urged to explore expanding the project scope to include mobile applications (tube trailers and mobile fuelers) and onboard vehicle systems (heavy trucks, trains, ships, and aircraft) in which QRA forms an integral part of the hazard and risk assessment of the fuel cell electric vehicle system. For vehicles, for example, the process is embodied in design failure mode and effects analysis and functional safety assessments per International Organization for Standardization (ISO) 26262. This project could support an improvement implementation of these assessments.
- One issue obtaining a good deal of attention is blending hydrogen into natural gas supplies in Canada, Europe, and elsewhere. The project's work might not lend itself to assessing elevated risks associated with introducing hydrogen into distribution and equipment designed only for natural gas, but it would certainly increase the relevance of the work.
- The project could evaluate how the Offshore and Onshore Reliability Data (OREDA) databank was structured to gather operational information.

Project #SCS-005: Research and Development for Safety, Codes and Standards: Material and Component Compatibility

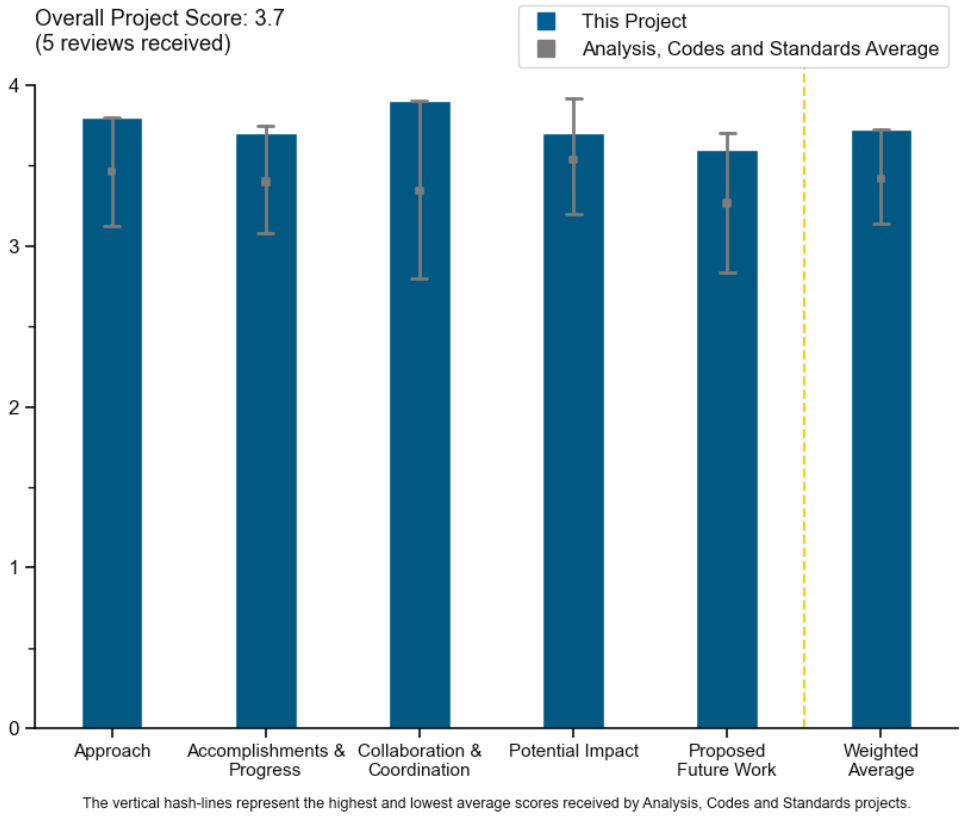
Joe Ronevich, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	CSA Group, American Society of Mechanical Engineers (ASME), SAE International, International Organization for Standardization (ISO), FIBA Technologies, Inc., Tenaris Dalmine S.P.A., JSW Steel, Swagelok Company, NASA White Sands Test Facility, Hexagon Digital Wave, Luna Innovations Inc., National Institute of Advanced Industrial Science and Technology (AIST) – Tsukaba, International Institute for Carbon-Neutral Energy Research (I2CNER), Materialprüfungsanstalt (MPA) Stuttgart, Korea Research Institute of Standards and Science (KRISS)
Barriers Addressed	• Safety data and information: limited access and availability • Consistent regulations, codes, and standards needed to enable national and international markets • Insufficient technical data to revise standards

Project Goal and Brief Summary

The main goals of this project are to enable technology deployment by providing science-based resources for standards and hydrogen component development and to participate directly in formulating standards. The project will (1) develop and maintain a materials property database and identify materials property data gaps, (2) develop more efficient and reliable materials test methods in standards, (3) develop design and safety qualification standards for components and materials testing standards, and (4) execute materials testing to address targeted data gaps in standards and critical technology development.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- As the project has progressed, different aspects of testing continue to be investigated. The current approaches of examining fatigue/fracture at different locations and orientations within "thick-walled" vessels is not fully understood. Similarly, it is not well understood if a correction factor should be applied to previous data for low-pressure applications (rather than extrapolation from worse-case data determined from high-pressure tests). Both efforts/approaches demonstrate this project is continuing to make progress and refine its previous work.
- Infrastructure advancement for hydrogen transport is a needed element to support climate goals. The project's approach addresses extending use of pipeline materials for gaseous hydrogen transmission as specified in ASME B31.12 code cases. The work advances the technical basis for fatigue design rules and test methodologies.
- The project approach is understandable and can easily be explained to those of us for whom materials testing is not a core expertise. The project also has the very practical objective of informing standards that will simplify the testing of equipment in hydrogen installations (the ASME code case for pipe evaluation).
- The project's goals are clearly identified, and the barriers have been addressed. Additionally, the project is sufficiently designed and easy to follow.
- Both general and specific testing approaches are well described and aligned with project goals.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and DOE goals.

- The project has made valuable contributions. It reduces uncertainty about the uniformity of fatigue and fracture properties and shows that fatigue and fracture in thick-walled pressure vessels can be independent of orientation and location. The project also provides a technical basis for code modification to allow pressure correction of fatigue design curves. The project demonstrates simple relationships to reduce testing burden for structural integrity assessment of hydrogen pipelines. In addition, test methods have been developed to characterize hydrogen effects on component fatigue.
- As a result of the refinement described in Question 2, both approaches yielded accomplishments, and the team's progress answered the nuances; fatigue and fracture do not depend on orientation of the crack within the thick wall of a vessel, and there is a correction factor that can be applied depending on stress intensity factor. This project has performed well.
- Although it has been in process for a very long time, the project has produced some clear scientific basis for understanding fatigue crack growth behavior in metals used for piping and components.
- Multiple slides demonstrate specific technical accomplishments and real-world impacts (application). Data charts are excellently annotated to point out data conclusions.
- There appears to be continual progress, proven by the status given on the project's milestones; however, this reviewer has little knowledge of material and component compatibility and cannot confidently state whether the project has adequately demonstrated progress toward addressing critical barriers to achieving DOE goals.

Question 3: Collaboration and coordination

This project was rated **3.9** for its engagement with and coordination of project partners and interaction with other entities.

- Given its longevity, the project has a breadth of collaborations/partnerships in various areas within the industry (e.g., standards development organization [SDOs], industry, and even international engagement). Engagement with international entities is crucial since international harmonization is a challenging yet vital endeavor.

- Collaboration is noted for research peers, code experts, and industrial groups. Data is well distributed and peer-reviewed. This effort demonstrates the outstanding quality and value of Sandia National Laboratories and its personnel.
- The project has good partnerships. The project has a good mix of industry, government (domestic and foreign), academia, and standards organizations.
- The range of SDOs, industry, and research partners is impressive and lends much credibility to the work.
- The project's collaboration and coordination are conducted with the right SDOs, industry partners, and international institutions.

Question 4: Potential impact

This project was rated **3.7** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project is crucial for the advancement and commercialization of hydrogen technologies. Also, engagement with international entities is crucial since international harmonization is a challenging yet vital endeavor. Such harmonization will significantly advance progress toward DOE research, development, and demonstration goals.
- The project relevance is clearly defined in slide 4 but could be amplified to qualify how this project fits into the overall high-level DOE Hydrogen Program goals and further advancement toward successful industrial hydrogen applications.
- The impact of the project will ensure that codes and standards are supported by the best information and made available to industry in a timely fashion to support development. In turn, the work is coordinated with international partners.
- The project would make testing/certification of materials in hydrogen service more clear-cut, quicker, and less costly and has great implications for industry.
- The team's work is leading the way on material embrittlement data.

Question 5: Proposed future work

This project was rated **3.6** for effective and logical planning.

- The future work described is useful, but it is unclear how much of it can be accomplished if the (20-year) project ends in September 2023.
- The co-principal investigators and the team are clearly building on past progress/achievements and plan to further develop their research.
- The project continues to refine and update existing methodologies of understanding material issues. The proposed future tasks are equally worthwhile and needed.
- The project's presentation clearly identifies barriers and qualifies them against the project scope to be completed and practical additional scope in the future.
- The proposed future work will continue to address barriers.

Project strengths:

- The project benefits from consistent and extremely knowledgeable investigative personnel who are well embedded in codes and standards organizations, as well as industrial groups. Project data will be extremely valuable in furthering industrial design and future codes and standards. The summary on slide 18 is outstanding in providing a high-level project description and results.
- The project uses a methodical approach to capture important learnings and has disseminated those learnings widely, particularly into ASME.
- This project continues to address industry and standards issues with focused effort by top researchers.
- The project is leading the world in gathering hydrogen embrittlement data for various metals.
- The project has an excellent history and diverse partnerships.

Project weaknesses:

- The project slides were missing safety planning and issues and mitigation. Since the poster slide presentation has key administrative and project data, an actual developed poster would have been more communicative at the poster session, rather than simply printing out the slides and mounting them on the poster wall. Diagrams and photographs of test process flow and equipment would have been more valuable. The project's key charts could be reproduced with several high-level bullets explaining impacts to industry and codes and standards.
- The project should expand upon/provide more information on the informational resources mentioned in the "Proposed Future Work" section and its plan to disseminate information on materials and component compatibility to the industry and the public.
- The project has taken a very long time to complete.

Recommendations for additions/deletions to project scope:

- It is recommended that the project consider evaluation and interface of past incidents involving piping and equipment fatigue failures in hydrogen service. Generalized data is readily available on H2tools.org and through the Center for Hydrogen Safety. The examples, along with other industry/working group input (e.g., NASA), may identify key incidents that could qualify future direction of testing scope and prioritize effort.
- The scope is defined primarily to advance hydrogen pipeline development, and this is being adequately addressed. However, expansion of the scope to include the evaluation of bulk metallic glass materials for use in hydrogen components could further serve hydrogen infrastructure advancement.
- Most of the data gathered to date is for thick-walled vessels. While this benefits large storage and gas line installations/industry, many newer applications use thin walls and tubing of various thicknesses (not typically considered thick-walled). Perhaps some future work could be to start determining whether these thin-walled systems demonstrate any different results from hydrogen exposure. Furthermore, this project could develop guidance for how to apply the materials data gathered to thin-walled systems.
- The project should probably look at the proposed future work and see whether there is a focused future project that can be defined from that. Then, the project team could close out this project and start a new one.
- The project should proceed and continue with its planned future work.

Project #SCS-010: Research and Development for Safety, Codes and Standards: Hydrogen Behavior

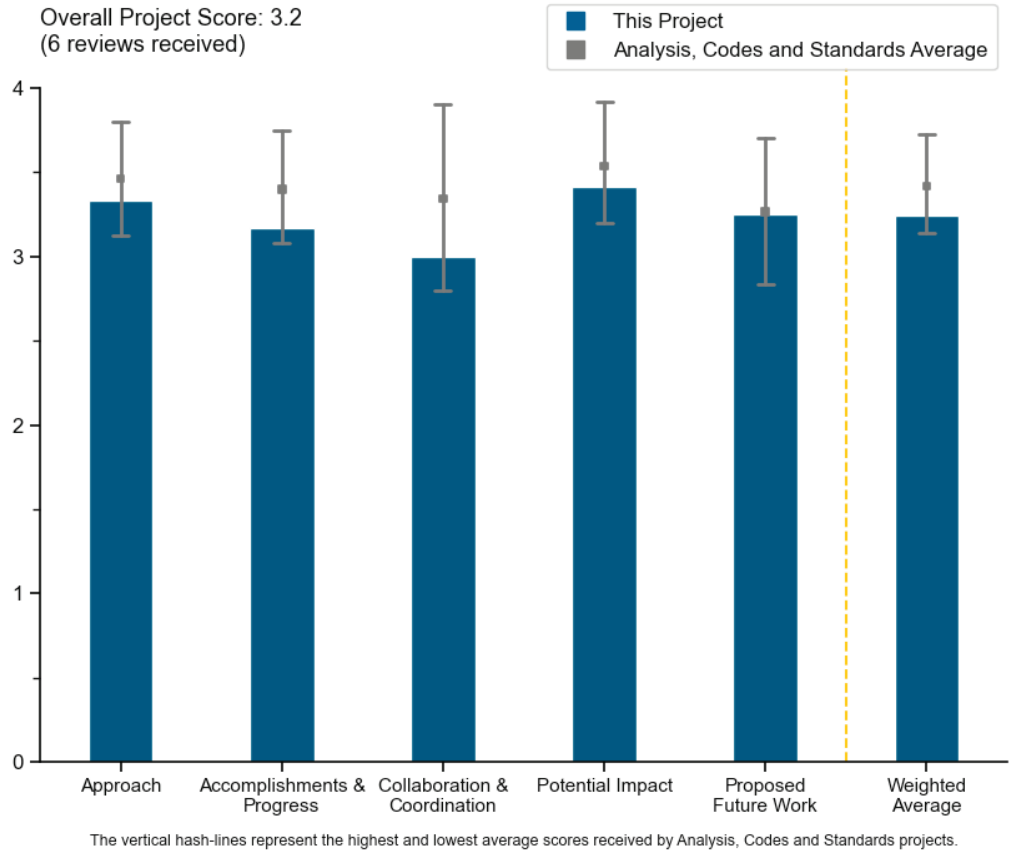
Ethan Hecht, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	National Renewable Energy Laboratory, Chart Industries, Inc., Air Products, National Fire Protection Association (NFPA) 2 Technical Code Committee
Barriers Addressed	• Conduct research to generate the valid scientific bases needed to define requirements in developing regulations, codes and standards • Enable the safe deployment of new hydrogen technologies

Project Goal and Brief Summary

Sandia National Laboratories is working to address the lack of safety data and technical information relevant to the development of safety, codes and standards (SCS) by (1) providing a science and engineering basis for understanding the release, dispersion, ignition, and combustion behavior of hydrogen across its range of use (i.e., high-pressure and cryogenic applications); (2) generating data to address targeted gaps in the understanding of hydrogen behavior physics (and modeling); and (3) developing and validating scientific models to facilitate quantitative risk assessment of hydrogen systems and enable revision of regulations, codes, and standards (RCS) to accelerate permitting of hydrogen installations. The project began in 2003.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Proactive RCS efforts were initially (1990s) stymied by insufficient physical data and models to support safety codes. DOE has, over the previous years, funded engineering studies to remedy this issue and continues to address needs. The efforts have yielded good results for safe handling of pure gaseous hydrogen media. Now, attention is logically focused on the technically more challenging work of liquid hydrogen media and a new topic of focus, hydrogen–methane blends. The current focus of RCS efforts is well justified. The complaint that more could have been done sooner is tempered by noting that, in years past, reasonable focus was applied at the time, given the technical challenges and the funding available.
- This project is part of a coordinated activity with two other projects that feed each other and complement each other to facilitate deployment of technologies. It is clear that this work is essential to address three major areas where further development is needed. It is clear how it fits into the bigger SCS picture.
- This project is timely and has industry support. The approach to conduct experiments needed to validate numerical models and to impact the codes and standards development process is necessary as the industry moves from one form of hydrogen to another.
- Much work is needed to model liquid hydrogen applications/spills/releases. This project has this goal in its sights and continues to make progress in this and many other areas.
- The work is relevant and demonstrates a practically driven approach to illuminating safety measures for hydrogen use.
- Overall, the project has a good approach to executing various activities with good laboratory capabilities.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The accomplishments presented include the following: the technical justification for National Fire Protection Association (NFPA) 2 (Hydrogen Technologies Code) liquid hydrogen (LH2) bulk storage setback distances has been formally documented, a generalized tunnel safety analysis has been developed, a physics model for the Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) is under development, a quantitative risk assessment (QRA) sensitivity analysis has been conducted for factors that drive distances to risk metrics, and a Python software backend has been made available for users to add their own software processing to HyRAM+. In addition, modeling of LH2 pool behaviors in HyRAM+ is under development, and actions to address reviewer comments from the previous year are in progress. These efforts are on focus to address barriers to RCS implementation.
- This project is making progress with the data (and funding) available. During the Annual Merit Review presentation, it was discussed that the model was validated with only a single data set. More data sets (which the team is working toward) will greatly improve the confidence in the model results.
- Specific milestones and go/no-go decision points are not identified, so it is difficult to assess progress toward specific goals in detail. Qualitatively, significant progress has been demonstrated on relevant technical issues, including the revisions to the 2023 edition of NFPA 2. Recognition and awards for the project are noted and demonstrate accomplishments.
- Several accomplishments are outlined in the presentation, and it seems like the project is successful. A few of them seem to need more data to be of additional value to the community. Nonetheless, significant progress is demonstrated.
- Modification to the NFPA 2 requirements is a valuable accomplishment.
- Outside of the LH2 activities to support the 2023 NFPA 2 publication, it is not clear how the additional activities support DOE goals.

Question 3: Collaboration and coordination

This project was rated **3.0** for its engagement with and coordination of project partners and interaction with other entities.

- The participating organizations includes adequate collaborations with national laboratories, industry, and national and international standards organizations.
- The current partners (National Renewable Energy Laboratory [NREL], Chart Industries, Inc., Air Products, and the NFPA) are great. There are also many other LH2 users whose data could be beneficial for this project; the team could reach out to them to get more data (NASA, U.S. Department of Defense, other industry LH2 users and producers, etc.).
- There are decent collaborations, but the reach is actually much broader and was not brought out within the presentation.
- There is strong coordination with key industry partners. With the growing interest in large-scale deployment, however, these types of projects can benefit from greater industry involvement.
- Collaboration through the NFPA 2 committee is indicated. However, this seems to be an area where the project could improve and involve additional institutions.
- Collaboration with NREL is noted. Revising codes and standards has been accomplished and requires effective collaboration with external stakeholders and committees.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project has a very high potential impact toward meeting DOE research, development and demonstration goals and objectives. The LH2 modeling and separation distance determination is very much needed for siting LH2 systems. The results from this modeling/validation will enable this team to work closely with SCS bodies to update LH2 separation distances for improved station siting.
- The existing code requirements are restrictive and could translate into higher costs. With the growing interest in decarbonization of various industries, this project will have direct impact on specific code requirements and provide supporting data for a smooth rollout of small- and large-scale hydrogen infrastructure.
- The impact of the work extends NFPA 2 standards on bulk LH2 setbacks and improves HyRAM+ modeling capabilities. Progress has occurred on analysis of hydrogen hazards due to hydrogen vehicles in tunnels, LH2 pool and gas blend modeling within HyRAM+, and sensitivity modeling within HyRAM+.
- The work on hydrogen blending with natural gas is highly relevant and can be impactful going forward as the physical phenomena are understood and brought forward into hazard mitigation methods.
- The fundamental data being generated by this project is making a large impact in advancing the understanding of hydrogen behavior and will be useful in so many applications.
- It is unclear where the impact will end up with regard to the LH2 pooling and blending activities.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- It is important to advance the HyRAM+ capabilities for LH2 pool modeling, QRA specifications for green-hydrogen–natural-gas blends, and a generalized tunnel safety analysis framework.
- This project has a clear focus on future work; there is an undeniable need for real-world data to improve the existing models.
- The proposed future work is essential to improving this model validation.
- Future work seems effectively planned and will continue to be of extreme value.
- The proposed future work is reasoned and relevant.
- It was hard to understand how the proposed future work will be utilized and continue to support the SCS subprogram and broader hydrogen community.

Project strengths:

- One strength is the persistent effort to address RCS needs with state-of-the-art engineering research. A second is the continued follow-through to incorporate the findings in HyRAM+. The presentations identify where in-depth reporting and analysis can be found.
- This fundamental research will enable and answer many questions regarding hydrogen behavior. The scope and approach are being used to investigate several areas of interest and need in the community.
- Project strengths include a track record of successful scientific progress, delivery of practical results, tangible progress in the form of code revisions, and relevant topics including hydrogen blending.
- The results produced by this project benefit NFPA 2 by improving the siting of LH2 applications.
- This project is timely and will be critical to the hydrogen infrastructure rollout.
- The project has strong capabilities.

Project weaknesses:

- Correlation of research to how the results will impact the hydrogen community was lacking. With the integration of risk, the coordination and collaboration activities are much broader and stronger than presented. Also, it was hard to understand the relevance of the project activities outside of the NFPA 2 LH2 support.
- More defined plans to engage more broadly with external partners might provide extended benefits.
- This project could benefit from expanding the network of collaborators.
- Real-world data is needed to best validate the models.
- Additional data for validation of models is needed.

Recommendations for additions/deletions to project scope:

- The only recommendation is to continue to pursue the research agenda and collaboration with RCS stakeholders. One technical recommendation is for pooling research to develop a metric that can identify when pooling behavior might pose a hazard of condensing and entraining air products with LH2 (the persistent LH2 drip scenario).
- As the team moves into the test phase, it would be wise to develop a process for tracking any leaks or issues to then be able to feed that data on component failures into HyRAM+.
- Continuing to work with the code development organizations and expanding on the validation efforts are both necessary.
- The proposed future work is an appropriate template for expansions.

Project #SCS-011: Hydrogen Quantitative Risk Assessment

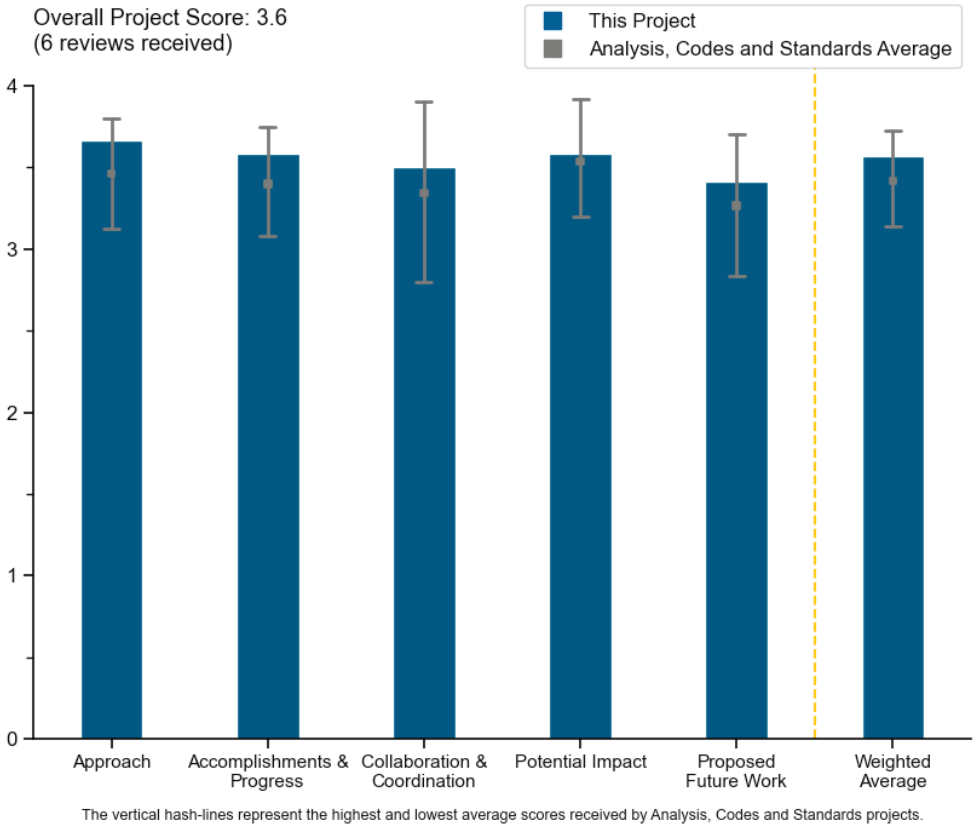
Ben Schroeder, Sandia National Laboratories

DOE Contract #	WBS 6.2.0.801
Start and End Dates	10/1/2003
Partners/Collaborators	Westinghouse Air Brake Technologies Corporation (Wabtec), Chart Industries, Inc., Hexagon AB, Hexagon Digital Wave, Air Products, Pacific Northwest National Laboratory, National Renewable Energy Laboratory, Argonne National Laboratory, HySafe, Sims Industries, National Fire Protection Association (NFPA) 2/55, U.S. Department of Transportation Tunnel Jurisdictions, International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), International Electrotechnical Commission (IEC), International Organization for Standardization (ISO), International Energy Agency (IEA)
Barriers Addressed	• Risk-informed codes and standards • Safe deployment of new hydrogen technologies • Harmonization of hydrogen standards

Project Goal and Brief Summary

The primary objective of this project is to provide a science and engineering basis for assessing the safety of hydrogen systems and facilitate the use of that information for revising safety regulations, codes, and standards (RCS) for emerging hydrogen technologies. Sandia National Laboratories (SNL) will develop and validate hydrogen behavior physics models to address targeted gaps in knowledge, build tools to enable industry-led codes and standards revision and safety analyses, and develop hydrogen-specific quantitative risk assessment (QRA) tools and methods to support RCS decisions and to enable a performance-based design code compliance option.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is a strong blend of experimental, analytical, and computational work. The development and dissemination of tools and scientific safety information requires this type of multi-modal approach. The approach also includes projects to develop information for RCS, with a particular focus on National Fire Protection Association (NFPA) 2 safety distances for liquid hydrogen (LH2) bulk storage, and some tunnel requirements. This direct safety, codes and standards (SCS) development is a larger portion of the work (slide 6 and several accomplishments and plans) than the approach (slide 5) indicates for SCS-011 scope. While the approach is sound, it is questionable whether this applied standards work is the best use of the national laboratories. The DOE national laboratories are world-renowned for developing scientific tools and capabilities that industry cannot develop. It seems that model and tool development and credible information dissemination are better uses of the DOE laboratories than near-term work on harmonization of standards and continued revision of safety distances.
- Given the historical loss of rationale to past codes and standards for hydrogen use, this work is critical. The development of physics-based models promulgated in application packages for developers to use is an excellent strategy for promoting the use of risk-informed analysis. The findings from this activity inform RCS work and promote harmonization with international partners.
- The project is comprehensive, from modeling to implementation, which is extremely important for the overall hydrogen industry. The use of "real-world data" is an essential part of this work and for improving the standards.
- The Hydrogen Risk Assessment Models (HyRAM) toolkit is being used by various other DOE projects. This is a great tool for QRA in hydrogen facilities, tunnels, etc.
- Promoting and enhancing modeling tools to advance codes and standards development is critical to rolling out hydrogen infrastructure and avoiding unnecessarily conservative and costly requirements.
- The overall approach and relation with the other ongoing projects are excellent and very well explained.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- Finally, there are updates to bulk liquid storage setback distance requirements. Work continues on the complicated real-world issues of hydrogen release in tunnels, with engagement with the Massachusetts Department of Transportation. A newer area of focus concerns hydrogen blends. Work to clarify what factors present the greatest risk will be helpful to developers, as will providing a means (Python) for users to perform custom work with the HyRAM software. Work on modeling LH2 pool spill behaviors will be an important addition to HyRAM and, given recent initiatives for enormous storage facilities, will be a critical safety tool.
- The work in tunnels (i.e., looking at different tunnel structures; moving to blow-down, not constant release) to make the scenarios more "realistic" is very positive and will aid in helping the authorities understand the scenarios more completely. The work in hydrogen blends, especially modeling true natural gas mixtures and hydrogen–natural-gas mixtures for HyRAM, is forward-thinking and a great use of resources.
- The Python package for simplified use by others is helpful. The progress on tunnel safety is good, and the work with Massachusetts may open the path for other states to follow.
- Considering the complex and various components of the project, the accomplishments are outstanding.
- The most notable scientific accomplishments this year are integration of new features to handle hydrogen blends, the new standalone Python package, and integration of new validated LH2 pooling models. The progress on the QRA algorithms is surprisingly limited and unbalanced, given the maturity of the physical behavior models and the amount of effort spent on the applied work. The sensitivity analysis overlooks the key aspect of risk mitigation, the system design choices. The QRA algorithms need more development. On the work to develop the tunnel safety analysis framework, the results provided are too vague to determine what progress has been made. No framework was presented; there are no details on the scenario variants

being modeled or the thermal–mechanical analysis tools being used, nor were there details on how any facet of the work has been validated.

- Direct impact on code modification, acceptance of hydrogen technologies, and reduced potential cost through developing models and numerical tools are critical to a smooth technology rollout. These efforts, however, could have more defined start and end dates where the work is closed out and new projects are started to best track the specific project progress.

Question 3: Collaboration and coordination

This project was rated **3.5** for its engagement with and coordination of project partners and interaction with other entities.

- There is ample collaboration across the industry and the standards development organizations. The input from users, which has led to changes/improvements, is useful and should be highlighted more in future presentations, demonstrating the feedback loop.
- SNL has collaborated with facilities, states, and other research organizations, and the tools they develop will be used by others for safety standard development and risk assessment.
- The demonstrated impact on NFPA 2 highlights the existing coordination and collaboration for this project. There is opportunity for more industry input and engagement, as more data is needed for further validation.
- The project has an excellent, well-rounded list of collaborators. It is unclear what support is being offered to the 40+ users of HyRAM+ (Hydrogen Plus Other Alternative Fuels Risk Assessment Models). The principal investigator indicated the team did not make systematic collection of user feedback a priority. The most recent user guide on the HyRAM website is from HyRAM 2.0.
- The project has great partnerships, but it could benefit from feedback from users.
- The collaboration and coordination appear adequate for this activity.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The impact is of utmost importance in furthering the hydrogen industry through quality safety codes and standards. SNL is an invaluable resource in this respect. The work in tunnels has involved not only public entities but private tunnel owners, helping them to understand hydrogen uses/properties, etc., which is a key first step in furthering the hydrogen economy. Unfortunately, the grassroots efforts are still very much needed, and although this is likely secondary to the planned approach, it is helpful and needed.
- This project provides a rigorous scientific and engineering basis for the assessment of risk in hydrogen systems, which informs RCS activities. The development of models for hydrogen behavior and their incorporation into HyRAM for users comprise an excellent outreach program and are important contributions.
- Developing scientific models and bringing them into a freely disseminated tool such as HyRAM+ is an excellent and high-impact way to reduce numerous DOE-identified barriers, especially the development of risk modeling tools and the need for scientific research and dissemination of scientific information to enable SCS both near- and long-term. However, direct SCS development is a larger portion of the work, and making revisions to RCS is not the long-term, high-impact work that DOE laboratories are uniquely positioned to create.
- This work has brought, and continues to bring, focus to the underlying and realistic technical requirements for codes and standards development.
- The tools are being used by other DOE programs to assess QRA. This tool would help with hydrogen infrastructure development and the use of roads, tunnels, and bridges by hydrogen vehicles.
- The project is essential to understanding risk and preventing safety issues.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- The tool needs to be enhanced for QRA of LH2 and different gas blends. Also, the work on tunnels and other safety matters regarding liquid pooling and hydrogen flames is needed.
- The work on tunnel risks and liquid pool risks (especially for large spills) must continue. Recent proposals for use of geologic storage will also require analysis.
- As the industry explores different forms of hydrogen for storage and utilization, it is good to see that the existing models are expanding to reflect those trends.
- The proposed future work is relevant and needed to progress the overall program.
- The proposed future work for this year is aggressive.
- There appear to be no specific plans for developing important aspects of the QRA, which is surprising, given the task name. QRA requires probabilistic models, logic models, failure causes, and data, in addition to consequence models. SNL has made great progress on the development and validation of the hydrogen consequence models and leak frequencies within HyRAM+. However, a large part of QRA involves development of the causal logic models, such as fault trees and cut sets, that enable QRA experts to obtain nuanced scientific insight into the causes of failure and how to prevent it. The current project appears to be well positioned to enable this, but this does not appear to be a focus of recent or future work. The QRA capabilities need to be more than consequence models. Version 5.0 of a QRA toolkit should have modifiable fault trees, at a minimum.

Project strengths:

- The entire project is a strength and is imperative to the advancement of the hydrogen economy. The credibility that SNL brings is extremely valuable.
- The project expands on previous work. Many of the recent accomplishments highlight the correlation to previous efforts. Collaboration, industry involvement, and end users are demonstrated.
- The project has well-thought-out research, with set goals and milestones, that forms a cornerstone for other DOE activities regarding the hydrogen economy.
- The project's scientific modeling capabilities are complemented by both experimental and computational experts.
- The project includes essential modeling to ensure risk assessment.
- The impact on RCS and outreach efforts is important and should continue.

Project weaknesses:

- The challenges and barriers are heavily bent toward applied analysis for near-term codes and standards needs rather than research and development. It is surprising that the capabilities of a national laboratory are doing applied, near-term work rather than being focused on further development of enabling tools for industry to do the applied analysis. The project has a lack of peer-reviewed publications. The future work does not address limitations in the QRA technique implementation in HyRAM.
- Although a good amount of work and progress showcased in this presentation is an expansion on previous work, it is important to know when to close one project to start a new one and whether those previous efforts met their respective goals.
- Validation is important, but the project's lack of data might be an issue. The collaborative approach will be key.
- It is not clear what emphasis in work is needed. It is important that funding for this work continue.
- The reviewer can identify no weaknesses.

Recommendations for additions/deletions to project scope:

- The project's work has primarily revolved around addressing risks from hydrogen behaviors and potential consequences for combustion. However, risks from materials selection in hydrogen systems is less clear from a QRA perspective. SNL does provide relevant materials data regarding embrittlement, and Pacific Northwest National Laboratory has research into the behavior of polymers exposed to hydrogen. Designers are constantly trying to find improved materials solutions, and many are not well-informed regarding hydrogen issues. This may be an area where QRA work can play a role both in clarifying risks and for outreach to users.
- The only recommendation is to highlight the user feedback and how that plays into the overall updating/ improvement of HyRAM. Otherwise, it is important to maintain a pulse on the industry to make necessary updates/improvements to the project. The fact that SNL is very involved in industry codes and standards should keep that feedback loop active.
- The project should expand user support, efforts to validate the information and models used, and data collection for leak frequencies.
- The project could benefit from broader international collaboration, such as the work on tunnels.

Project #SCS-019: Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources

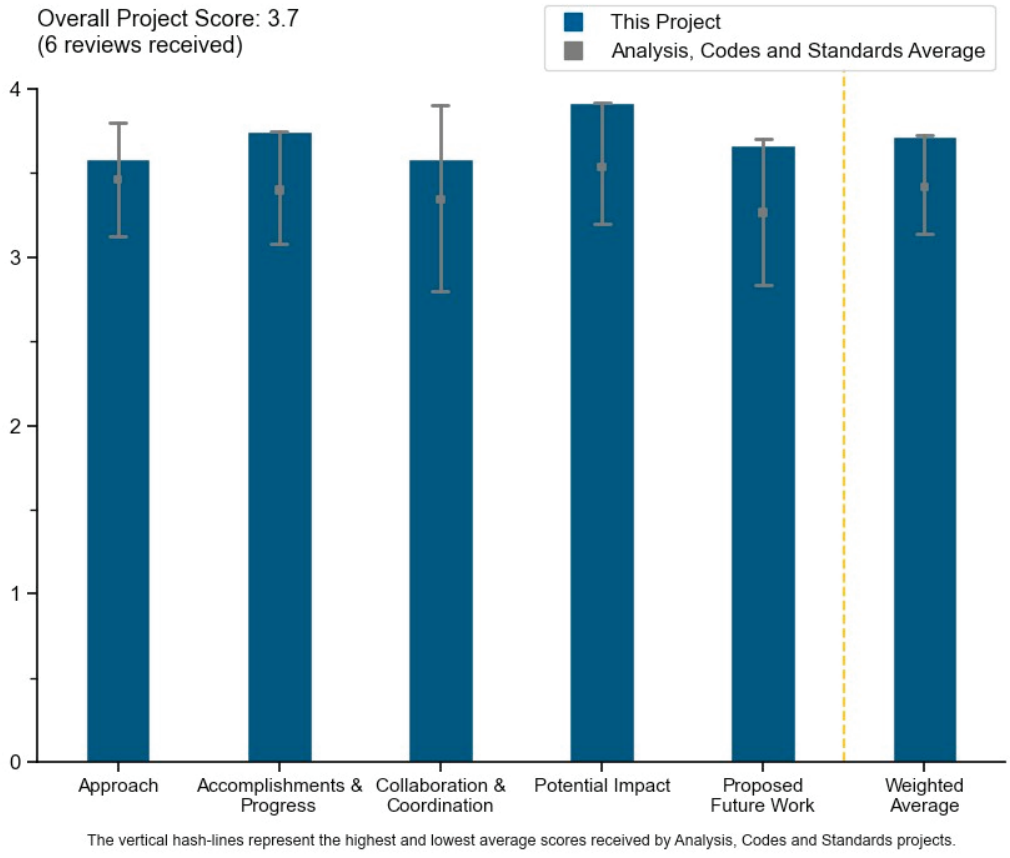
Nick Barilo, Pacific Northwest National Laboratory

DOE Contract #	WBS 6.1.0.702
Start and End Dates	3/1/2003
Partners/Collaborators	California Energy Commission, American Institute of Chemical Engineers' Center for Hydrogen Safety
Barriers Addressed	• Safety not always treated as a continuous process • Limited access to and availability of safety data and information • Lack of hydrogen knowledge by authorities having jurisdiction

Project Goal and Brief Summary

This project provides expertise and recommendations through the Hydrogen Safety Panel (HSP) and through the Hydrogen Tools Portal, H2Tools.org (H2Tools), to identify safety-related technical data gaps, best practices, and lessons learned, as well as help integrate safety planning into funded projects. Data from hydrogen incidents and near-misses is captured and added to the growing knowledge base of hydrogen experience to share with the hydrogen community, with the goal of preventing future safety events.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Congratulations are due to the project team on winning the Hydrogen and Fuel Cell Technologies Office's Safety, Codes and Standards award at the 2023 Annual Merit Review; the award is well deserved. The HSP, and now also the Center for Hydrogen Safety (CHS), are perfectly aligned to the needs of DOE and to the needs of the international hydrogen community, as witnessed by responses to the safety portals in place.
- The HSP, hydrogen safety tools, and first responder training are essential for deployment of hydrogen vehicles and other technologies. The approach of disseminating information on hydrogen to researchers and potential hydrogen facilities is important. Some of the courses and educational materials available are useful for safety standards development.
- The project has grown over the stretch of two decades, which is highlighted by the quantifiable metrics presented. The focus to promote safety is critical, and this project has grown in reach by partnering with key organizations and establishing global structure.
- With several years in the making, the project has an excellent approach to bringing hydrogen safety to the world.
- The project objectives and many critical barriers have been clearly identified and are being addressed. The project could be improved by expanding the approach regarding the two noted barriers on data. Access to and availability of the safety data and information are limited, and the project has insufficient technical data to revise standards. Fully addressing these barriers may require new approaches to obtaining data that has been difficult to obtain from industry experience.
- The barriers are clearly identified, and methods to address them are explained. However, the project might benefit from mapping against other existing ones to help gather more support. There is also a significant amount of information, as well as a number of activities, and explaining how the topics are prioritized could be useful.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and DOE goals.

- Significant measurable progress has been made, particularly with the HSP. The streamlining of the HSP review process is notable. Regarding safety knowledge tools and first responder training, one focus of the project is on the cooperative research and development agreement with the American Institute of Chemical Engineers (AIChE). Pacific Northwest National Laboratory (PNNL) transferred its first responder hydrogen safety training resources to AIChE to enable broader access to online and in-person training resources. It would be helpful to see metrics, if there are any, to measure how effective this has been. The project could consider including this in the presentation next year.
- While the initial focus was to ensure safety across all DOE-funded projects, throughout the last couple of decades, this project has expanded to become a critical part of all projects, including those outside DOE. While not mentioned in the slides, the adoption in other countries and in multiple languages highlights the success of this project.
- HSP accomplishments include various project plans, hazard analysis, training courses, an incident management guide, and incident investigation. Hydrogen Tools (H2Tools) provides lessons learned from incidences, best practices, and relevant codes and standards. These tools have been used worldwide by many. The first responder training by HSP is very useful. There are currently problems with first and second response for electric vehicles, and it looks like CHS is ahead of the game for hydrogen vehicles.
- This project continues to grow, providing outstanding accomplishments and progress toward implementing safety as a continuous process in hydrogen deployment in the environment. The addition of AIChE has proven to be a fantastic resource and is proving that in the seminars, training, and sessions it has been hosting.

- This project has accomplished outstanding metrics and established several pathways to gain know-how in hydrogen safety.
- The objectives are clear, and progress is well demonstrated.

Question 3: Collaboration and coordination

This project was rated **3.6** for its engagement with and coordination of project partners and interaction with other entities.

- By nature, this project maintains excellent collaboration and coordination with other institutions. The relationship with AIChE has helped to foster these collaborations. A question was posed during the presentation to elucidate the relationship with the International Association for Hydrogen Safety (HySafe) and the International Conference on Hydrogen Safety (ICHS). The response was that, by agreement, ICHS focuses on pre-normative effort, while CHS focuses on the applied part of the problem. As a result, CHS is frequently invited to provide a presentation at the ICHS meetings, and vice versa.
- The project continues to grow in the number of reviews and amount of data-sharing throughout the last couple of decades. Even more noticeable is the collaboration and partnering with relevant organizations to promote broader reach, real impact, and global adoption.
- This project has successfully coordinated with many organizations. To fully utilize the value of the safety information, the safety know-how should be shared with companies and standards organizations. Industrial gas companies hold a significant amount of operational experience in hydrogen, and these companies develop best practices for safety and safety standards through organizations such as the Compressed Gas Association and European Industrial Gases Association. There is currently little overlap between this project and these standards organizations, and this relationship should be improved to achieve the goal of this project.
- The project's existing partnerships are strong. The project may benefit from expanding partnerships to organizations that could provide access to incident and accident data. Also, the project could consider new partnerships that may be needed to accomplish the HySCAN tool development presented. To be able to drill down into applicable codes and standards, access to these copyrighted documents may be necessary. The project team should elaborate on this project next year.
- Collaboration is essential for this project and is well established.
- HSP/H2Tools and CHS outreach and collaboration are very good.

Question 4: Potential impact

This project was rated **3.9** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project excels at what it is intended to do, which is provide a safety resource to the community. Moving the safety panel to AIChE and combining that with CHS was an outstanding move. The Center provides the visibility, training, and tools necessary to accomplish the goal. The value is easily discerned when the "progress by the numbers" is considered on slides 12 and 23.
- The most important aspect of the hydrogen industry is safety. This project has done a superb job of collecting safety information, analyzing safety information, and utilizing the information to prevent accidents.
- Program and subprogram presentations emphasized the importance of safety, codes and standards to a higher degree this year than in years past. This project is well aligned with those goals and supports and advances those objectives.
- The project is critical, particularly the HSP part. It has become an essential expertise for new projects.
- The active sharing of safety data and the promoting of a safety culture in all projects are advancing the goals and objectives of the DOE Hydrogen Program and subprogram.
- This project would help with safe deployment of hydrogen technologies and garner public confidence.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- The project expanded to support California with its critical fueling infrastructure and is now looking at expanding to further include translating material into other languages for international dissemination. This is an important piece to promoting safety globally, as well as the alignment of the HSP for the launch of hydrogen hubs and the mentoring process to gain more talent.
- As hydrogen technology is introduced, HSP, H2Tools, and CHS are needed. There needs to be outreach to first responders for training and for standardized emergency response guides.
- This reviewer looks forward to seeing the continuation of this work, as it is crucial for the hydrogen industry.
- Progress, focus, and deliverables are outstanding; the project should stay the course.
- The proposed future work is well aligned with the needs of the industry. However, it could be of benefit to better explain the procedure in place to exchange knowledge and experience with other organizations around the world and how it translates in existing (or new) codes and standards.
- Continuing activities is important. Plans to expand, such as "deploy additional best practices on new and uncovered topics," are vague. The project should elaborate on these next year, with consideration to new collaborations that may be necessary.

Project strengths:

- The HSP has become a key advisory group for many new hydrogen projects. The new process in place to review proposals is an excellent improvement. The project resources created are essential. The trainings have become well recognized and aligned with the industry needs.
- The presentation covered a multitude of activities that are important to achieving DOE goals in safety, codes and standards. The project allows suitable flexibility to make measurable progress.
- The project's strength lies in the collective knowledge of experts and the pursuit of aggressive metrics to promote safety across all hydrogen projects.
- The project is well-thought-out and is needed for deployment of this new technology and for public acceptance.
- The project is clearly the best on the planet. It is a real gem for the global hydrogen community. The team is encouraged to keep it up.
- The project has an amazing body of work around hydrogen safety.

Project weaknesses:

- The portal may not be clearly updated, as some of the references are not exactly aligned with existing documents. It is unclear how the new HySCAN tool will work. During the presentation, it was specified that it will focus on National Fire Protection Agency (NFPA) 2 first. The project should reference accordingly once the page goes live.
- The project covers so many useful activities and tools, with too much to cover in a single presentation. The project could consider splitting HSP and H2Tools into separate presentations in the future (as evidenced by the speed of the presentation and number of questions). The project's data needs remain a barrier.
- There is opportunity to advance codes and standards in the hydrogen space, particularly in infrastructure. While it has a successful track record and it is a critical part of all hydrogen activities, the impact of the HSP, the various training curricula, and safety data could be further promoted.

Recommendations for additions/deletions to project scope:

- The answer to the document review given in slide 18 does not address one critical point the reviewer mentioned in the review. It was recommended that "PNNL and the CHS should create a formal review process, drawing experts from both inside and outside the organization, before approving anything for general distribution." No reference was seen on slide 18 to going "outside" the organization during the

review process. It is critically important to seek a "fresh pair of eyes" on documents that the general public will see and potentially use. If someone from outside the organization is not available to perform the review, then a person inside the organization who is distant from the creation of the product/document should be used as an independent set of eyes.

- This project should increase the focus on liquid hydrogen (LH2) safety because there are many LH2 sites being installed and operated near the public.
- The project scope is very large and may benefit from a longer time presentation for future Annual Merit Reviews.
- HSP could help promote advances in codes and standards to establish new and technically sound requirements.
- The project could include standardized emergency response guides and rescue sheets so emergency responders know where to look for different types of incidences.

Project #SCS-021: National Renewable Energy Laboratory Hydrogen Sensor Testing Laboratory

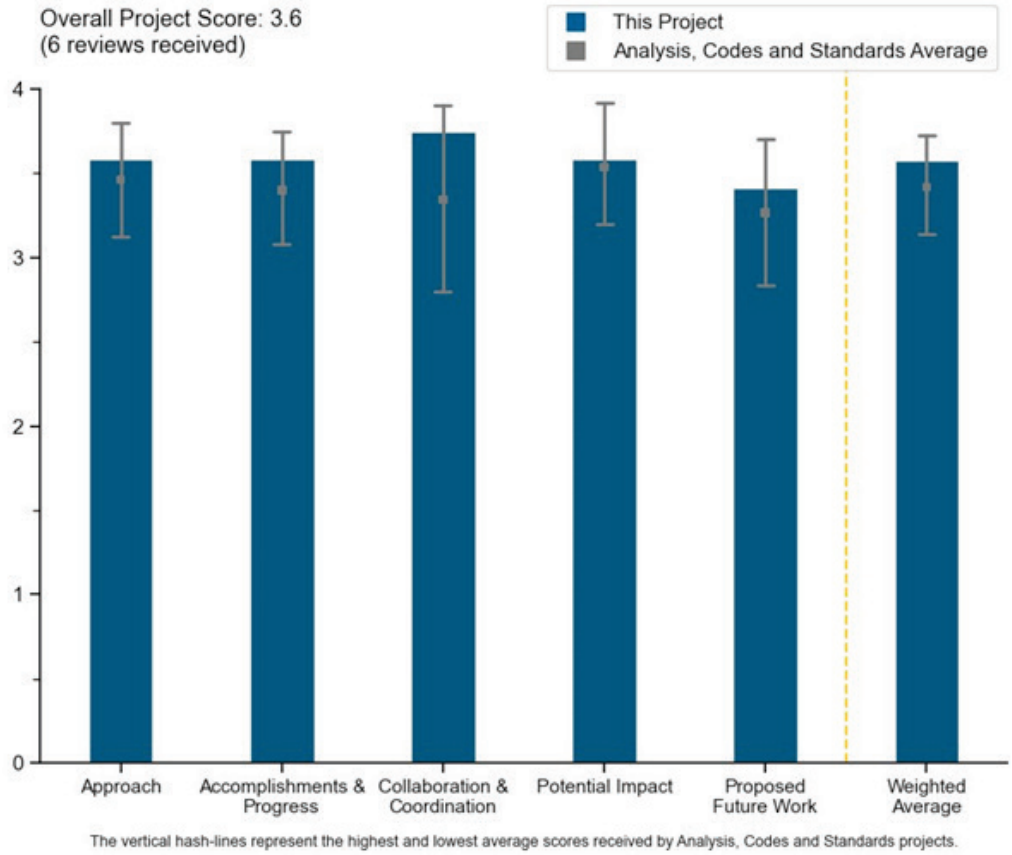
William Buttner, National Renewable Energy Laboratory

DOE Contract #	WBS 6.2.0.502
Start and End Dates	10/1/2010
Partners/Collaborators	AVT and Associates, Element One, Inc., University of Maryland, KWJ Engineering, Inc., Los Alamos National Laboratory, Shell, Amphenol, California Air Resources Board, GTI Energy, Electric Power Research Institute, Paulsson, Inc., Renewable Innovations, Boyd Hydrogen, LLC
Barriers Addressed	• Insufficient technical data to revise standards • Insufficient synchronization of national codes and standards • Limited participation of business in the code development process

Project Goal and Brief Summary

Sensors are a critical hydrogen safety element and will facilitate the safe implementation of the hydrogen infrastructure. The National Renewable Energy Laboratory (NREL) Sensor Testing Laboratory tests and verifies sensor performance for manufacturers, developers, end users, regulatory agencies, and standards developing organizations. The project also helps develop guidelines and protocols for the deployment of hydrogen safety sensors under a variety of conditions and applications.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Because of hydrogen behaviors, improvement in detection technologies is still critical for monitoring safety and environmental concerns. The mission of the NREL Sensor Testing Laboratory is important for development of a national hydrogen infrastructure. The current focuses of the project are appropriate for national needs (early detection, trace-level detection, fuel blends, wide-area networks, modeling, etc.). In addition, the laboratory stands in as a "standards" lab for evaluating the true capabilities of new detection technology. The experience and findings from this lab are shared with regulations, codes, and standards (RCS) groups.
- The project goals slide is a great summary for the value of this project; "secondary greenhouse impacts" should not be used as a factual statement (the word "potential" should come in front of that phrase). The way the principal investigator said it was more accurate and less accusatory: "...losses along the value chain that impede market acceptance." The ability to do parts-per-billion detection for emissions monitoring for profitability is a realistic concern, as opposed to potential environmental impact, which is to be determined and might be secondary to the financial incentive for preventing leakage.
- The project has a multipronged approach to advancing sensor technology for improved safety and control and is conducting excellent work.
- The project continues to excel and is highly productive, producing excellent results, including new sensors; mentoring young scientists; and collaborating with a broad range of collaborators. It is simply outstanding.
- The project is sufficiently flexible to be able to identify and implement specific research and development (R&D) activities that support DOE and project goals.
- This effort does not appear to be a traditional DOE project in the sense that it has a single focus and mission; rather, it is a funded test facility and staffing that address multiple issues related to hydrogen detection technologies. As such, the approach will vary with the individual tasks assigned to the lab, and for the tasks reported this year, the approaches seem perfectly sound.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and DOE goals.

- Accomplishments for this period are appropriate and include upgrading the laboratory to address questions involving fuel blends, validation of sensor nets and trace detection technologies for emissions monitoring and quantification (for both open air leakage and fuel exhaust), and detection of contaminants. The work has included evaluation of sensors for cold hydrogen releases and evaluation of indoor leak scenarios.
- The project continues to remain aligned with the goals and needs of the DOE Hydrogen and Fuel Cell Technologies Office and especially the Safety, Codes and Standards subprogram element. Sensors are key components of all installations of hydrogen technologies, when properly deployed, and this project provides the background and support to ensure the appropriate and safe deployment of sensing technologies. The project excels at all the DOE performance metrics.
- This work started with "how well do sensors work" and has progressed to how to use them properly. The model validation for larger applications, such as hydrogen–natural-gas blends and manufacturing, is relevant and needed. While there is attention to the environmental concerns of leakage, care should be taken not to raise this to the top of the priorities to call unneeded attention to an issue that may not be an issue or may be of little consequence. Realizing that any potential issue should be addressed/resolved, there should be caution as to how much weight is given to each (i.e., a financial incentive not to lose molecules is warranted, versus an outcry—from those unfriendly to the industry—about an unknown "harm"). Any results/data that can be applied should be, but perhaps as secondary. Hydrogen sensors and monitoring is always important for safety and economic reasons, both from a leakage and hydrogen fuel quality perspective.
- The project has made really good progress toward the DOE goals, especially the great pivoting to cover timely topics such as blended fuels and hydrogen emissions, which have recently become a naysayer sounding bell against fuel cell electric vehicles (FCEVs). In this latter issue, it is great to see the national

laboratories doing productive work to address this head-on. The need for venturing into particulate analysis/testing is questionable. Regarding the choice of this issue as a course of study/focus, it is not clear where the facility gets its recommendations for future work. Greater effort must be made to ping industry for critical needs as they relate to the core expertise of the facility.

- The project has multiple accomplishments that seem to be demonstrating the success of the project and advancement of technology.
- This project demonstrates progress in detection and sensor equipment validation, but application to new markets may potentially require new approaches.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- This project continues to maintain an active mentorship aspect to the project. Indeed, several of those being mentored moved on to be hired by NREL as staff. This project also maintains a well-constructed collaboration/coordination activity. This is outstanding.
- Collaboration is broad and well represented. The new sensor technology being demonstrated with GTI Energy and at the Advanced Research on Integrated Energy Systems (ARIES) facility is a great example of working with industry in R&D.
- The project's collaboration and coordination are impressive. The intern involvement is nice to see, as this is educating our future workforce.
- Existing collaborations are very appropriate, and there continues to be effort to expand collaborations to support implementation of sensors and new and emerging applications.
- This project continues excellent interaction with RCS groups, industry, academia, and international partners.
- The project has a fantastic list of collaborators and coordination efforts, but it would be good to do more focused feedback loops with industry. As the list is rather large, the non-academic, research, and other institutions far outnumber industry.

Question 4: Potential impact

This project was rated **3.6** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This work is spot on, advancing the safe deployment of sensing technology relevant to the application at hand. The project has been developing wide-area monitoring for the detection and location of leaks at large facilities over the past few years, which is a focused activity driven by H2@Scale. This is well done. This capability will also find application in quantifying leaks into the atmosphere to understand the secondary effects on climate and the primary effects on the commercial need to quantify fugitive leaks. A leak to the atmosphere represents molecules one cannot sell. Again, this is outstanding.
- The facility and this work product are critical to the success of the hydrogen industry. Safety is paramount, and the rapid, reliable, efficient detection of hydrogen releases is directly linked to safety and the ensuing success of the industry. All of the accomplishments achieved this year are noteworthy, with only minor regrets for a wish for re-focus, as indicated elsewhere in the review comments.
- Using the onboard vehicle sensors as an example, this is important, and there is more work to be done, as demonstrated by an audience question around "what can be done to prevent sensors from being poisoned by environmental conditions" (or, say, a truck pulling into a paint facility). Care needs to be taken in how the data is presented. That said, there is certainly valuable work being done, such as the SAE International paper on qualifying sensors for onboard vehicles.
- The project and the efforts of the laboratory include assisting technology developers, validating technology developments, identifying issues and directions for their solutions, and providing critical communications to the sensor development community and to RCS developers.
- A reliable sensor can make all the difference in a hazardous scenario. The project's work has the potential to help prevent many incidents.

- The project focuses on mitigating releases and addressing process control, which are both important to ensuring safety as more hydrogen projects are deployed.

Question 5: Proposed future work

This project was rated **3.4** for effective and logical planning.

- Advanced methods of detection are needed and will aid the industry. The way the project's work is presented in the slides is very positive and forward-looking.
- The project continues to expand upon needs that will benefit the industry. The project seems sufficiently flexible to address many of these needs, albeit with significant challenges, as described in the presentation.
- Progress, focus, and deliverables are outstanding; the project is encouraged to stay the course.
- The project's future work seems feasible and well-focused on overcoming barriers.
- The scope of the test facility and experts should be broadened to include automotive/onboard hydrogen sensor technology.
- The project should work on detection regarding hydrogen release behavior, active area monitoring, and specialized needs in emerging markets. Low-level detection still requires support by the laboratory.

Project strengths:

- The hydrogen sensor laboratory is clearly a much-needed resource for DOE and industry and should be expanded and supported to address even more topics. All project accomplishments listed for this year are well delivered and demonstrate the high caliber of the facility and experts there.
- The project is concentrating on the overall safety and economic drivers for sensor development and improvement. Improving the safe implementation of all hydrogen systems is nothing but positive.
- The project addresses key aspects of hydrogen detection and risk mitigation. Learnings are shared with codes and standards development organizations.
- The NREL sensor laboratory continues to perform relevant and critical work on a multitude of topics. This reviewer hopes that this can continue.
- This work is essential to the hydrogen community and will help enable the hydrogen economy's progress.
- This project is clearly the best on the planet and is a real gem for the global hydrogen community. The team is encouraged to keep it up.

Project weaknesses:

- It is difficult to optimize a project when the applications are a moving target. Having said that, it is appropriate that this project has the flexibility to make progress on established objectives, while also exploring solutions for new and emerging applications.
- The accomplishments for this project are not easily measured, nor does the future work outline metrics by which success of the project can be measured.
- The project is not as aggressively funded as one might hope.
- The project has no obvious weakness but should expand the scope a bit—and keep up the excellent work.

Recommendations for additions/deletions to project scope:

- The project should consider onboard "vehicle" hydrogen detection technology, especially in light of the expanded end uses for FCEVs, including Class 8 trucks, rail, marine, and aviation. Following are some topics for future consideration:
    - Pursue/develop a mock functional safety assessment for onboard vehicle hydrogen release monitoring, and show how the safety concept of the vehicle design drives the Automotive Safety Integrity Level (ASIL) rating of the sensor and the electronics that report the sensor results to the operator. Then select and test specific sensor designs/technologies to confirm the performance and ASIL rating.

  - Examine how poisoning of the hydrogen sensor affects performance and what mitigating factors could be employed to improve performance. This recognizes that the "vehicle" is never stationary and could come into contact with various airborne chemicals.
  - Evaluate hydrogen sensor technologies that can be employed inside the FCEV exhaust, where the sensor must operate in hot, wet environments.
- Related to sensor placement and the quantitative risk assessment (for Hydrogen Risk Assessment Models [HyRAM]), the project could produce a report/white paper for a less technical audience—a document with solid resources/references that can be used in project packages and readily absorbed by those reviewing said projects. The report or paper could potentially be a safety resource on other public websites and perhaps is already being considered.
- One area that the laboratory is probably aware of but has not mentioned specifically as a topic to investigate has to do with sensor development that uses "artificial intelligence" or "machine learning" in conjunction with analyzing what real time arrays detect. It is not clear how this technology works and what the claims of developers are with this technology. As with any other attribute of detection, what this technology delivers should be subject to evaluation and testing.

Project #SCS-022: Fuel Cell and Hydrogen Energy Association Codes and Standards Support

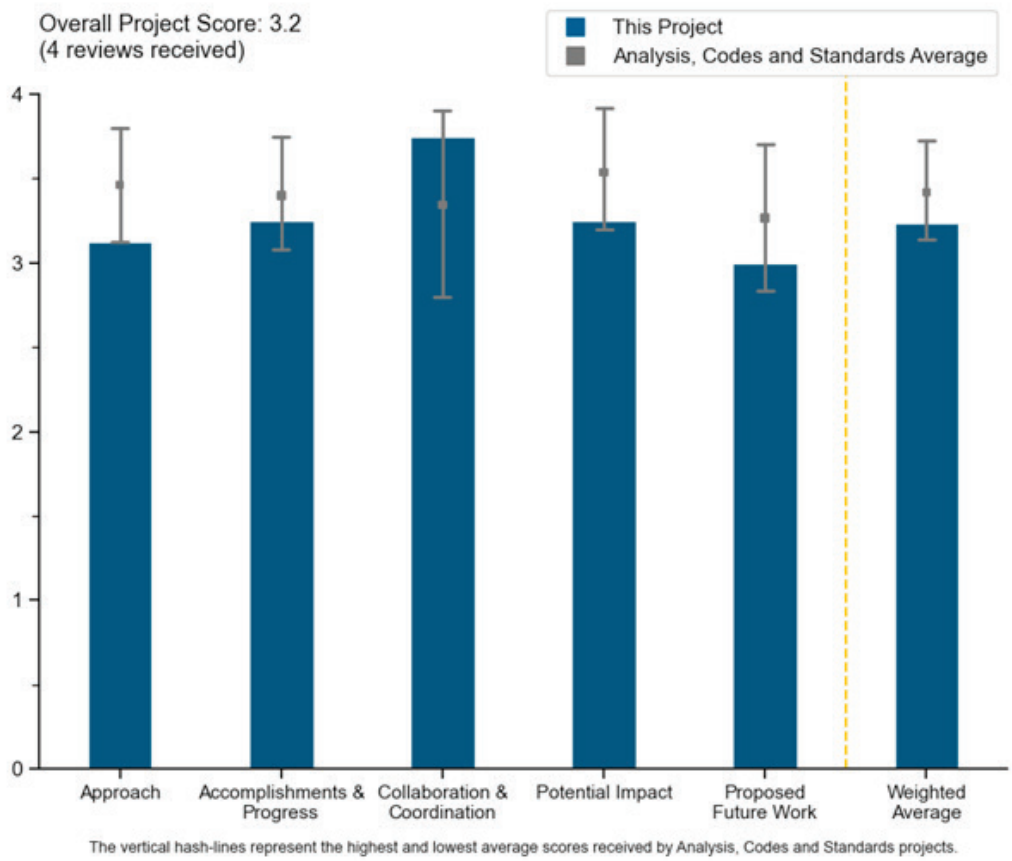
Karen Quackenbush, Fuel Cell and Hydrogen Energy Association

DOE Contract #	DE-AC05-00OR22725
Start and End Dates	05/05/2021–01/31/2023
Partners/Collaborators	National Hydrogen and Fuel Cells Codes and Standards Coordinating Committee, Pacific Northwest National Laboratory, Oak Ridge National Laboratory
Barriers Addressed	• Need for consistent regulations, codes, and standards to enable national and international markets • Insufficient synchronization of national codes and standards • Limited participation of business in the code development process

Project Goal and Brief Summary

The goal of this project is to facilitate widescale adoption of fuel cells and hydrogen energy systems through the development of consistent regulations, codes, and standards (RCS) that incorporate industry best practices. The Fuel Cell and Hydrogen Energy Association (FCHEA), under contract to Oak Ridge National Laboratory, participates directly in key domestic and international RCS technical committees and encourages its members to participate directly in technical committees, working groups, and discussions. FCHEA also develops and enables widespread sharing of safety-related information resources and lessons learned with first responders, authorities having jurisdiction, and other key stakeholders.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- In coordinating standards, it is critical to engage industry, assess needs, harmonize requirements, interact closely with stakeholders, and disseminate information in a timely manner. This project continues to successfully achieve these tasks.
- The approach supporting the DOE effort is greatly detailed. The chart on slide 7 is extremely valuable in displaying the vast interfaces involved with the project. The Approach: Coordination and Outreach slide (slide 9) also provides excellent approach details, while the use of working groups amplifies the continued value of the project effort. One approach area is unclear. FCHEA appears a very valid industry group, but it is unclear whether there is an end point to the formal project, what would demonstrate success, or whether there is a plan for FCHEA to be fully funded without DOE project support. It would be valuable to describe FCHEA's vision. Slide 27 is valuable for evaluating the "Matrix." The track changes approach is extremely valuable.
- It is difficult to discern the plan for this work based on the poster and responses to reviewer questions. The approach to Barrier J (Limited Participation of Business in the Code Development Process) is the strongest element. The approach to Disseminating Safety Information is reasonable, although there could be more specificity about the quality and sources of information used in newsletters. The approach to the Development and Harmonization of Regulations, Codes and Standards is not clearly articulated in the poster, and it is unclear how the project will make an impact on barriers. The key aspects of the approach are coordinating working groups, creating a newsletter, and updating various websites. The project would benefit from a clearer articulation of the project goals, plans, and milestones and a narrower scope to allow more effective progress on Barrier J.
- The approach is fine for the stated goals, but the question is really about whether the goals are particularly relevant at this point. This effort has been underway for a long time, including prior to 2021, and it is not clear that it is a critical part of the codes and standards effort. There are many organizations that have similar roles.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The overall application to DOE goals was described. Five slides detail accomplishments of both overall interfaces and working groups. The scope of activities is very broad, supporting the challenge of interfacing with national and international codes and standards. Multiple backup slides (35–40) were provided that qualify scope activities against DOE goals with prescriptive details. Data indicates a very strong project interface with DOE planning.
- Significant progress continues to be made in various working groups, website hits, code updates, and coordination with stakeholders.
- The volume of work is evident, but it would be good to see more articulation of what efforts are taken to ensure the output is high-quality and meaningful. It is difficult to identify which aspects of the approach are FCHEA activities versus codes and standards committee activities versus the Pacific Northwest National Laboratory (PNNL) activities versus the activities of the FCHEA member companies. The monthly discussions are an important activity, and FCHEA pulls together a large number of participants—this is commendable. However, this accomplishment is diluted by vagueness about what is being achieved and by whom. The newsletters and fuel cell standards database contain large volumes of information, but they are not archival and do not appear to be curated; the website has a good deal of information that is out of date or completely missing. Additionally, it would be helpful to see more articulated accomplishments from the FHCEA work (versus the accomplishments of the code committees versus PNNL versus the member companies).
- There are specific accomplishments, but these are anecdotal and/or tactical actions and are not as much on a strategic level to harmonize global codes and standards. For additional value, this project should take the lead on some specific needs or issues and drive them to conclusion, rather than being more reactive.

Question 3: Collaboration and coordination

This project was rated **3.8** for its engagement with and coordination of project partners and interaction with other entities.

- The heart of a successful project effort involves integration with a wide variety of industrial and laboratory partners. The project highlights this collaboration from the very beginning of the presentation and continues with this theme throughout the presentation. Successful transition of data to the PNNL H2Tools.org website is an example of direct collaboration. Discussion with project personnel indicates a desire to increase knowledge and utilization of this data for improved application, with future work qualifying potential scope. Added details of how the project has and will interface with key safety organizations involved with codes and standards review (e.g., the Hydrogen Safety Panel and Center for Hydrogen Safety) could be expanded to provide interface specifics, including possible future transitions. The technology transfer effort detailed in slide 24 is noteworthy.
- This project collaborates exceedingly well with members who represent the full global supply chain, including universities, government laboratories and agencies, trade associations, fuel cell materials, component and system manufacturers, hydrogen producers and fuel distributors, utilities, and other end users. A tremendous amount of coordination between stakeholders occurs thanks to this project's continued involvement.
- FCHEA has many member companies and a network of contacts within the codes and standards organizations.
- This project pulls together an excellent, industry-focused team with an exceptional list of participants.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- At this stage of the industry, the project is critical to new technologies for synchronization of codes and standards development. Integration value is especially qualified in the backup slides, while the overall FCHEA working group effort directly supports safe advancement of hydrogen technologies. Codes and standards will always lag technological development, so the project effort will always be valuable. It is anticipated that as the hydrogen industry and codes and standards mature, along with the completion of DOE goals, the potential impact of this integrating project will lessen.
- All large-scale commercialization starts with standardization of components and hardware. This effort is entirely needed and must be continued to achieve DOE target goals.
- The most effective work is for overcoming Barrier J, Limited Participation of Business in the Code Development Process. It is unclear how the project is advancing progress toward "Conduct R&D to provide critical data and information needed to define requirements in developing codes and standards" or progress toward "Ensuring that best safety practices underlie research, technology development, and market deployment activities supported through DOE-funded projects." Adding more research engagement would improve translation of research into industry best practices. Slide 22 shows that FCHEA membership is almost entirely industry. To improve on these barriers where progress is limited, it is recommended that the project find a way to engage more research groups, academics, small businesses, and consultants that have expertise complementary to that of the medium and large companies that are already members of FCHEA.
- The accomplishments are not particularly impactful or relevant to specific DOE Hydrogen Program goals. While there are a number of useful tools managed by the project, it is not clear whether there would be a discernable impact if this project went away. For example, the six proposals to National Fire Protection Association (NFPA) 2 would have still happened; they would just have been submitted by someone else. It is not clear that FCHEA was a driving force behind important changes that otherwise would have not moved forward.

Question 5: Proposed future work

This project was rated **3.0** for effective and logical planning.

- The proposed work identified is absolutely needed. As always, the hard part is getting everyone's time to work on these codes and standards.
- The Remaining Challenges and Barriers slide, along with Proposed Future Work and backup slides, provides a detailed, logical, valid, and compelling basis for future effort. One area that could be improved

is documenting and demonstrating specific approaches for the thrusts of "Work with…" and "Continue to..." noted on slide 18. Backup slides to document FCHEA vision and strategy would be valuable, specifically addressing how successful the Association has been and why its approach will be successful in addressing the challenges generally described in slide 33.

- The future work is not clearly articulated. It is difficult to identify the activities and goals for many of the working groups. It would be prudent to consider narrowing the scope and focusing on developing higher-quality work products where the FCHEA team has differentiating strengths, rather than to take a scattershot approach to so many goals.
- The work proposed is very general in nature, without specific goals or metrics. There are not specific actionable items that show clear benefits above and beyond the ability of individual FCHEA members.

Project strengths:

- Strengths include past transition effort, establishment and continued management of the Regulatory Matrix, key working groups, extremely strong collaboration, and very knowledgeable and passionate project personnel.
- The project serves as a forum for new entrants to possibly better understand the hydrogen codes and standards arena and make contacts. Management of the Codes and Standards Database on H2Tools.org is also useful for the industry.
- This project has a tremendous amount of coordination and connecting of industry and RCS bodies, and this project does this very well.
- There is excellent coordination of industry stakeholders, as evidenced by number of member companies.

Project weaknesses:

- There is a lack of excitement or specific new activity to sustain the project long-term. Comments are made about participating in numerous activities, but just participation and monitoring is not enough to make a difference in many of these forums. Being a consensus organization of numerous parties who are already participating in the codes and standards process does not lend itself to effectiveness. This is reflected in the relatively static number of visitors, unique visitors, and pages viewed. Doing the math seems to imply that visitors are not returning on a daily or weekly basis to use the tools, information, and websites actively as a go-to location for additional information.
- The work appears ad hoc. A clearer plan, objective, and set of metrics are urgently needed. Lack of publications and presentations in scholarly or archival venues is a significant weakness. Peer review of the information is an important next step to consider, even if it means allocating additional resources. Ensuring high-quality, trustworthy information is critical. The poster does not effectively communicate the work and accomplishments.
- The project lacks prescriptive details for addressing challenges.

Recommendations for additions/deletions to project scope:

- Because so many members have such busy schedules, it is difficult to show major (and quick) progress on certain standards developments. This is not a weakness of this project, however. Perhaps something could be created to show who an action is assigned to, something that has outward visibility, in order to pressure/ shame the action owner into making progress. One other recommendation could be to introduce or emphasize (via the working groups) the concept of hydrogen users needing to create and track incidents, leaks, and failures and report them back to DOE for incorporation and improvement of quality risk analysis tools such as the Hydrogen Risk Assessment Models (HyRAM).
- The team should emphasis quality work over quantity of work. The codes and standards database is important, but some information is significantly dated, the website does not indicate when the information was last updated, and the information is extensive but does not appear curated. A more systematic, curated approach would provide more trustworthy information.
- The project could consider whether the work should be paid for directly by FCHEA rather than requiring DOE funding. If the work is valuable, the industry should be willing to pay for it.
- Clarification of high-priority RCS would be valuable to qualify scope applied to challenges and future thrust and focus.

Project #SCS-028: Hydrogen Education for a Decarbonized Global Economy (H2EDGE)

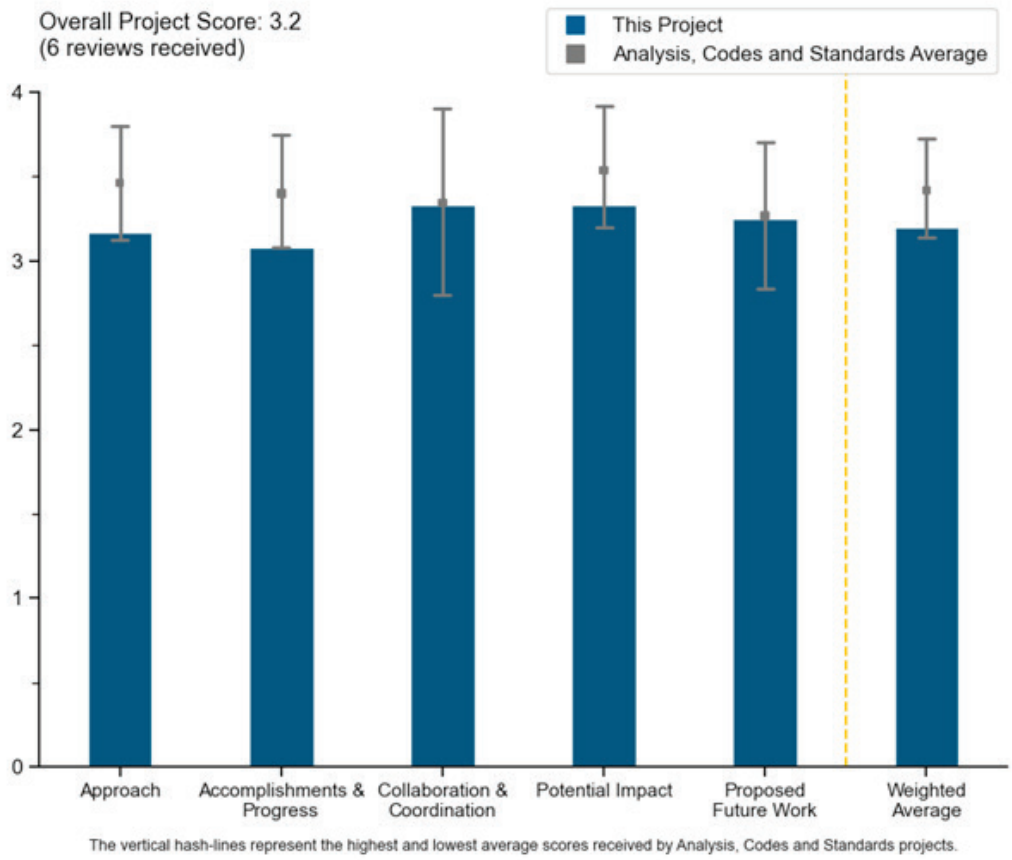
Eladio Knipping, Electric Power Research Institute

DOE Contract #	DE-EE0009253
Start and End Dates	10/01/2020–03/31/2025
Partners/Collaborators	GTI Energy, Oregon State University, University of Delaware, University of Houston
Barriers Addressed	• An increasing need for well-qualified professionals for the growing hydrogen economy

Project Goal and Brief Summary

As an emerging field, the hydrogen industry faces the challenge of mobilizing an experienced workforce—a critical need in which safety must be emphasized. This project establishes the Hydrogen Education for a Decarbonized Global Economy (H2EDGE) initiative. H2EDGE enhances workforce readiness by collaborating with industry and university partners to develop and deliver training and education materials, including professional training courses, university curriculum content, certifications, credentials, qualifications, and standards for training. H2EDGE will establish regional university hubs and an affiliate university network to train the workforce for the hydrogen economy. Professional short courses and university curricula will focus on the four pillars of the hydrogen industry: production, delivery, storage, and use.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach being taken to educate both industry professionals and university students seems like an excellent way to reach the right people in the community. This work is critical to try to respond to the demand for well-trained professionals for the growing hydrogen economy.
- The project has a very good approach to building a wider curriculum on hydrogen across the partners. Overcoming the retirement of the principal investigator does not seem to have slowed progress based on the team's approach.
- The approach of initially focusing on four-year schools; moving to two-year colleges and trade workers is perhaps difficult. Given the large scope (spanning the entire value chain), one could see building the curriculum at the trade and two-year colleges initially and building it up for the four-year schools. However, the train-the-trainer approach may work well in this top-down model, and working with and through the Low-Carbon Resources Initiative (LCRI) may make it easier. Another aspect is the consideration for not just catering to those who have the means to attend the four-year colleges but building the workforce and giving the opportunities to those from disadvantaged communities, concurrently.
- This project is focused on increasing the number of well-qualified professionals needed for the growing hydrogen economy. This is a big job, and this project is an important step to achieving the objective. Ultimately, much more will need to be done to effect wide-scale deployment of educational opportunities.
- The overall approach is good. It is, however, very ambitious to look at university curricula and professional trainings in parallel.
- Professional short courses are a plus and have been a need for some time. Affiliate networks at four-year institutions seem interesting, but it is not clear how this will promote and increase the workforce.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- It is great that the project is engaging with the Hydrogen Safety Panel (HSP) to ensure safety is in all materials. The first professional short course was delivered recently (May 31, 2023, Intro to Basic Hydrogen Science), and an electrolyzer course is coming in July 2023 from Electric Power Research Institute, in person at the Institute's offices; other courses that are in development are to be delivered in the fall. The hope is that the expansion of courses delivered via webcast and/or self-paced online training happens relatively soon, given the timing of the project.
- Accomplishments outlined in the presentation demonstrate success in beginning to develop content and educate a number of individuals. The hands-on lab experiments course in the university seems like it could be very successful in truly making an impact on students through first-hand experience assembling and using fuel cells.
- Several courses have been developed, have been reviewed by the HSP, and are being deployed. Capstone projects are underway that help meet specific needs.
- Overall, the project is moving in the right direction and answering the overall objectives.
- The project milestones and go/no-go decision points are not specified, so it is difficult to gauge specific progress toward project goals. Qualitatively, development of offerings across the universities is a noted sign of significant progress, and the courses span the sciences and business. A clearer articulation of how ideas and best practices will be shared and scaled for the maximum impact would be helpful.
- Progress and execution are decent, but additional efforts should be made to get the material out and gather feedback, especially for the short course.

Question 3: Collaboration and coordination

This project was rated **3.3** for its engagement with and coordination of project partners and interaction with other entities.

- Collaboration is outstanding. The project seems to be involving the right types of institutions and plans to continue to grow in this regard.
- There appears to be very good collaboration in place, particularly with other universities.
- There is good collaboration and coordination. It was mentioned that the advisory board has expanded to 16 members, but it is not clear whether the board provides a good snapshot of the relevant stakeholders. From the presentation, it is very heavy on the utility member side.
- Partnership with universities and industries is good. but the project could benefit from partnerships with other technical schools. For example. other resources might be needed, especially for the professional courses. Use of STEM/STEAM (Science, Technology, Engineering, [the Arts], and Mathematics) schools may help to find high school students. The support of social justice might include training after incarceration.
- Overall, there is great collaboration with the academic community; students are generating relationships with organizations such as national laboratories. The industry collaboration, as well, seems solid, although there are no educational institutions on the advisory board.
- Each of the partners is doing work that is relevant, but practical collaboration toward scaling results is not evident.

Question 4: Potential impact

This project was rated **3.3** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Developing strong technical content in a way that engages people and educates students and professionals could make an enormous impact and significantly advance the hydrogen economy.
- If both the university curriculum and the professional trainings are successful, this project will be key for the future of the hydrogen landscape.
- The project is an important early step toward accomplishing DOE goals and objectives.
- The work to build academic curricula is important, and progress is being made. The effort to include a focus on historically black colleges and universities (HBCUs) is noteworthy and great. For maximum impact of the DOE grant, it would be good to see how the individual universities' efforts will be shared and scaled up. A gap that does not seem to be addressed at all is occupational training, which will be a critical aspect for success. Not all workers in the hydrogen economy will be from four-year universities. This occupational training is especially relevant for workers potentially displaced from other established jobs by increased hydrogen deployment.
- While the advisory board has grown from 7 to 22 members over the past few months, and there are 18 industry participants who will nominate universities in their jurisdictions to develop curricula, the overall scope is wide, and there is a risk of there not being enough resources or the project being spread thin, as it is reaching broadly across the industry. The impact has the potential to be huge, but again, given the scope and the timing, it is a huge reach.
- There could be relatively good impact, but the focus on workforce development should be more on the two-year or trade schools. Additional efforts under other opportunities could quickly overshadow this effort.

Question 5: Proposed future work

This project was rated **3.3** for effective and logical planning.

- Proposed future work seems ambitious, as there are many topics outlined that the project is planning to address. However, the plans set forth seem logical and indicate the work could be effective.
- The proposed future work presented reflects important next steps to achieve objectives.
- Future work, including the roadmap, is worthwhile.

- Proposed future activities are good, but the right stakeholder feedback might not be aligned correctly to maximize impact. Also, it would be nice to understand who is developing the curriculum and how is it vetted.
- The proposed future work is well aligned with the objectives of the project and clearly explained. It is, however, quite broad and may benefit from extra support and prioritization.
- Much is going on in the future work, so hopefully there are plenty of resources available to get it all done, and done with quality. There is no lack of enthusiasm, to be sure.

Project strengths:

- This topic is essential, and creating a network of universities would benefit the hydrogen sector overall. Supporting the workforce by reaching out to the industry is an asset. Interesting coursework is proposed on the business aspects of hydrogen.
- Education of the current and future workforce is a key piece that will need to take place to ensure the hydrogen economy can continue to grow and be a safe environment for everyone involved. The knowledge this project will pass on could make a significant impact.
- This project includes key partnerships to design and implement courses to lead to workforce development. Future work identified is appropriate and necessary for success.
- The project is creating an industry gap assessment to allow focus on which trade associations to work with to strengthen the program.
- Strengths include a strong network of universities and good industry partnerships, development of new curricula, and a worthwhile concept.

Project weaknesses:

- There are concerns for maintaining and updating the training content. Continuous funding might be a challenge in the future. Marketing and announcements should be further developed to help advertise to the broader community. There are already gas fitters who have skills in natural gas areas; there is a need to connect with the workers and unions. It could be done by looking at other skilled trades—e.g., construction, plumbing, electrical—and studying their recruitment strategies.
- There are no well-defined metrics by which one can see what the full scope of the project will be. There are no measurable metrics that tell if the pace of the project is right. The scope is too wide for the project to truly be successful; it would need time beyond the life of the project.
- Project weaknesses have, for the most part, been identified and are addressed in the future work description. Expanding partnerships and marketing courses are very important.
- Weaknesses include overall publicizing of the programs and availability and lack of academic institutions on the actual board.
- Opportunities to expand scaling, industry partnerships, and occupational education are noted.

Recommendations for additions/deletions to project scope:

- The scope is fine. The reviewer looks forward to seeing progress on the proposed future work at future Annual Merit Reviews.
- In the future, discussion could include how the maintenance will be updated/kept fresh with the most recent information/resources (i.e., through the subject matter experts at LCRI, GTI Energy, and the universities). Working with the HBCUs is great, but the project should also include other target communities (Native American, for example) and other under-represented groups. The project should include information on tracking and metrics of the outcomes of these courses (who and how many get jobs, and where).
- The project team could consider narrowing down the scope to pieces of work that can be accomplished, potentially focusing on a few areas of expertise.
- This is a large project that would benefit from a clear workplan and priorities.

Project #SCS-030: MC Formula Protocol for H35HF Fueling

Taichi Kuroki, National Renewable Energy Laboratory

DOE Contract #	WBS 8.6.2.1
Start and End Dates	10/1/2021–9/30/2023
Partners/Collaborators	Frontier Energy Inc., ElDorado National, GTI Energy, Luxfer Gas Cylinders, New Flyer of America, South Coast Air Quality Management District, Sunline Transit Agency, Southern California Gas Company, Shell, Trillium
Barriers Addressed	• Lack of a publicly available and verified high-flow fueling protocol for H35 medium- and heavy-duty hydrogen-powered buses and trucks

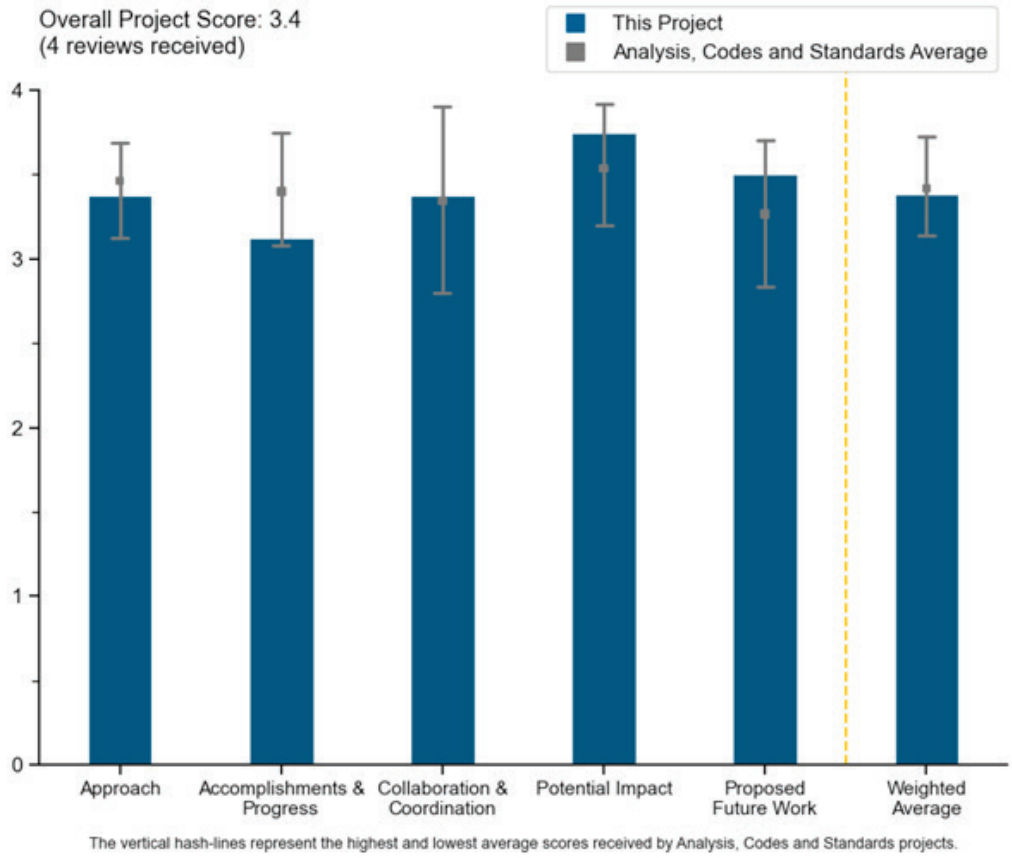
Project Goal and Brief Summary

The project aims to develop a validated H35HF[1] MC Formula[2] fueling protocol for medium-duty (MD) and heavy-duty (HD) buses and trucks, with the goal of standardizing fueling procedures. The protocol will be reflected in SAE J2601-2, and the National Renewable Energy Laboratory's (NREL's) hydrogen fueling model, H2Fills, will be upgraded for H35 MD and HD fueling and made publicly available. The project team has conducted surveys, integrated survey results to define boundary conditions, upgraded H2Fills for protocol development, and started implementing the MC Formula control logic in NREL's HD dispenser for protocol validation testing. The project seeks to address the need for a standardized fueling protocol to enable the growth of the hydrogen market and prevent potential issues with incompatible vehicle designs and the lack of accessible H35 stations.

[1] Refueling hydrogen at a high flow (HF) rate to an onboard pressure of 35 MPa (H35).

[2] A method that allows a hydrogen refueling station to directly and accurately calculate the temperature at the end of the filling in a hydrogen tank.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The approach is well structured and well defined and suggests an excellent chance of achieving the project goals. The three main themes to discern boundaries, develop the model, and validate the fueling maps are well suited to a successful outcome.
- The project clearly states its goals and objectives and identifies remaining challenges and barriers. Furthermore, the project provides methods to overcome such challenges and barriers. Lastly, the layout of the project's approach is easy to follow.
- This project is well-thought-out, although it is not yet complete with only three months left. The German contract seems to be the rate-limiting step in supplying the component validation thermal masses needed to complete this work.
- The approach will work to meet the objectives of the project. It will be important that additional real-world testing be completed prior to standardization in SAE J2601.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and DOE goals.

- The project is proceeding on its stated pathway and making progress. However, there was no mention of how the barrier to controlling the dispenser flow/pressure will be resolved, especially since it is listed as not being capable with existing hardware.

- The project clearly delineates its excellent progress toward objectives, categorized by themes. However, some incomplete items in "Theme 3: Validation testing" lack expected timeline dates.
- Themes 1 and 2 are complete, although it would be preferable if more information could be provided regarding the results of the Theme 1 surveys. It is unclear why this information was not shared in the presentation. More results should be presented, rather than indicting tasks are complete.
- The progress for this work is good but not excellent. The progress of the German contract was scheduled to be completed in April 2023. At the time the view graphs were due, that work had not yet been completed. Presumably it has been done, or will be done soon, so this project can finish its work by the close of this fiscal year.

Question 3: Collaboration and coordination

This project was rated **3.4** for its engagement with and coordination of project partners and interaction with other entities.

- The collaborators are perfect for this work. It also appears that a concrete active line of communication is maintained. This should yield transparency and excellent working environments. The reviewer anticipates that this project will be successfully completed by the end of Fiscal Year (FY) 2023.
- This project has a comprehensive list of industry partners. Additionally, the project demonstrates excellent participation capabilities by meeting with partners bi-monthly and having such partners provide data and feedback.
- This is an excellent group of project partners that can provide adequate guidance and credibility to the work for 35 MPa fuel systems. Bi-monthly meetings are more than adequate.
- The partners seem to be mostly aligned with the bus industry, so it is possible that the fueling protocol will be tailored more to that industry at the risk of negatively affecting other markets. Additional partners in other industries could provide additional perspective.

Question 4: Potential impact

This project was rated **3.8** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- On completion of this work, the United States will have a number of protocol fill tables based on the MC method. The MC method has gained recognition over the past couple of years as a fill protocol based in science. It has been recognized by SAE J2601 and hence used for light-duty vehicle filling. Moving this to the MD and HD vehicle filling protocol will be enormous in accelerating the development of the fueling infrastructure.
- The ability to broaden fueling infrastructure to allow any MD/HD vehicle to safely fill at stations that meet a standard protocol will help enable broader acceptance of vehicles. Consistent specifications for H35 MD/HD vehicles have been challenging, thereby leading to difficulty with specifying hydrogen fueling stations for these markets. This project could have a significant ability to improve safety by making these specifications clearer for consistent operation.
- This project is of much value since a publicly available and verified high-flow fueling protocol for H35 MD and HD hydrogen-powered buses and trucks does not exist. The project goal of developing a protocol has the potential to significantly advance progress toward DOE research, development, and demonstration goals and objectives.
- An HD high-flow fueling protocol for 35 MPa fuel systems is greatly needed, and this project is poised to deliver the results that can be fed into fueling protocol standards development activities immediately. It is not clear whether the stated SAE J2601-2 standard is the intended target, as it is understood that this effort would be incorporated into SAE J2601-5.

Question 5: Proposed future work

This project was rated **3.5** for effective and logical planning.

- The future work activities are as required per the project plan, with the final and most critical deliverable being the creation of language to allow the incorporation of this work product into industry standard SAE J2601-2 (or possibly J2601-5). This is an extremely valuable project to the industry.
- This project is scheduled to be complete by the end of FY 2023. Assuming that happens, the proposed future work is appropriate.
- This project has effectively planned its future in a logical manner by incorporating future goals.
- The future work mentions adoption within SAE J2601-2 but does not describe how that will be done or whether the project team has developed consensus within that team that this work will be adopted. The partners are primarily related to bus fueling, so the protocol might not gain broad support unless a plan is in place. In addition, limited testing at one site might be insufficient to lock into a standard. Additional testing might be needed first.

Project strengths:

- This project is to develop several filling tables to fill MD and HD vehicles derived from the MC method. These tables will be validated using NREL's hardware. This is a good project aimed at building and deploying fueling protocols to enable the rapid development of the fueling infrastructure for MD and HD vehicles. It is very nice work.
- The project strengths include a well-defined approach and timely deliverables. The end result will be extremely valuable to the industry in that it will fill a critical industry need. The project team members are extremely well qualified, and the test facility is top-notch in support of the project objectives.
- The ability to standardize the bus and fueling specifications will reduce some of the confusion (and as a result, safety issues), which will enable better adoption of hydrogen-powered vehicles. If a reasonable common specification can be developed, then this will be a major step forward.
- The project is filling in knowledge gaps regarding codes and standards and has the potential to guide stakeholders in the hydrogen space (e.g., standards development organizations, code development organizations, and industry).

Project weaknesses:

- The results of a lowest common denominator approach might result in raising the cost/complexity of H35 fueling stations if the new tables become a minimum requirement. In particular, the difference between Type 3 and Type 4 tanks at H35 can result in significant differences in fueling time or precooling temperature. This may have unintended consequences in other markets.
- There are very limited weaknesses to this excellent effort. Perhaps it would be good to see the results of the initial Theme 1 survey (sanitized for anonymity) to justify the approach. In future presentations or reports, it would be great to see more of the actual deliverables, as opposed to merely listing that tasks are completed. Other than that, this is an excellent effort.
- The only weakness found is the inability of the German firm to deliver on its contract. This could be a supply chain issue, and it could have already been resolved.
- The contents of the survey used to define protocol structure should be provided.

Recommendations for additions/deletions to project scope:

- A barrier is listed that existing hardware might not be sufficient to meet the developed H35HF MC protocol. If so, then it is premature to advance that in SAE J2601 unless that issue is resolved first.
- The project should proceed and continue with its planned future work.
- There are no recommendations for increase or decrease in scope.

Project #SCS-031: Assessment of Heavy-Duty Fueling Methods and Components

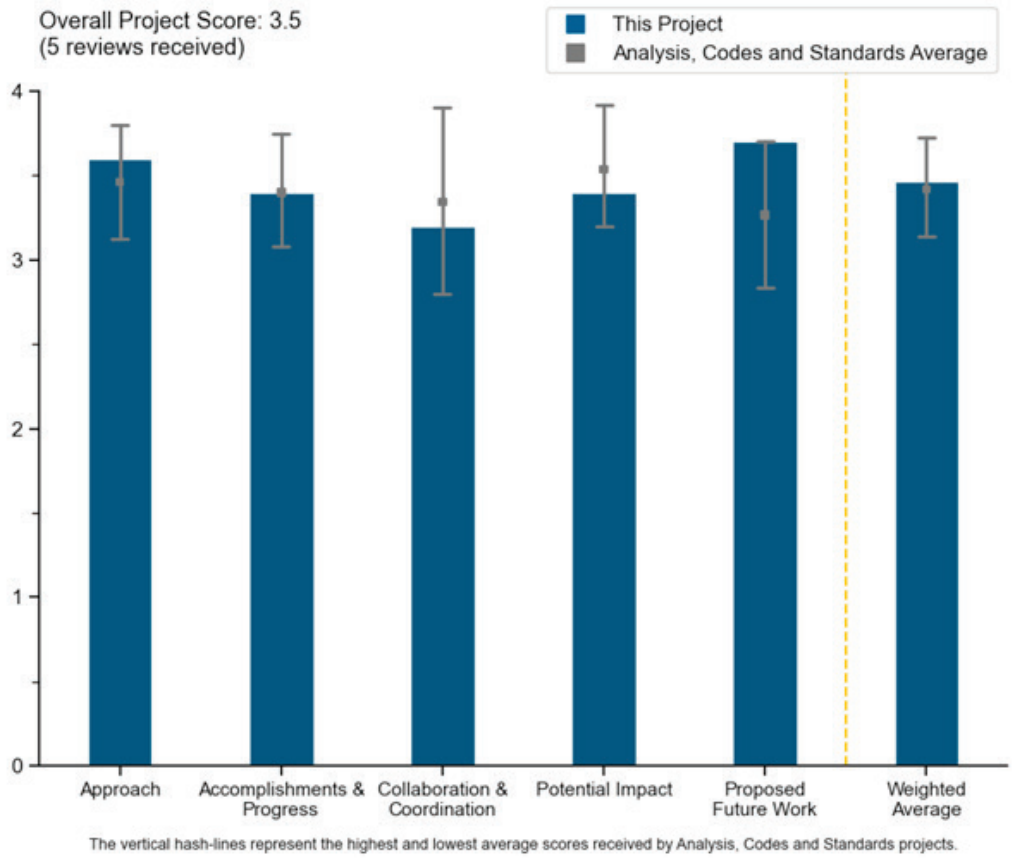
Shaun Onorato, National Renewable Energy Laboratory

DOE Contract #	WBS 6.2.0.504
Start and End Dates	2/2/2022–2/1/2024
Partners/Collaborators	Argonne National Laboratory, NextEnergy, Chevron
Barriers Addressed	• Limited availability (globally) of heavy-duty hydrogen fueling infrastructure to evaluate the performance of fueling protocol concepts and hardware • Lack of understanding of how heavy-duty fueling concepts will influence infrastructure and vehicle design, specifications, and cost • Lack of robust modeling tools for heavy-duty fueling concepts

Project Goal and Brief Summary

The goal of this project is to develop a comprehensive assessment of heavy-duty (HD) fuel cell electric vehicle (FCEV) fueling protocols and hardware to understand their impacts on station design, vehicle design, functional safety requirements, and total cost of ownership (TCO). The project involves evaluating prototypes and industry-supplied HD hydrogen fueling components and protocols at the National Renewable Energy Laboratory's research station. The project will also conduct modeling and analysis using computational fluid dynamics (CFD) and perform techno-economic assessments (TEAs) to determine TCO. This project aims to provide information and data to industry stakeholders, support the uptake of hydrogen-powered HD vehicles, and build clean energy infrastructure.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project has a great approach, with the hardware evaluation feeding into the modeling efforts, and then the iterative process of performing analysis, to then go back and improve the model—and all this while coordinating with the many partners/collaborators.
- Lack of an HD fueling protocol is a barrier for the industry. The multi-pronged approach of developing the fueling protocol/hardware with advanced CFD modeling capabilities and a techno-economic tool provides a full evaluation of the protocol, including the impacts to the vehicle equipment and station design.
- This project is well-thought-out, is well-connected, has a team of partners that are well focused, and provides excellent feedback to the project management.
- The project addresses an industry need for hardware, modeling, and analysis to facilitate HD FCEV fueling.
- The project has a good approach on filling a big industry need to validate HD fueling components.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- The progress demonstrated is very good to excellent—particularly good progress during the pandemic. There is concern about the CFD modeling and the interpretations of the results. The principal investigators showed two jet entrances into the tank, one straight on axis and one jetting at an angle. The discussion indicated that the angled jet was deemed better because it promoted increased turbulence within the tank, thus mixing the fluid better than the straight-on injector. While there is no problem with that observation, there is a problem with the jet impinging on the tank wall. It is not the fluid temperature that is of interest but the tank material temperature, specifically the liner. Impinging a hot jet on the tank wall will increase the temperature of the liner and could result in permeation damage. Because of the Joule–Thompson effect under these conditions, this jet will heat up when it expands—the jet will be hot. The researchers have the data to investigate this phenomenon.
- The project team has been able to accomplish 60–100 kg in less than 10 minutes without exceeding the temperature limits of the vessel, which is impressive progress. It seemed like many people in the room did not know that a model for doing this type of fill already existed (a link was provided on slide 11). Surely many people will be checking out this link/application.
- It was very exciting to see that HD fueling has occurred. The fueling needs to be conducted with the final hardware and tested significantly to ensure robustness.
- The project has good accomplishments and progress toward meeting DOE goals.
- Commendable progress has been shown in all three areas of the project focus.

Question 3: Collaboration and coordination

This project was rated **3.2** for its engagement with and coordination of project partners and interaction with other entities.

- The collaborators are perfect for the project's work. It also appears that a concrete active line of communication is maintained, which should yield transparency and excellent working environments. The collaborations with the standards development organizations (SDOs) (International Organization for Standardization [ISO], SAE International, etc.) are also spot-on.
- The project has good coordination with industry and collaboration to support refueling protocol development for 70 MPa high-flow fueling.
- Although existing partners bring many key players to the table, future collaborations expanded to a broader set of industry partners, as well as to codes and standards committees and working groups beyond ISO/TC (technical committee) 197 WG (working group) 5 and 24, would be beneficial. In particular, hoses are included as a hardware component, and a relationship with ISO/TC 197 WG 22 is essential to facilitating

an international standard on hoses for HD FCEV refueling. ISO/TC 197 WG 20 addresses valves, including the dispenser breakaway. Several ISO/TC 197 component working groups have industry experts expressing a need for HD hardware requirements quickly; however, the working groups do not yet have any performance metrics with which to identify or develop suitable requirements or testing. The project should consider sharing HD component performance requirements with ISO/TC 197 (beyond WGs 24 and 5) to facilitate development of these requirements.

- This project has good coordination with industry partners. The project should coordinate with a standards organization to adopt the fueling protocol into a standard for rapid adoption of the fueling protocol.
- The project has a great number of partners. NextEnergy is an industry/partner group on its own. It is unclear in the slides how well this group is coordinated and tied into this effort.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- On completion of this work, the United States will have its first validated model of the fill physics during a fueling process. This is critically important to creating a "filling" protocol to fill hydrogen tanks on board vehicles (light-duty, medium-duty, and HD vehicles) to meet the customers' requirements. This project is on track to do just that.
- Defining the HD fueling protocol and developing the proper hardware will significantly accelerate the infrastructure build-out of HD fueling stations and the adoption of HD FCEVs.
- The project is certainly impactful and fills a substantial gap within the domestic and international hydrogen community.
- The project's work is very important in facilitating deployment of suitable hardware and protocols to support HD FCEV refueling.
- This project helps contribute to achieving four DOE goals.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- Future work should focus on definition of the HD fueling protocol and rapid industry adoption of the fueling protocol by partnering with a standards organization. For hydrogen fills to be a realistic tool, the actual cost and performance of equipment should be utilized from companies operating equipment.
- The proposed future work is needed for this project/effort to improve the hardware <=> modeling <=> analysis iteration, which will feed into regulations, codes, and standards; recommendations for hardware on stations; and enabling of adoption of hydrogen-powered HD vehicles.
- The proposed future work aligns well with the need and timing.
- The project's plan is spot-on with respect to achieving the project's and DOE's goals.
- Proposed future work is focused toward achieving project objectives in all three project areas.

Project strengths:

- The project is developing a model of the fill process in a hydrogen high-pressure tank during the fill process. The project compares results with other models internationally (e.g., PRHYDE [PRotocol for heavy-duty HYDrogEn refuelling]), which is excellent. The project also is on a few SDOs (ISO WG 24, WG 5, SAE 2601, etc.) to help guide that development.
- This project's work on fast fills, HD fuel cell applications, and modeling/analysis/applications for industry and the public to use will greatly help shepherd in a hydrogen economy.
- The project is well timed because industry is actively looking for a clear HD fueling protocol.
- This project is unusual, as it addresses hardware, modeling, and analysis.

Project weaknesses:

- Attention is needed to all the details provided by the modeling effort (e.g., the comment about jet impingement). This is easily dealt with simply by coding up the tank material and monitoring the temperature, pressure, and space–time history of the entire system. That will be very instructive.
- The project timeline should be accelerated to release the final protocol and equipment. The HD fuel cell market is awaiting these components before the HD fueling infrastructure can be widely designed and installed.
- The project should expand collaborations with industry partners and codes and standards bodies to meet objectives.
- Peer evaluation of the internal tank temperatures achieved during the fast-fill tests could be of benefit. The data appears to be inconsistent with other test facilities' knowledge and experience.

Recommendations for additions/deletions to project scope:

- This is a very good project in execution, planning, and collaborations. The only recommendation is to code up the tank material, along with the gas phase, and calculate the temperature, pressure, and space–time history throughout the filling process. That will prove to be very interesting. Having a complete validated computational package in the United States will be very valuable.
- Liquid hydrogen onboard solutions are ideal for semi-truck applications. A liquid hydrogen fueling protocol and the associated hardware will be a barrier for the industry. Addition of this scope is recommended to support adoption of fuel cell electric semi-trucks.
- There may be a need to support a broader set of codes and standards development committees and working groups beyond the two-year timeframe for this project to ensure the project learnings can inform developing requirements for HD FCEV refueling components.
- The project could find more ways to advertise the hydrogen fill website link/application to a bigger audience.

Project #SCS-033: Risk Assessments of Design and Refueling for Hydrogen Locomotive and Tender

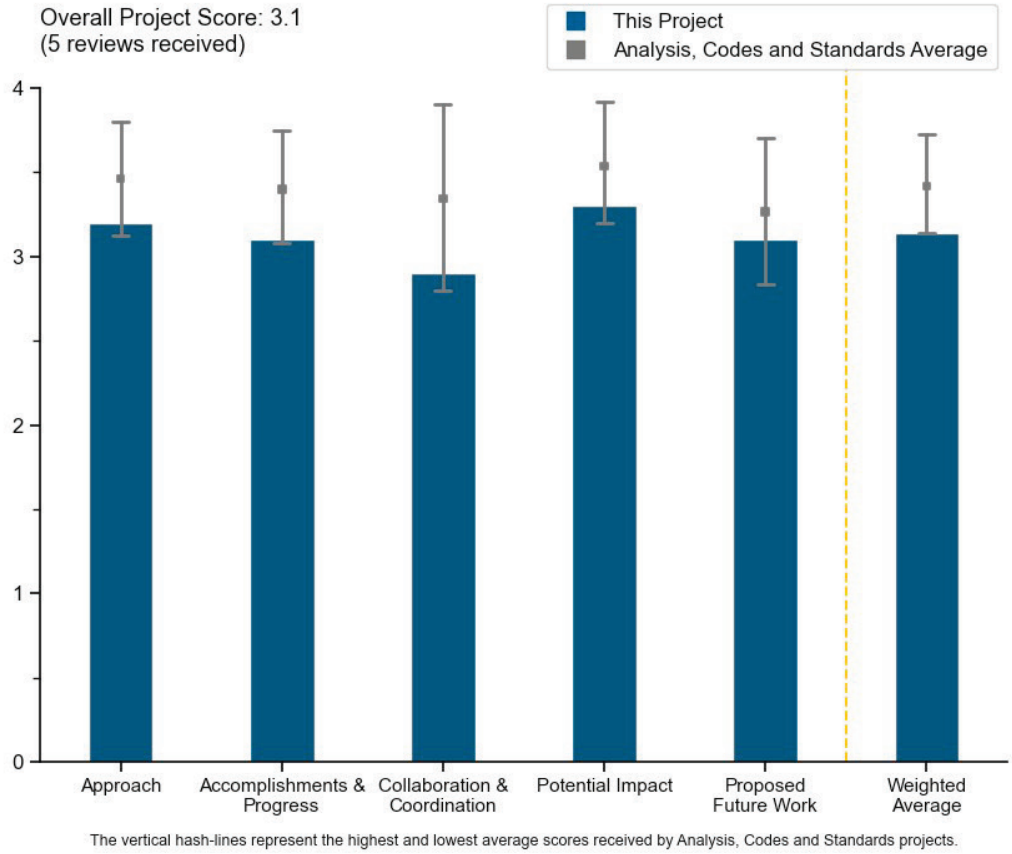
Brian Ehrhart, Sandia National Laboratories

DOE Contract #	NL0038749
Start and End Dates	2/1/2022–12/31/2023
Partners/Collaborators	Wabtec Corporation
Barriers Addressed	• Lack of requirements for new applications • Lack of scientific bases for defining requirements • Lack of widespread dissemination of safety-related information resources

Project Goal and Brief Summary

The goal of this project is to utilize qualitative and quantitative risk assessments to enable the near-term deployment of hydrogen-powered locomotives. The project aims to inform the regulatory community about the developments, needs, and identified gaps in the hydrogen-powered rail transportation sector that require attention. Existing codes and standards developed for conventional fuels (e.g., diesel) will serve as a starting point. Failure mode and effects analysis (FMEA) or a hazard and operability (HAZOP) study will be conducted to generate qualitative and quantitative risk ranking for hydrogen release scenarios, and fault tree and event tree analyses will be used to quantify risks in refueling processes and transfer scenarios. The results will help improve safety measures, inform design modifications, and contribute to the development of specific codes, regulations, and standards for hydrogen-powered rail systems.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project's goals and barriers have been clearly identified. Additionally, the project is well-designed and thus easy to follow.
- The goal of the project is to create a qualitative risk ranking for release scenarios for a hydrogen-powered locomotive by applying FMEA and HAZOP studies. This should be valuable to the railroad industry, which is an important part of national transport infrastructure. However, the reporting constitutes that of a high-level progress report, with few details describing the findings from the FMEA and HAZOP analyses. Little except the most general information about the application was provided. The explanation offered for the lack of detail was that the information was of a proprietary nature. As an approach, this may be good for the developer of hydrogen-powered rail to receive expert government-furnished help, but it does not enlighten regulations, codes, and standards (RCS) efforts.
- Proposed approaches to the technical work are appropriate. The use of Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) to develop the release and consequence behaviors is strong. More detail could be provided on which standards are being followed to conduct the FMEA or HAZOP, what the team configuration is, and what type of expert reviewers are being engaged. These are important considerations for determining the appropriate execution of the proposed work. The proposal to use fault tree analysis is sound, but it is unclear which validated tools or solution methods will be used to conduct this analysis.
- The approach was methodical and thorough with regard to individual leak sources. However, quantifying the number of failure modes and leak sources as a milestone seems odd and seems to be trying to force something that might not be there. The project mentioned an FMEA or a HAZOP being completed and then proceeded down the path of the FMEA. A HAZOP, at least to consider the potential differences that pertain to rail, could also be helpful. It is not clear whether previous refueling experience from National Fire Protection Association (NFPA) 2 was applied as a starting point for the risk analysis. It is also unclear whether rail fueling is expected to be significantly different from on-road heavy-duty vehicle fueling and, if so, how.
- Goals are clearly defined, along with relevance and potential impact. The project is clearly focused on RCS. The milestone table (slide 6) is valuable to understanding project effort and status. The risk analysis approach is centered on hydrogen gas leaks in locomotive and tender equipment. The fueling center is not in scope.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- This is a new market, and validating the safety of the overall activity can lend assurance to many that the activity is acceptable. The project laid out milestones and is working through them.
- Project slides provided clear status in the milestone table (slide 6) and in the progress slides (7–9) of effort toward project goals; however, no information was provided comparing activities against DOE goals. RCS scope contributes to DOE goals, but the project needs to clarify effort. The basic approach slide has the project conducting either an FMEA or a HAZOP. It was not clear which was performed. It is not listed in the milestone chart. Data on slide 7 can be used to infer an FMEA was performed. Reasons were not given why the HAZOP was not performed. It was unclear what specific risks are being evaluated, as noted on slide 8. A leak by itself has minimal risk to personnel unless ignited, so it is unclear whether the risk is a fire or deflagration. It is unclear whether personnel protective barriers in the locomotive are being assessed for failure, i.e., if a steel plate is being used to protect people in the locomotive cab from a deflagration and if failure of this barrier is being evaluated. This would seem to be a key protective feature mitigating risk.
- While the impression is that more in-depth results have been received, the poster did not effectively articulate the accomplishments to date. Instead of accomplishments, the poster provided a restatement of the proposed methods. The milestones state that, in the past year, failure modes were identified, outreach to the Association of American Railroads was conducted, and likelihoods of leaks were estimated. However, none of these results were described in depth in the poster or in follow-up questioning by the reviewer. It

would be instructive for the team to publish specific results. The reviewer would like to rate this section higher, but the documentation of the accomplishments is too vague.

- Although this project is relatively new, substantial progress has been made. However, since the project is due to end by December 2023, further information is needed on how the team plans to complete the four remaining 0%-completed milestones.
- The progress reported indicates a useful expenditure of effort. The results are so general that how the results apply to the locomotive setting is not clear.

Question 3: Collaboration and coordination

This project was rated **3.2** for its engagement with and coordination of project partners and interaction with other entities.

- This is an excellent example of industry coordination, involving a national laboratory, Wabtec, and American Public Transportation Association (APTA) working groups. Compared to other projects with similar budgets, this project has a relatively small amount of collaboration, but the quality of collaboration appears strong, with frequent meetings among the collaborators. The work would be strengthened by engaging additional expertise from the quantitative risk assessment (QRA) or process safety community or consulting firms.
- Wabtec was clearly a valuable partner and key contributor to the effort. Involvement of the regulators was also a good aspect of the project, as is the involvement of the APTA. It would have been helpful to have included other railroad manufacturers or possibly an end-user railroad operating company for their perspectives on their rail operations. HAZOP studies and FMEAs are typically required to have an "operator" for their input. Wabtec may have been able to provide a broad perspective of relevant experience, but additional parties at the beginning stage are usually helpful for brainstorming.
- The project presentation did not specifically identify collaboration with any entity other than the APTA. It is expected that the project would utilize peer review of the approach and data used in risk assessments with other national laboratories and national and international working groups working to qualify equipment and instrument failure rates. For example, the Center for Hydrogen Safety is specifically working on collecting failure data in hydrogen operations. This was not noted. Slide 9 did mention that Federal Railroad Administration (FRA) regulations apply to locomotive design, but the project did not identify how it is working with FRA to qualify data for risk analysis, nor did the project identify the gaps in FRA criteria. Slide 9 mentions that refueling facilities will "likely" be subject to NFPA 2 but fails to identify how this is relevant to the project since the project scope is only the locomotive. NFPA 2 will clearly be applicable to any hydrogen storage and fueling facility, suggesting that the project is unaware of key criteria in the code; similarly, the presentation did not mention the clear gaps in NFPA 2 for prescriptive criteria applied to locomotive operation. Slide 11 identifies collaboration with Wabtec, but this relationship is better understood as a client; therefore, the data provided may represent a potential conflict of interest in promoting Wabtec's design.
- Excellent collaboration exists with Wabtec since Wabtec provides vital information and there is consistent bi-weekly correspondence. However, the inclusion of more project partners would add breadth to the project.
- The work is coordinated with the FRA and NFPA 2 with participation of the APTA. This coordination with regulators and standards organizations is essential, but the only industry member is Wabtec.

Question 4: Potential impact

This project was rated **3.4** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- Development and dissemination of safety information is a highly necessary enabling activity. The project is on track to make strong advances for the Hydrogen Program. The detailed project results must be made public to meet the goal of widespread dissemination of safety information and to fill the technical gaps. The FMEA is a good start and should be published to allow stakeholders beyond Wabtec to benefit from the detailed safety insights developed. Furthermore, if the work continues as planned to include a rigorous QRA, as discussed, it will represent excellent progress toward the use of a scientific basis for RCS requirements. The work is especially powerful because of its blend of qualitative and quantitative

techniques with scientific underpinnings. The team should be encouraged to include full details of both the qualitative and quantitative pieces in its reports.

- This project aligns well with the Hydrogen Program. It has the potential to significantly advance progress toward DOE research, development, and demonstration goals and objectives since it is crucial to have a risk assessment of a relatively nascent application of hydrogen (e.g., hydrogen-powered locomotives).
- The project clearly aligns with DOE goals to expand the use of hydrogen as a clean fuel in a particularly difficult application.
- The project qualifies progress toward its major goals but fails to qualify this progress and future effort toward any DOE goals. Alignment with DOE goals supporting rollout of new hydrogen technologies can be inferred.
- The beneficial impact is that the FRA becomes familiar with hydrogen and rail issues. Wabtec benefits with expert assistance. It is not clear, beyond a generic rendition of how the analyses proceeded, how industry in general is helped.

Question 5: Proposed future work

This project was rated **3.7** for effective and logical planning.

- The future work extends analysis and examines different sets of hydrogen rail refueling. Also promised is evaluating the variability of risk and potential improvements for safety. The most important aspect is the goal of performing a gap analysis for rail-related RCS.
- The project has effectively planned its future in a logical manner by establishing reasonable future steps. For instance, performing a gap analysis of regulatory codes and standards is paramount and critical.
- The future work listing is consistent with project goals and the completed scope thus far. Future effort fails to identify any effort addressing the key barrier of limited data for hydrogen equipment failure rates. There are other hydrogen-fueling-related RCS that most probably apply to the project scope that are not listed for future evaluation, such as SAE International fueling protocols and the Compressed Gas Association (CGA).
- NFPA 2 is referenced as part of future work. It would be helpful if a section on rail fueling would include the results of the risk study, along with an annex note that this work has been done and perhaps a summary of the paper.
- Strong technical work is planned. The team should clarify how peer review of the FMEA and QRA results will be conducted.

Project strengths:

- Scientific approaches to RCS development are commendable and important. They provide meaningful progress toward reducing DOE-identified barriers. Using QRA provides a powerful, objective basis for developing safety insights and recommendations.
- This project can advance the rail market by serving as a means to assure people that the activity can be safe. It is good to see that the work will be publicly available through publication of a paper. The partners were well suited to do the work.
- Strengths include the working relationship with the key client (Wabtec) on specific component and design information, a passionate attitude in the project team, and selection of multiple components in risk scenarios.
- The project demonstrates to the FRA the future importance for rail carriers to perform FMEAs and HAZOP studies and what these analyses entail.
- The project is filling in knowledge gaps and guiding the applicable regulatory community.

Project weaknesses:

- There is minimal collaboration to qualify equipment failure rates. No peer review or analysis of data was identified. There were no source citations of equipment failure data. Risk analysis is limited to failure producing a leak without consideration of combined risk of ignition sources. For example, a leak that results in direct hydrogen flow away from any ignition sources is much lower in risk than a leak in an

ignition-rich environment. Another weakness is failure to formally qualify the project against DOE goals. Also, the project fails to qualify the experience and value of Wabtec data. Finally, as a new industrial application, it is unclear how Wabtec's design is incorporating necessary safety equipment and features so that the project can have high confidence that it is evaluating failure of key equipment.

- Weaknesses include lack of articulation of specific results to date. There is also a lack of detail on configuration of the analysis team and engagement of external reviewers in the process. It is unclear which specific codes or standards will be informed. The collaborations would benefit from more perspectives.
- One barrier mentioned in the project is the lack of widespread dissemination of safety-related information resources. However, the H2Tools website provides various safety-related resources.
- The findings are pretty high-level, and it is difficult to understand what specifically the analyses addressed.
- A weakness is the lack of a HAZOP study along with the FMEA.

Recommendations for additions/deletions to project scope:

- It is unclear what is being achieved by the milestone of presenting results to minority-serving institutions or similar educational groups—whether this is a mechanism to engage experts from diverse backgrounds, to increase engagement with universities, or to mentor students from underrepresented groups. The team should articulate a clearer goal and develop a strategy to meaningfully engage educational groups from a variety of institutions to achieve these goals.
- It is recommended that the project involve peer review collaboration in its risk analysis and investigate equipment failure data from multiple sources. It is also recommended that the project investigate other RCS sources (e.g., SAE International and CGA) for failure data and code gaps.
- The team should perform a HAZOP study on the actual fueling activity, as well as co-location of a dispenser and fueling equipment in a rail yard.
- A recommendation is that future industry participants must share findings more openly.
- The project should proceed and continue with its planned future work.

Project #SCS-H2042: Hydrogen Contaminant Detector

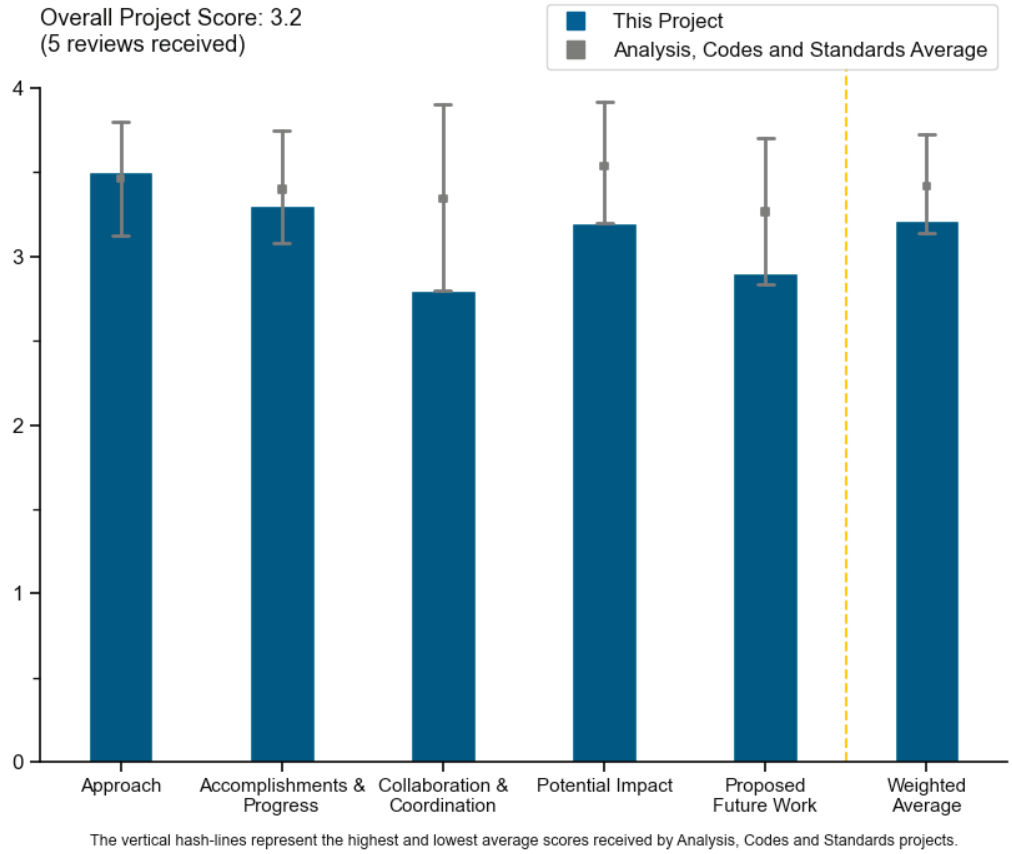
Matthew Post, National Renewable Energy Laboratory

DOE Contract #	WBS 8.6.2.1
Start and End Dates	10/1/2021–12/31/2023
Partners/Collaborators	Sandia National Laboratories, Argonne National Laboratory, California Governor's Office of Business and Economic Development, California Air Resources Board, California Energy Commission, South Coast Air Quality Management District
Barriers Addressed	Lack of information on operation and evaluation of high-flow infrastructure for heavy-duty hydrogen vehicles including: • Infrastructure examples • Tools to evaluate designs • Test devices for performance

Project Goal and Brief Summary

The goal of this project is to ensure safe and reliable hydrogen fueling by addressing the need for improved contaminant detection in hydrogen fueling infrastructure. The project will identify and evaluate viable hydrogen contaminant detector (HCD) technologies for real-time, in-line verification of hydrogen fuel quality. The project involves selecting promising HCD instruments and testing them to SAE J2719 fueling standards. Identified detectors will be integrated into high-pressure hydrogen fueling stations, including the National Renewable Energy Laboratory's (NREL's) Hydrogen Infrastructure and Testing Research Facility (HITRF) and the forecourt of a California hydrogen fueling station.

Project Scoring



Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project seems to focus on sampling techniques more than detection techniques, which is fine. As such, the work can definitely help meet the project goals by creating a stable sampling system for assessing different HCD technologies. Two different detectors have been looked at; whether they are most effective depends on what specific contaminants are being sought.
- The project's objectives/goals and critical barriers are clearly identified and have been addressed. The project is sufficiently designed and easy to follow. Its approach is clearly delineated into several parts.
- The approach process is logical and well-thought-out. Testing plans are valid and adequate for minimal data-gathering. The graphic wheel on slide 6, for ranking characteristics, is outstanding.
- The approach of the project is to develop a system with which to test HCDs. In that regard, the test setup appears to be well done, and a test facility has been developed. The larger question of whether an HCD is going to be practical is a related, but separate, question.
- The concept is very relevant, and work has illustrated some important practical issues for deployment. The practical advancement seems somewhat limited. The choice to focus only on CO contamination in this round of work is understandable but also limits impact. The ability to detect in near-real time is good. It is not clear how that can be parlayed into proactively preventing contaminated hydrogen from being deployed; this should be the goal, rather than indicating in near-real time that the fuel cell has already been contaminated by the fueling event in process.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- Excellent progress toward project objectives is proven by the project's clear and measurable performance indicators. The extensive and well-detailed slides in the reviewer-only slides are much appreciated. Lastly, the visual aids (e.g., pictures of the NREL dispenser HCD interface and enclosure) show the project's accomplishments.
- It appears that the test facility is set up and tested, so it is a major accomplishment to now have a location to do such testing.
- Identification of the top two HCD methods meets specific goals. Development of test apparatus and integration with the NREL system are outstanding. Appropriate safety precautions (personal protective equipment) are noted in slide pictures. However, there are several weaknesses in the presentation, validated by questions to the principal investigator, that prevented accomplishments and progress from being outstanding. First, there is no project timeline/bar chart/Gantt chart noting project status compared to a schedule or goals. Second, the investigation evaluated several detector systems, but only two are noted on the presentation. The project should list all instrument systems reviewed and provide a general ranking conclusion. The identification of only two instrument approaches is difficult to understand from just the data provided in the slides.
- The project milestones and go/no-go decision points are not clearly identified in the materials provided for reviewers. This makes it difficult to gauge the progress. Qualitatively, the description of progress shows advancement in CO contaminant detection, which has apparently been identified as the primary focus in executing the project.
- The project has set up a good sampling system and tested two different HCD technologies. However, perhaps there are other HCD technologies that should be considered.

Question 3: Collaboration and coordination

This project was rated **2.8** for its engagement with and coordination of project partners and interaction with other entities.

- The specific collaboration activities with Los Alamos National Laboratory (LANL) are excellent. Presented data could be clearer by noting collaboration effort matched to project approach/goals. It is unclear whether

the project plans to hold, or has held, discussions with industrial manufacturers or industry technical groups (e.g., the Microelectromechanical Systems [MEMS] and Sensors Industry Group). This interface would be valuable for validating the breadth of sensor investigation, validating the state of the art for applied technology, and identifying deployment issues for future scope.

- Collaboration with LANL is noted and seems to be well positioned for potential positive outcomes. Work with the California Air Resources Board and station operators has not been productive yet, and there is not sufficient information provided to anticipate future progress or removal of blockers.
- There is sufficient collaboration with partners such as LANL (e.g., providing electrochemical sensor and other services, e.g., evaluation). However, partnership and collaboration with industry and standards development organizations need to be included.
- The collaboration with LANL on the CO detector is good. In addition to that detector and the Fourier-transform infrared (FTIR) spectrometer, it would be good to look at two or three additional detectors to see how the sampling system works more broadly.
- It would be better if there were a fuel station provider partner to enable the installation of an HCD at a fuel station location and to provide feedback on what is realistically deployable. Even if that is part of a future project, the test apparatus, as configured at NREL, appears as if it would be very challenging to deploy at a fuel station, given the space and utilities required.

Question 4: Potential impact

This project was rated **3.2** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project is critical to the Hydrogen Program and has the potential to significantly advance progress concerning hydrogen fuel quality and make fuel quality verification more efficient. It is important to make improvements when detecting hydrogen contamination, especially since current fuel quality verification protocol may prove inadequate. For a burgeoning, nascent industry such as the hydrogen and fuel cell industry, it is paramount to have adequate fuel quality verification protocol to bolster station commissioning.
- Work on scoping the range and impact of contamination modes and on practical detection of CO contamination are noted. DOE might find that these more modest accomplishments satisfy its goals and objectives. Work to support practical field demonstrations, address other contamination modes, and convert the new detection capabilities to effective mitigation of contamination appears to remain more aspirational.
- This is definitely a high-impact project since there are many contaminants that can cause temporary or permanent loss of performance in a fuel cell electric vehicle, and, as the network of stations with different sources of supply and different hydrogen production technologies is used, it will become more important to be able to monitor for contaminants in real time.
- There is no question that the HCD technology would be useful to have as an additional tool to ensure product purity. Valid questions, though, become “Is it needed?” and “Is it feasible and cost-effective?” In terms of need, the likelihood of contamination when H_2 is shipped to a site is low when compared to onsite production. The prevalence of contamination-inducing onsite production has been reduced to where maybe onsite monitoring of the full slate of contaminants is less important. The more common contaminants might not be CO or S but rather O_2, inert contaminants, H_2O, and maybe lubricating oil. Similarly, a target cost per kilogram should be estimated to see if the technology would ever be cost-effective based on expectations of the technology within 5–10 years.
- The presentation did not identify how the project aligns to DOE targets and performance goals. The impact can be deduced but appears to be primarily supporting consumer cost reduction in alignment with reducing hydrogen costs. The in-line testing for contaminants has a strong value in reducing supply chain costs and should be better highlighted.

Question 5: Proposed future work

This project was rated **2.9** for effective and logical planning.

- The project has effectively planned its future in a logical manner. For example, a technical webinar to educate potential stakeholders is an excellent next step. Also, expanding heavy-duty applications is necessary since hydrogen trucks will be an important part of the future of heavy-duty transportation.
- The list of proposed work is thorough and valid, especially for interface with industry. The two slides (Remaining Challenges and Barriers and Proposed Future Work) could be better amplified to describe scope yet to be completed and new potential scope derived from results and issues thus far. For example, the presentation could say whether the project foresees any revision to its scope or effort to address negative impacts from sulfur and ammonia on the FTIR testing protocol. Also, it is not clear what the difference is between uncompleted project scope and "proposed" future effort. For example, it is unclear whether testing at a commercial hydrogen fueling station is in the project scope or proposed future effort. This activity is listed on goal slide 2, approach slide 6, and barrier slide 18, yet it is also listed on proposed slide 19. The addition of a slide depicting the remaining scope to be completed would help qualify the issue. This type of testing project has great value to practical system operation, and the project has a unique place in defining the state of the technology and future thrust for industrial research. Identifying improvements and the path forward for industry would be helpful.
- Expanded practical demonstrations are proposed and would be relevant in gauging the potential real-world impact of the work.
- There are good plans to validate additional HCD technologies and to implement the system into the HITRF and into one or more retail stations to validate the system effectiveness.
- It is hard to question any individual item in the proposed work since all are needed, but that also means there is a potential lack of focus or potential to be spread too thin. It would be better to select two or three specific items and provide greater detail, goals, and milestones for each for more measurable results. Alternatively, the project might lay out the objectives with a realistic timeline that is based on the current (and future) technology and amount of resources and time available.

Project strengths:

- Use of actual scale instrument systems and NREL test equipment is extremely valuable, bringing the knowledge base forward beyond literature search and laboratory-scale testing. The principal investigator is passionate and knowledgeable of technology and testing protocols. The interface with NREL testing systems is logical and well planned; actual test equipment systems appear valid for appropriate data-gathering. The presentation and poster session photographs and charts were extremely valuable. The project earns kudos for preparing an actual poster rather than simply posting slide copies. The project has a great start and should help to practically advance the fueling industry.
- The use of an HCD can take the place of periodic and relatively ineffective batch sampling. In that regard, this could be a useful approach to ensure good product purity for situations where that is necessary. The project test facility was well designed and is available for its expected role. The project was also forthright about the challenges that the HCD technology will face and that question the validity of the approach.
- The work has resulted in new capabilities for CO contamination detection. Work to assess modes and impact of contamination supports future work targets.
- The project has set up a very practical sampling system to allow sampling on a per-fill basis.
- The project is laser-focused and easy to follow.

Project weaknesses:

- The testing and apparatus will be useful only if there is a credible HCD that can be deployed. As configured, this would be very challenging to deploy commercially to a station. As a result, the project is only as good as the HCDs that are available. A fair question is whether there will ever be an HCD that meets the needs of being able to cost-effectively measure the key contaminants. The project is not giving an assessment of two key items: (1) what the cost of a deployed HCD might be, along with expected operating costs and whether those costs are feasible for a fuel station, and (2) whether there will be an HCD that can

measure the full breadth of contaminants from CO to S to H_2O to inert contaminants, etc. If either of the above are not answered, then the testing may be of limited value.

- Understanding more about two potential weaknesses would be helpful. (1) Sampling is done when the hose is vented at the end of the fill, and that means that the sampling/detection is always "one fill behind." This seems like a concern, and it is not clear how the sampling system might be configured to take the sample at the beginning of the fill instead of the end. (2) It is acknowledged in the poster that contaminants such as sulfur and oil can be very "sticky" and, as such, can contaminate the inside of the sampling system, be difficult to clean, and possibly cause false positive detections. It was unclear whether consideration has been given to how to purge the sampling system or how to filter results to avoid "echoes" from previous contaminants.
- This is the first time this project has been reviewed at an Annual Merit Review. The basic data is provided, but more information would be helpful to understand the investigative process, alignment with DOE goals, and project status. Additional collaboration with industry would be very valuable since the project involves actual sensor systems at scale. Identification of a complete listing of considered instrumentation is lacking, along with the results of the strategic evaluation. Safety planning should be described.
- Significant challenges remain to be addressed, and the plans to mitigate risk are not entirely clear. Practical field demonstrations will be important and have not occurred beyond the single installation. Some collaboration with LANL is noted, but the contributions of other project partners to the work that has been accomplished are not clear.
- More in-depth information on the numerical ranking of the prioritized specifications and the estimated amount of time used for real-time fuel quality verification would be appreciated.

Recommendations for additions/deletions to project scope:

- Addition of an amplified interface with industry and/or industry sensor groups is recommended. Deletion of the full-scale testing forecourt demonstration at a commercial hydrogen fueling station is recommended unless agreements are in place already and funding is available. Obtaining this agreement seems unlikely, with the risk a commercial fueling supplier would need to take on, and the demonstration would require a large amount of resources. Slide 3 notes that there is no planned Fiscal Year 2023 funding from DOE; remaining project dollars would be best used in completing testing at NREL and project improvements noted in the review. The NREL test facilities appear adequate to provide a full-scale demonstration and data collection instead of testing at a commercial facility.
- An estimate of a best-case installed cost of an HCD long-term should be added, as should a technical assessment of whether the concept of an HCD is feasible for this application, even given expected advancements in technology in the foreseeable future.
- If the narrowed scope is acceptable to DOE, driving to more practical validation of the CO detection might yield the most impact from this project as it currently stands.
- The project should consider purging the sampling system and sampling at the beginning of the fill.
- The project should proceed and continue with its planned future work.