# Analysis, Codes and Standards – 2024

## Analysis, Codes and Standards Subprogram Overview

### Introduction

The Analysis, Codes and Standards subprogram performs enabling activities to inform research, development, demonstration, and deployment (RDD&D) within the Hydrogen and Fuel Cell Technologies Office (HFTO) aligned with priorities in the *U.S. National Clean Hydrogen Strategy and Roadmap*. The subprogram comprises two key activity areas: Systems Analysis (SA) and Safety, Codes and Standards (SCS). The SA 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. Both the SA and SCS portfolios support workforce development and environmental justice activities that are coordinated across HFTO's subprograms.

The SA activity area funds crosscutting analyses to identify technology pathways that can facilitate large-scale use of clean hydrogen and fuel cell systems to enable decarbonization, enhance energy system flexibility and resilience, and advance energy and environmental justice. 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.

In Fiscal Year (FY) 2024, the SA activity area focused on user-friendly tools to characterize costs and emissions of real-world deployments, analyze costs and emissions of additional hydrogen production technologies, and incorporate hydrogen into energy market models used by the global community to identify scenarios to achieve 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 2024, the SCS activity area focused on approaches to streamlining permitting, research and development (R&D) on hydrogen release behavior and materials compatibility to inform codes and standards, and safety component R&D (e.g., sensors).

The SA and SCS portfolios have contributed to several additional HFTO outcomes related to workforce development and environmental justice, including (1) release of HFTO's first solicitation on development of best practices associated with community engagement within hydrogen projects, and (2) development of informational resources for the general public addressing benefits and common concerns associated with hydrogen.

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.).

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## Goals

The SA activity area informs 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. Key activities in support of these goals include:

- Developing user-friendly modeling tools that characterize costs and emissions of specific hydrogen production, delivery, and use technologies.
- Publishing technical reports that depict current and potential future supply and demand for hydrogen in scenarios with varying levels of R&D success.
- Coordinating analysis activities with other DOE offices and federal agencies, and informing activities with feedback from the private sector and nonprofits.

The overarching goals of the SCS activity area are to enable the safe deployment and use of hydrogen and fuel cell technologies and ensure that key stakeholders have confidence in their safety, reliability, and performance. These goals are 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 SA 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:

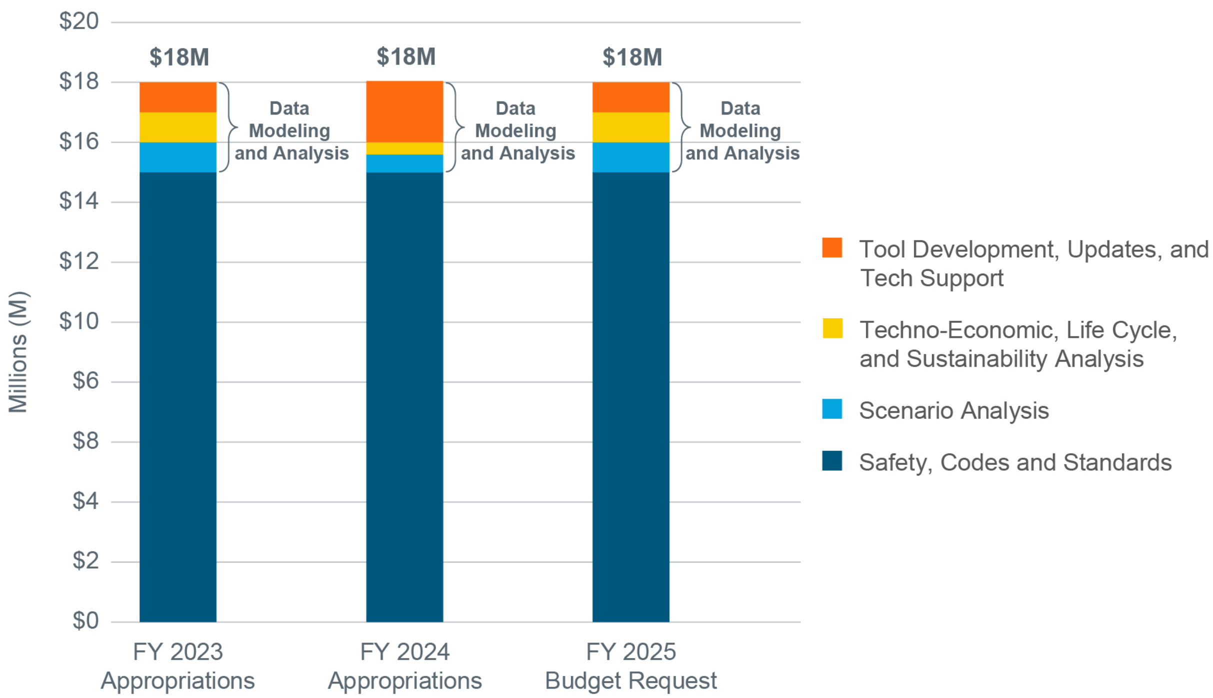
- Lay regulatory groundwork for large-scale clean hydrogen deployments across production, processing, delivery, storage, and end use. **(2025)**
- Develop streamlined guidance on hydrogen pipeline and large-scale project permitting with stakeholder engagement while addressing environmental, energy, and equity priorities. **(2025)**
- Develop hydrogen sensors with low-level (parts-per-billion [ppb]-level) detection limits. **(2025)**

- Develop hydrogen release quantification technologies to track emissions for environmental monitoring. **(2025)**
- Enable international harmonization of codes and standards related to hydrogen technologies. **(2030)**
- Address regulatory challenges to increase access to hydrogen electrolysis using renewable and nuclear energy. **(2030)**
- Develop national guidance for blending limits. **(2030)**
- Enable access to tunnel infrastructure for fuel cell electric vehicles in at least one new region. **(2030)**
- Support development of a Federal Motor Vehicle Safety Standard for hydrogen vehicles. **(2030)**

## Budget

The FY 2024 appropriation for the Analysis, Codes and Standards subprogram was $18 million. The budget for the SA activity area was $3 million; funding focused on development of user-friendly tools to characterize cost and emissions; analyses of cost, emissions, and sustainability; and analyses of hydrogen demand scenarios in strategic sectors. The FY 2024 budget for the SCS activity was $15 million and included funding for approaches to streamline permitting, R&D on hydrogen release behavior and materials compatibility, component R&D, safety resources and support, and community engagement.

The FY 2025 budget request of $13 million includes $3 million for SA activities and $10 million for SCS activities.



## Annual Merit Review Results

During the FY 2024 Annual Merit Review, 26 projects funded by the Analysis, Codes and Standards subprogram were presented, with 4 SA projects and 16 SCS projects reviewed (a breakdown of number of projects reviewed by budget category is shown in the table on the right). The reviewed SA projects received scores ranging from 3.1 to 3.6, with an average score of 3.3. The reviewed SCS projects received scores ranging from 2.8 to 3.7, with an average score of 3.3. The complete list of reviewed projects and the average score for each can be found in the Prologue Table.

Following are reports for the 20 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 | |
|---|---|
| **Systems Analysis** | |
| Tool Development, Updates, and Tech Support | 2 |
| Techno-Economic, Life Cycle, and Sustainability Analysis | 1 |
| Scenario Analysis | 1 |
| **Safety, Codes and Standards** | |
| Codes and Standards Harmonization | 3 |
| Component R&D | 3 |
| Hydrogen Behavior and Risk R&D | 7 |
| Materials Compatibility R&D | 1 |
| Safety Resources and Support | 2 |

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

Amgad Elgowainy, Argonne National Laboratory

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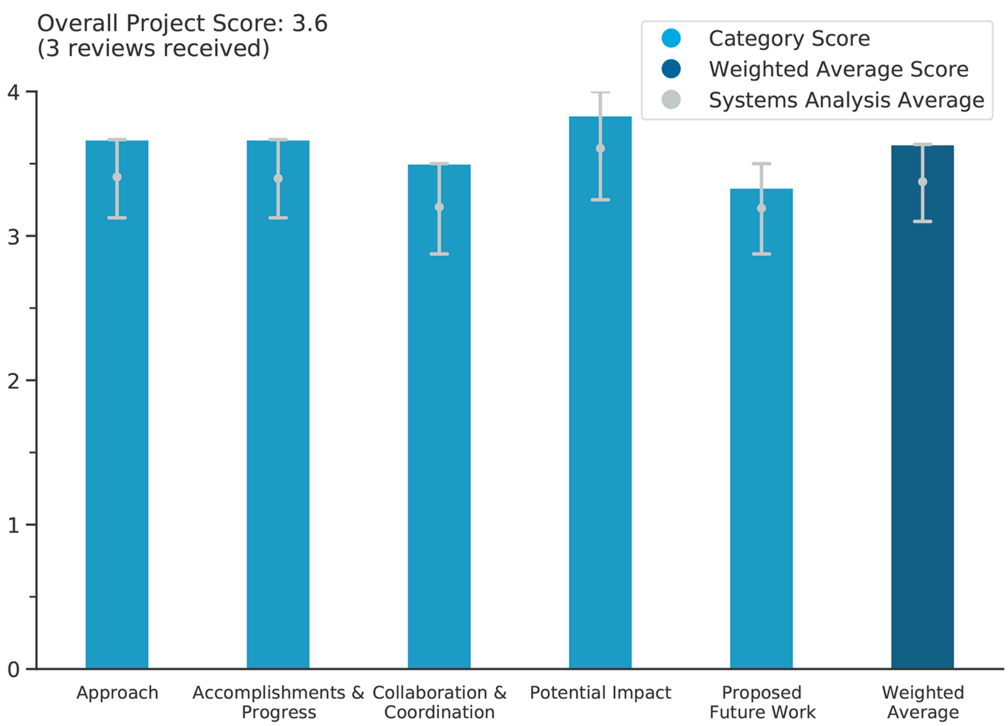
|---|---|
| **DOE Contract #** | 5.1.0.6 |
| **Start and End Dates** | 10/1/21 |
| **Partners/Collaborators** | U.S. DRIVE Partnership's Integrated Systems Analysis Tech Team, Strategic Analysis, Inc., Argonne National Laboratory Autonomie Team |
| **Barriers Addressed** | • Inconsistent data, assumptions, and guidelines<br>• Insufficient suite of models and tools<br>• 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




The vertical hash-lines represent the highest and lowest average scores received by Systems Analysis projects.

## 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 project approach is strong overall, incorporating relevant hydrogen technologies into the GREET and Autonomie models to investigate the life cycle impacts of different transportation technologies. The relevant technologies for road transportation and fuel production are well-represented. The partners appear to be well-utilized to provide needed technical information for the modeling work. The results comparing different pathways are generally clear and well-presented, highlighting strengths and weaknesses of each.

- Generally, the project showcases very good methodology, given the significant variability of inputs for the various types of vehicles and the impact on emissions overall. It will be difficult to provide accurate data on a project-by-project base; however, the approach provides an overarching framework to compare differing drive types and their relevant inputs.
- The approach adopted is well-aligned with the project objective to evaluate C2G economic and environmental impacts of fuel production and vehicle technology pathways.

### Question 2: Accomplishments and progress

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

- The expansion and update of data provide a strong reference set for helping to determine industry uptake and policy support settings for various vehicle types. Importantly, the project highlights some additional opportunities in the future, which can also create value and overcome barriers to uptake. In particular, the Class 8 work highlights the challenge of moving industry away from diesel, given the relatively small efficiency gains currently.
- The accomplishments presented this year are of great interest and allow an increased range of vehicles to be considered in GREET. For the GHG emissions, it is not clear whether wheels and tires have been included. If not, they have to be included. It is expected to see different values of GHG emissions from tires, depending on the weight and the type of energy used. Proposing the option of including capital expenditure emissions is really appreciated, as this is needed to ensure a fair and level playing field comparison between the different energy vectors. Using the GHG emissions of the components' production site is also the right approach. It is unclear how the GREET model compares the GHG emissions for transport versus International Organization for Standardization (ISO) 14083:2023. In the considered pathways, it is also unclear why low-temperature electrolysis is limited to renewable electricity and high-temperature electrolysis to nuclear energy. The lifetime and degradation rate used for the different electrolyzers should be provided for the GHG emissions comparison. Hydrogen produced from steam methane reforming (SMR)/carbon capture and storage (CCS) may be added to the figure as a reference.
- Good progress has been made on adding embodied emissions and making clear, useful comparisons between different vehicle technologies and fuel production pathways, highlighting the strengths and weaknesses of each.

### 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 partners appear to be well-utilized to provide needed technical information for the modeling work.
- There is strong collaboration with specialized expertise, which supports a more accurate dataset. It is possible that additional opportunities to collaborate more broadly would get better diversity into the assumptions.
- 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 transport sector transition is one of the critical first-adopter sectors that can facilitate offtakes and can accept a higher price of fuel source. Providing peer-reviewed data and analysis on different fleet options helps industry and policymakers to better understand the various options and impact on their organizational targets. The biggest challenge is the variability of inputs and the fact that the model is a snapshot in time and can rapidly change with transitional activities across a very wide range of inputs. Regular updates of assumptions will need to occur to maintain relevance in the market.

- The usage of GREET has a significant impact in the choice of transportation from an economic and environmental point of view and in terms of the level of potential subsidies. It is thus important to develop a transparent and reliable tool.
- The results of this work have high strategic value for the Hydrogen Program and the public in improving understanding of the environmental impact of different vehicle and fuel technologies.

### Question 5: Proposed future work

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

- The future work corresponds to the needs, in particular, to evaluate the total cost of ownership (TCO), which is usually the main decision driver.
- The future work is reasonable overall but vague. Publishing the C2G analysis and including TCO analysis are good future plans. It would be helpful to have a clearly articulated strategy for the selection of emerging technologies to study.
- There is a significant amount of change still occurring in the transport and energy sectors, which requires a continuing scan of potential impacts. The proposal to remain across this is important. In particular, the use of hydrogen in internal combustion engines, gaseous blends, etc. will require consideration. The incorporation of combined wind and solar options is important in reflecting the increased utilization and potential cost reductions of hydrogen production.

### Project strengths:

- GREET is a tool developed over many years with many users. It appears quite robust, and it is continuously improved owing to these kinds of projects.
- Good progress has been made in improving understanding of life cycle impacts from transportation technologies. There was a clear presentation of valuable findings from the project.
- Understanding overall sustainability of medium- and heavy-duty vehicle fleets is useful to all.

### Project weaknesses:

- There is no particular weakness to mention.
- The variability of inputs will require regular updating to ensure relevance in the future and utilization by industry to make informed choices.
- Aspects of environmental impacts beyond GHG emissions and energy use have not clearly been addressed.

### Recommendations for additions/deletions to project scope:

- In addition to the proposed future work, the impact of the hydrogen refueling station geographical density may be assessed.
- Expanding environmental impacts to include other pollutants (particulates, oxides of nitrogen, etc.) would be of value, especially considering recent interest in environmental justice related to energy technologies.
- The reviewer supports the consideration of combined wind and solar being evaluated in the future. This is likely to provide a much higher utilization of variable renewable energy (VRE) and further diminish the carbon intensity and operating costs of battery electric vehicles and fuel cell electric vehicles. For example, the utilization of an electrolyzer in South Australia using wind and solar will enable annual utilization in excess of 75% on VRE.

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

Page Kyle, Pacific Northwest National Laboratory

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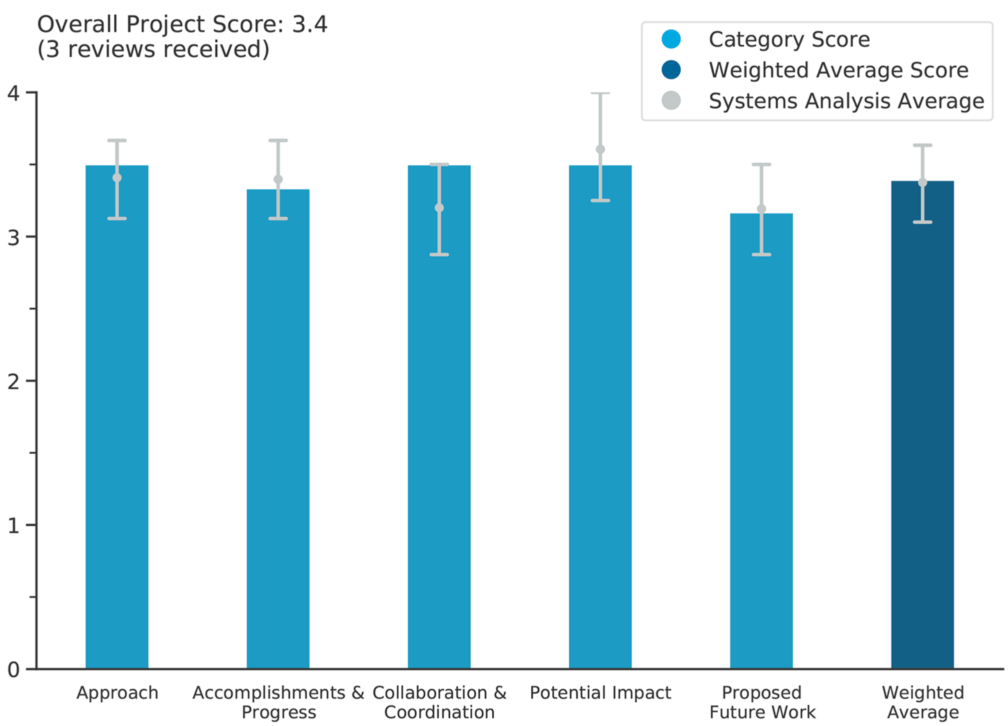
|---|---|
| **DOE Contract #** | WBS 5.2.0.107 |
| **Start and End Dates** | 05/1/2021 |
| **Partners/Collaborators** | Argonne National Laboratory, National Renewable Energy Laboratory, University of Maryland |
| **Barriers Addressed** | • Complexity of modeling structures<br>• Large number of assumptions to be reviewed<br>• 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 roles 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



The vertical hash-lines represent the highest and lowest average scores received by Systems Analysis projects.

### 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.

- Extending hydrogen into energy-system-wide models is critical to highlighting the value proposition and to enabling fair comparisons between hydrogen and alternative options. GCAM is a well-developed and functional platform to which to add hydrogen, and doing so effectively is critical for larger Hydrogen and Fuel Cell Technologies Office goals. The way in which the model is being applied so far is very granular but includes extending more broadly.
- The approach reflects the refinement of likely hydrogen end uses and supports the increased understanding of climate impacts by utilization of hydrogen more broadly. Taking it to a state-by-state estimate is useful in understanding regional variations for hydrogen production costs.
- The approach adopted is well-aligned with the project objective to update hydrogen in GCAM, which has long been needed.

### Question 2: Accomplishments and progress

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

- There appears to be good progress on expanding hydrogen end uses, production, and transmission and distribution options and incorporating updates in the model. It is important to consider the impact of replacing the use of fossil fuels with clean hydrogen. In the structure of hydrogen in the GCAM model, the usage of a pressure of 35 MPa in pipelines is not realistic (6-8 MPa currently). The presentation of quantitative results would be appreciated in the future to better assess the model. Perhaps regional criteria could be included in Hector. The team should consider how the infrastructure cost is integrated in the model.
- The model update is planned for release in June 2024 and keeps GCAM contemporary.
- The proprietary nature of how the model has been exercised is a real limitation in this area, as no results have been presented. Once the model is made public or if qualitative results could be shared, it would be easier to assess. Eventually, when modeled results become available, this will be easier to assess.

### 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 collaboration is at an appropriate level. It is a small project, centered at Pacific Northwest National Laboratory, and this seems exactly appropriate.
- There is good collaboration with other labs and utilization of their expertise for input data.
- The level of collaboration appears correct for this project.

### Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- There is a huge need to include hydrogen in energy-system-wide models. GCAM includes all of the content for areas such as water impact, criteria air pollutant impact, and global warming potential impact, which makes GCAM a great platform. Hydrogen needs to be in a complete system context to be evaluated fairly against other options.
- Understanding the role of hydrogen in the GCAM model and its potential impacts on climate change and decarbonization will be important in informed decision-making by policy makers and industry alike. Still more work is planned to improve outputs from the model.
- As the model is being considered in Intergovernmental Panel on Climate Change reports and high-profile climate studies, this may have a significant impact in including the evaluation of hydrogen in supporting global climate goals. However, the real impact is difficult to gauge, as GCAM appears complicated, and no quantitative results have been presented.

### Question 5: Proposed future work

This project was rated **3.2** for effective and logical planning.

- There are good plans for co-located wind/solar resources—which can often lead to much higher utilization in some areas and lower production costs. Behind-the-meter/onsite production of hydrogen will likely be an important part of the mix, so adding this to the model will support better decision-making. This is interesting work on hydrogen in the atmosphere and its impact—this will be useful.
- The future work corresponds to the needs with some proposed additions. The team should:
  - Include the use of nuclear electricity—and not only solar and wind—in the electricity mix for hydrogen production.
  - Consider a holistic and systemic approach when assessing the atmospheric hydrogen impact on climate and not only the hydrogen emissions along the value chain.
  - Consider the sources of $CO_2$ when producing e-fuels.
- The model's release, planned for the next month or so, is probably the most important piece of the future work. Once public, model results can be shared more openly, and the true value of the work and any shortcomings can be better assessed.

### Project strengths:

- The project is of utmost importance, considering the widespread use of GCAM in high-stakes climate and technology modeling. Hydrogen has to be considered as a climate solution. Therefore, the expansion of hydrogen end uses and transmission and distribution technologies appears relevant.
- The model is used widely in informing climate change reports. Maintaining and updating the model is critical to having more effective and more accurate information included in these reports.
- Hydrogen needs to be considered in an energy-system-wide model, and domestically, this is the only project looking to do so.

### Project weaknesses:

- Variability of the data on a project-by-project basis makes it difficult to get granularity of accuracy; however, it provides an overarching view of climate impacts and the role of hydrogen in the economy.
- The focus on small nodes is likely driven by political considerations and the idea that all hydrogen will be generated and consumed locally. Going larger and using the electricity grid and/or hydrogen/natural gas pipelines to come up with more global optimums rather than local optimums is something that has been proposed in future work but has not had the level of effort that would be preferred.
- No quantitative results have been presented, which makes the assessment of the model quite challenging.

### Recommendations for additions/deletions to project scope:

- The team should support the proposed work plan included in the presentation.
- Hydrogen has to be considered as a climate solution from a systemic approach, with clean hydrogen replacing unabated fossil hydrogen in existing applications and clean hydrogen replacing fossil energies in new applications.
- The team should integrate more larger-scale simulations and ready access to areas that include water, criteria air pollutant, and global warming potential impacts.

# Project #SA-187: Heavy-Duty Hydrogen Fueling Station Corridors

Mark Chung, National Renewable Energy Laboratory

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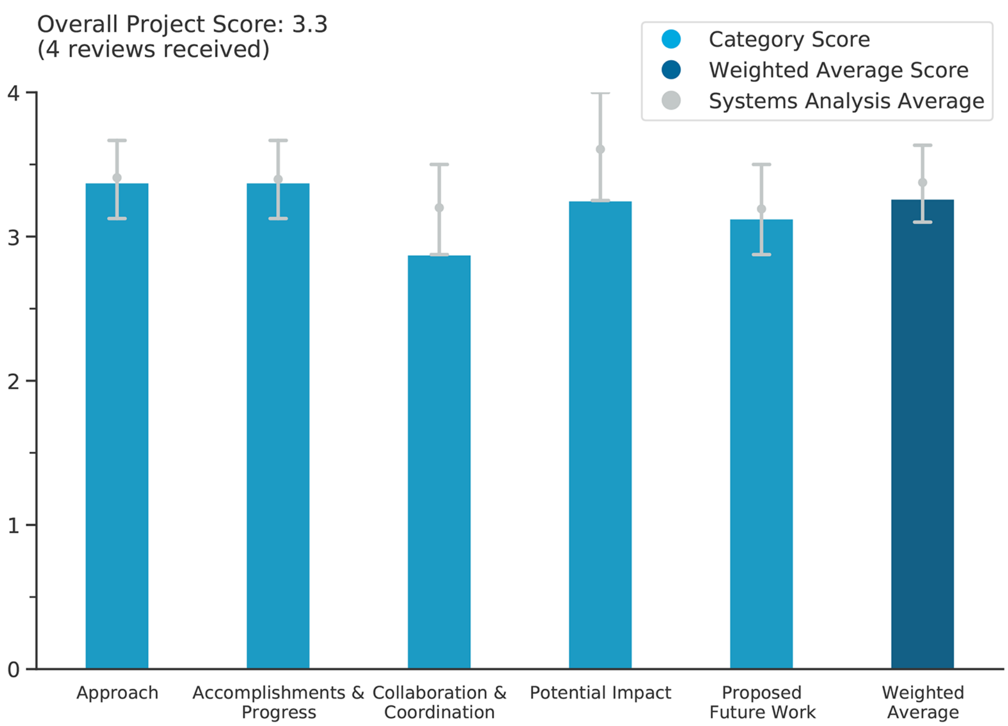
|---|---|
| **DOE Contract #** | WBS 8.6.2.1 |
| **Start and End Dates** | 10/1/2022–3/1/2024 |
| **Partners/Collaborators** | Lawrence Berkeley National Laboratory |
| **Barriers Addressed** | • Closes the information/knowledge gap barrier for strategic heavy-duty vehicle infrastructure deployment with respect to location, volume, and station type (e.g., gaseous or liquid) and for the most economic pathway for heavy-duty hydrogen vehicle dispensed costs<br>• Supports DOE freight vehicle infrastructure planning efforts and accelerates zero-emission vehicle adoption in the United States |

## Project Goal and Brief Summary

The project aims to assess infrastructure costs and requirements to meet the demand for hydrogen fueling in the medium-duty (MD) and heavy-duty (HD) sectors, with the goal of supporting the development of hydrogen refueling corridors in the United States. The objectives include identifying datasets, developing methodologies, and forecasting national freight demand to optimize the placement and sizing of refueling stations. The project addresses the knowledge gap in strategic MD/HD vehicle infrastructure deployment, supports the decarbonization of MD/HD hydrogen fleets, and provides valuable information for similar transportation studies nationally and internationally. By leveraging models and data analysis, the project aims to facilitate early adoption of hydrogen fueling corridors, calculate the levelized cost of dispensed hydrogen, and accelerate the transition to zero-emission vehicles in the United States.

## Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Analysis projects.

## 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.

- This project consists of three tasks for assessing the cost of dispensing hydrogen for HD vehicles and is in line with DOE freight vehicle infrastructure planning. The project considers two reasonable paths for hydrogen dispensing: (1) delivered liquid hydrogen (LH2), which is vaporized and compressed, and (2) onsite production of hydrogen, which is pressurized. The assessment is for compressed gas storage at 700 bar. Argonne National Laboratory's (ANL's) Hydrogen Delivery Scenario Analysis Model (HDSAM) is used to calculate and compare dispensing costs.
- The defined approach for the derivation of HD station deployment and dispensed cost of fuel is well-planned-out and includes a reasonable stepwise plan of defining boundaries and assumptions, running the cost model, and then assessing the results. The project is highly relevant in today's environment, with HD fuel cell trucks and stations being deployed now. It would be useful to consider a broader range of fueling speeds more relevant to HD fueling, say 5–18 kg/min, or simply take an expected average of 10 kg/min, per DOE goals. There was no mention of a safety plan; a diversity, equity, inclusion, and accessibility plan; or a community benefits plan, so presumably they were not required for this modeling effort.
- The approach and structure are solid. The use of existing models and needs, including both gaseous and liquid pathways, was noted.
- The approach and methodology were clearly described, but the descriptions remained at a high level. Specifically, the system boundaries and technology pathways were defined, and then HDSAM was run to estimate costs. However, some additional details would have been useful. For example, slide 5 stated that the two pathways were chosen because of a higher level of commercial readiness, but it was not clear how this was assessed or what other pathways were considered. It was unclear how commercial readiness was determined. Additionally, there was no discussion of the appropriateness of HDSAM as a tool. The origin of costs in HDSAM and whether they were relevant for this analysis was unclear.

## Question 2: Accomplishments and progress

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

- he project is complete. A cost assessment has been delivered for a standard filling station with a defined set of parameters, limited to 20 50-kg-fills per day. Fuel quality is assumed equal for both dispensing pathways, with hydrogen production cost set at $1.5/kg. Included in the liquefied hydrogen cost is transportation and liquefaction. Capital cost estimates for liquefied hydrogen dispensing ($24 million @ 18 MTPD [metric tons per day]) are about half the cost of gaseous hydrogen dispensing. However, overall dispensing cost is generally less than for gaseous hydrogen. The project delivered its objective.
- The breakdown of different pathways and station size outputs is outstanding. The outputs were appreciated, as were a few "simple" slides that provided many initial insights and analysis opportunities.
- In spite of being only in its first year, the project has made significant progress and likely requires only additional considerations based on reviewer feedback and addressing the stated challenges/barriers and future work. The two chosen pathways (delivered liquid hydrogen and onsite production) are relevant, and the cost model is useful to support industry decision-making on expected station cost performance. It was unclear whether maintenance and operating costs were included in the model, but this could be gleaned from the light-duty case and scaled (possibly); feedback from industry could also be sought.
- Results show a detailed listing of capital equipment costs for multiple station design pathways, and these results clearly show some of the main drivers for levelized cost of dispensed hydrogen (particularly liquefaction). However, all costs listed appear to be capital expenditures, and it is not clear whether operating expenses were included in the levelized cost. This is especially relevant since the two pathways chosen include a dispenser and chiller for one design, which can have substantially higher power usage than the cryogenic pump included in the other design. If only capital costs were considered, that should be clarified.

### 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.

- The project was well-coordinated using the expertise of ANL, Lawrence Berkeley National Laboratory (LBNL), and the National Renewable Energy Laboratory (NREL).
- Collaboration highlights input from federal sponsors (the Hydrogen and Fuel Cell Technologies Office and U.S. Environmental Protection Agency), as well as other national labs (ANL and LBNL); these groups are known experts in this area, so this collaboration makes sense. However, collaboration could be added between industry partners, especially refueling station operators or component suppliers. While this sort of analysis should not be based on a single company's experience, having industry partners review the analysis can provide context and feedback as to whether the cost numbers in the analysis are reasonable.
- There is good coordination with national labs (e.g., ANL and LBNL) for relevant topics (such as HDSAM), but there is no industry support/feedback/contact. For example, the team could consult with the NREL team working with the HD industry group on their fueling cooperative research and development agreement. HD station providers and HD fuel cell vehicle manufacturers are included in this industry group.
- Existing collaboration with partners is good. However, the project could benefit from additional industry partners and inputs, as well as potentially getting access to additional data.

### Question 4: Potential impact

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

- This cost analysis is one of the greatest industry (and fleet) needs to address adoption (and investment decisions). Work is well-laid-out and helpful.
- This project provides one baseline for assessment, which is valuable toward developing hydrogen infrastructure. As mentioned by the presenter, future refinement can be done, which can include capital cost, hydrogen and electricity cost, and usage profiles.
- The project is extremely relevant to the deployment of HD fuel cell truck fueling infrastructure. The cost model is well-defined and could use some minor improvements with the addition of maintenance/operating costs and with some consultation with industry as a means of checks/balances. The addition of several "what if" tax incentive scenarios would also be useful, if only for an indication of what is possible.
- The barriers/targets, potential impact, and goals all highlight improvements to knowledge about refueling infrastructure cost. However, it is not clear how this type of analysis can best be used. The importance of informing industry is mentioned, but other potential impacts emphasize facilitation of deployment/adoption or accelerating decarbonation. It is unclear how this type of cost analysis study helps to achieve those goals. This study does not appear to generate any new cost information but rather applies what information already exists in HDSAM. It is unclear if these results are meant to inform future research and development efforts (e.g., to reduce the cost of liquefaction).

### Question 5: Proposed future work

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

- The proposed future work emphasizes working with hydrogen hubs, national labs, academia, and industry to get better data and refine assumptions. This is critically important and will absolutely improve this type of analysis, which can then benefit future studies.
- Planned future work will further refine costs for the currently considered pathways. However, it would also make sense to consider a similar analysis for liquid dispensing for HD applications. This is the onboard storage method considered by some manufacturers, such as Daimler. Also, it is unclear what type of onsite hydrogen production is considered—perhaps electrolysis. The capital cost and reliability of different types of onsite production should be a factor for staged infrastructure development.
- The proposed future work does cover some of the improvements identified thus far and so, in this regard, does a good job of recognizing weaknesses and areas in which shoring up is required. More emphasis

should be placed on seeking industry feedback and less on national labs and academia. HD stations are in the ground and operating today; it would benefit the team to visit some of them.

- The presenter recognized that additional inputs will be needed as real-world data and inputs are received, which was appreciated. The team could include more industry partners to gain more holistic inputs and compare/contrast to other analyses.

## Project strengths:

- Project strengths include the project approach, defined boundaries, cost model implementation, and output. There is good recognition of what is needed for the future. The topic is highly relevant. This is generally a very well-executed effort. The reviewer is looking forward to the final report.
- This project focuses on a critically important topic (HD vehicle refueling) and clearly identifies major cost drivers for different technologies and system sizes. Assumptions around cost and scale are clearly explained, and sensitivity to various inputs and parameters (e.g., system size, utilization) is shown.
- The project defined reasonable assumptions on dispensing pathways and showed a clear cost distinction based on utilization.
- The project is addressing a critical need and is well-constructed and -implemented.

## Project weaknesses:

- The project lacks comparisons to real-world systems; HD vehicle refueling stations are rare, but some do exist. It is unclear how the system costs in this analysis compare to those systems. If specific cost information cannot be shared, then the system design and overall cost assumptions could at least be reviewed by those refueling stations' teams. The project is not clear about whether operating costs are included; focusing on capital costs is fine and may make sense, but different technology pathways may end up with vastly different operating costs because of energy usage. Incorporating these kinds of costs into a true levelized cost would be much more informative. The project is not clear about the goals/outcomes of this analysis or whether the intention is to inform industry about the current state of the art, identify future research/development needs, or make comparisons between different technologies.
- Project weaknesses are minimal, but the project could use shoring up that the assumptions are reasonable via industry consultation. Some minor adjustments are needed in fuel throughput, which could drive slightly higher capital expenditures for additional liquid pumps, for example.
- Some weaknesses and limitations were listed in the presentation and will be addressed in proposed future work. Liquid dispensing should also be considered, as well as the assumption that the onsite hydrogen is equivalent to that of a large-volume plant.
- It is still early in the market development, so insufficient data and information were included (yet can easily be added as a future consideration).

## Recommendations for additions/deletions to project scope:

- Adding a quantification of the effect of reliability would be very much of interest. For example, compressors have been shown to require shutdowns often; it would be interesting to see what effect (if any) would result to the levelized cost if the reliability of some key component(s) could be improved by a certain amount. This may have already been done, but given that the refueling station is one of the main cost drivers, it would be interesting to see what system components drive that cost and how that might vary. For example, perhaps the compressor/pump could be sized down if the high-pressure buffer storage was increased (or vice versa).
- It is suggested that the team follow through on the recommended next steps as defined and focus more on seeking industry feedback. This is a highly relevant exercise and should continue.
- More industry input is recommended. Comparisons with other analysis and real-world data as it becomes available are also recommended.
- The project is completed.

# Project #SA-188: Sustainability Criteria for Hydrogen Deployments

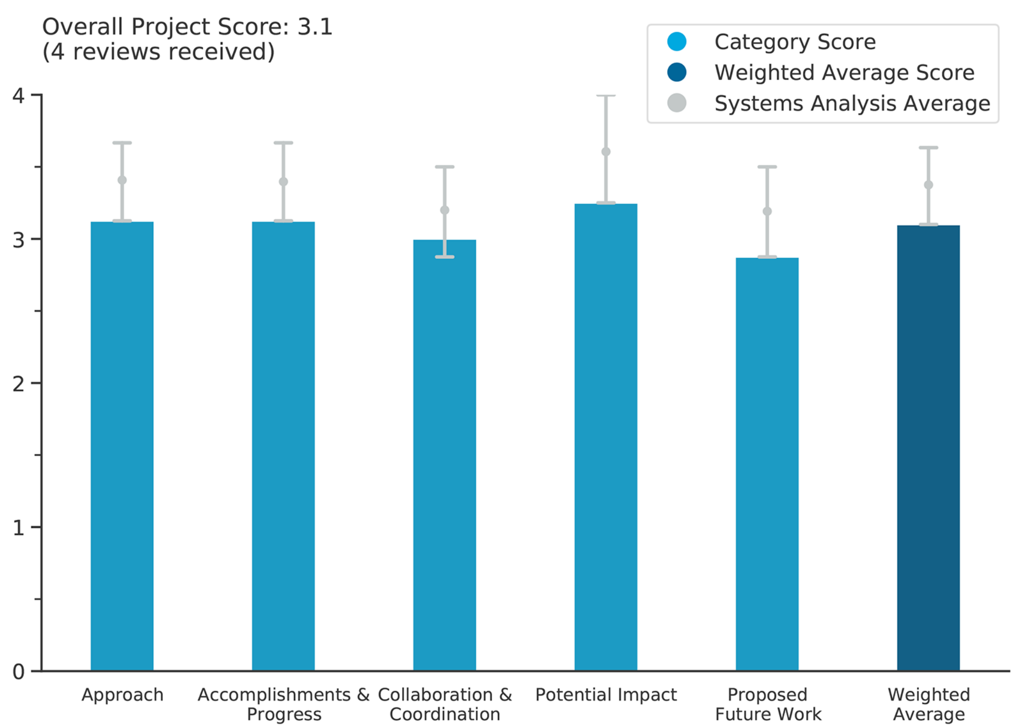
Mark Chung, National Renewable Energy Laboratory

| | |
|---|---|
| **DOE Contract #** | WBS 8.6.2.1 |
| **Start and End Dates** | 9/1/2022 |
| **Partners/Collaborators** | Mission Innovation via U.S. Department of State, Hydrogen and Fuel Cell Technologies Office, DOE, BRE Group, HDR, Inc., Institute for Sustainable Infrastructure |
| **Barriers Addressed** | • Identify gaps in literature and existing sustainability rating systems that are applicable to hydrogen projects<br>• Address these gaps by improving existing frameworks with quantifiable sustainability metrics<br>• Apply this framework to at least two international case studies to assess the appropriateness and impact of such sustainability metrics |

## Project Goal and Brief Summary

The project aims to enhance the framework for quantifying and characterizing the sustainability benefits of hydrogen projects, specifically in the supply chain. The work involves identifying existing sustainability metrics, assessing gaps in the metrics applicable to hydrogen projects, and proposing guidance to improve them. The project will contribute to the growing development of hydrogen infrastructure and the need for mature frameworks to assess the sustainability of such projects, guide investment decisions, and ensure positive outcomes for stakeholders. The project involves collaboration with industry experts, literature reviews, consultation, refining metrics, and applying them to case studies. The goal is to refine existing economic and environmental metrics and include social factors to provide a comprehensive and holistic approach to hydrogen sustainability.

## Project Scoring



The vertical hash-lines represent the highest and lowest average scores received by Systems Analysis projects.

### 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.

- The approach adopted is well-aligned with project objective to provide guidance to characterize the sustainability of hydrogen benefits.
- The assessment of hydrogen development with respect to sustainability is a challenging project, and the approach used here, building upon the sustainability metrics developed for similar markets/applications, is quite reasonable. There are two parts of sustainability that are not well-captured in this approach. First, economic sustainability, which is a necessary element to market growth and in developing scale, is also a critical key performance indicator (KPI) for evaluation of public investments in projects that are intended to develop markets, such as the Clean Hydrogen Hubs Program (Office of Clean Energy Demonstrations) and the related downstream market development initiatives. Second, there needs to be a mechanism that values the contributions of the early adopters. Early adopters, in many cases, may not have the capacity to address sustainability, but they lay the groundwork for the market followers to develop sustainability at scale.
- The approach to work is good, but the project might consider how the metrics may be modified to give more of a system perspective. That is, hydrogen-related technologies have inherent metrics (emissions, efficiency, noise, etc.), and provided multiple technologies have exactly the same inputs/outputs, then these are good metrics to compare among technologies. However, often technologies may have similar but not exactly the same inputs/outputs or may be competing against alternative approaches that do not involve hydrogen, and as such, the metrics should be considered in a system perspective more than just the intrinsic metrics of the technology itself.
- The project's approach in developing a common framework for hydrogen sustainability metrics is sound, considering this is the first DOE-funded project addressing this important area. The plan to conduct a literature search for a white paper, develop initial sustainability metrics, seek expert input to refine the metrics, and develop a case study sounds like a reasonable first step. However, given the current diverse hydrogen value chain—from production types to end uses—it may be necessary to have a more refined approach that accounts for diverse stakeholder feedback and multiple case studies that reflect the breadth of hydrogen systems.

### Question 2: Accomplishments and progress

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

- There appears to be good progress on defining sustainability for hydrogen, but the proposed criteria seem limited, especially when considering the outcomes from the literature review. Environmental, social, and governance (ESG) issues and sustainability overlap on the topics covered. However, ESG reporting appears weak, and it is important to rely on transparent and well-defined metrics. Thus, instead of defining specific criteria, perhaps the project should try to propose quantification and better reporting of ESG issues. Regarding the proposed hydrogen metrics:
    - Public education may include criteria on skills development.
    - Criteria concerning hydrogen leakage are too narrow and may lead to confusion, if not being counter-informative. Any hydrogen emissions have to be minimized all along the value chain to optimize the environmental benefits of hydrogen. But this reflects only a small part of a holistic approach in which the hydrogen benefits have to be assessed by considering replacing unabated fossil hydrogen with clean hydrogen in existing applications and replacing fossil energies with clean hydrogen in new applications. Therefore, the criteria should consider the atmospheric hydrogen and not only the hydrogen leakages.
    - Water consumption and land use may also be considered with the same approach used for the atmospheric hydrogen, taking into account the local resources.
    - No social metric was proposed. The proposed metrics should also consider the maturity of the project.
- The literature review and categorization of known hydrogen sustainability metrics is nicely summarized and clearly presented as a rainbow chart. The project's key accomplishments around establishing a

framework process flow and the selected expert partners are easy to follow. The team also provided a highlight of the key lessons from the literature review, including the lack of a holistic review and the subjective nature of the sustainability metrics for hydrogen systems, comparisons to other industries, and lessons on community benefit plans and Justice40. The comparison between ESG and sustainability was helpful. However, it is not clear whether one of the project goals has been accomplished—the goal to "apply framework to at least two international case studies"—nor is it clear why "international" is specified in the first place.

- A comprehensive literature review has resulted in a holistic understanding of current thinking on this topic.
- Using established sustainability metrics is a good first start. Economic sustainability may need some additional emphasis.

### 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.

- Collaboration appears correct. It should be ensured that the industrial experts cover the whole hydrogen value chain.
- The collaboration teams appear to be well-qualified and cover a wide range of sustainability topics.
- Industry, national labs, and stakeholders are all represented.
- The collaboration and partnership with the three private entities is positive. However, from the work presented so far, it is not clear what, if anything, came out of the stated collaboration with the federal agencies. Of more concern is the lack of collaboration with private or industrial partners that specialize in hydrogen systems. The three private partners (BRE Group, HDR, Inc., and the Institute for Sustainable Infrastructure) do not seem to have any demonstrated experience with any sector of the hydrogen value chain. They seem to be focused on educational or civil and structural engineering areas. BREEAM® (Building Research Establishment Environmental Assessment Methodology) and LEED (Leadership in Energy and Environmental Design) certification standards are not enough to convey the selected or all the needed sustainability metrics for hydrogen systems. Also, if it is deemed that international case studies are critical, the project team ought to consider partners with the relevant international experience that can provide the case studies.

### Question 4: Potential impact

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

- Assessing the sustainability of hydrogen is of utmost importance, as any investor, user, and producer needs to trust that hydrogen has not only an economic value but also contributes to achieving environmental and sustainability objectives. This project considers a difficult issue: quantitative and holistic evaluation of sustainability criteria, including a social metric assessment.
- Although the project's impact from the current accomplishments may be limited, the objectives of the project are essential to advancing a sustainable future in hydrogen. That said, the future impact of this project is likely to grow with more input from additional partners and stakeholders with direct hydrogen experience that can help refine the sustainability metrics.
- This project aligns with DOE goals and has the potential to advance those goals. However, it also has the potential to become a rarely read report, so it will be up to DOE to incorporate the learnings into other projects and to incorporate other projects into these learnings.
- Sustainability metrics or KPIs need to be developed for deployment projects. These can be critical to determining the success of the proposed projects, especially for deployment projects such as the Clean Hydrogen Hubs and downstream initiatives.

### Question 5: Proposed future work

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

- The proposed next steps look good. The reviewer looks forward to seeing how this project develops.

- The future work needs to be more ambitious, with more granular and quantitative metrics. The project team should consider additional sustainability metrics based on relative average weighting of their significance or provide additional guidance to users to do so based on their specific technology, location, community, resources, etc.
- The overall approach of finalizing and publishing is reasonable, but identifying specific decision points associated with the future work and its conclusion would have strengthened this section.

### Project strengths:

- The project's strengths include interaction with sustainability-recognized organizations and with industrial hydrogen stakeholders.
- The project's main strength is tackling this difficult problem in the first place and daring to come up with a sustainability benchmark.
- The importance of the topic is critical to evaluating deployment projects.
- The breadth of the literature review and the collaborators are strengths.

### Project weaknesses:

- The initial sustainability metrics seem too broad to be implemented by most projects or stakeholders in the hydrogen value chain. Some way of quantifying the metrics or introducing their relative materiality may be needed. Otherwise, multiple case studies on every segment of the hydrogen value chain will have to be presented for wide use.
- The proposed metrics appear too focused on the project itself and do not appear to consider the broader beneficial environmental and social impact of using clean hydrogen.
- Proposed metrics may not be useful in decision-making because they lack system and alternative contexts.
- Economic sustainability needs more emphasis.

### Recommendations for additions/deletions to project scope:

- It is recommended that the project consider quantification and better reporting of ESG issues as hydrogen criteria for the consideration of metrics on skills development, the atmospheric hydrogen not limited to the leakages, water consumption, and land use, as well as the proposal of some social metrics.
- The project might consider collaborating with industry leaders from the key segments in the hydrogen industry, such as production (gray, blue, and green hydrogen), compression and transmission, delivery, and end use (chemical, transportation, power, and heat). Relative quantification and a greenhouse gas life cycle analysis component should be introduced to the list of metrics.
- The project should consider how to incorporate the perspective of system metrics.

# Project #SCS-001: Component Failure Research and Development

Genevieve Saur, National Renewable Energy Laboratory

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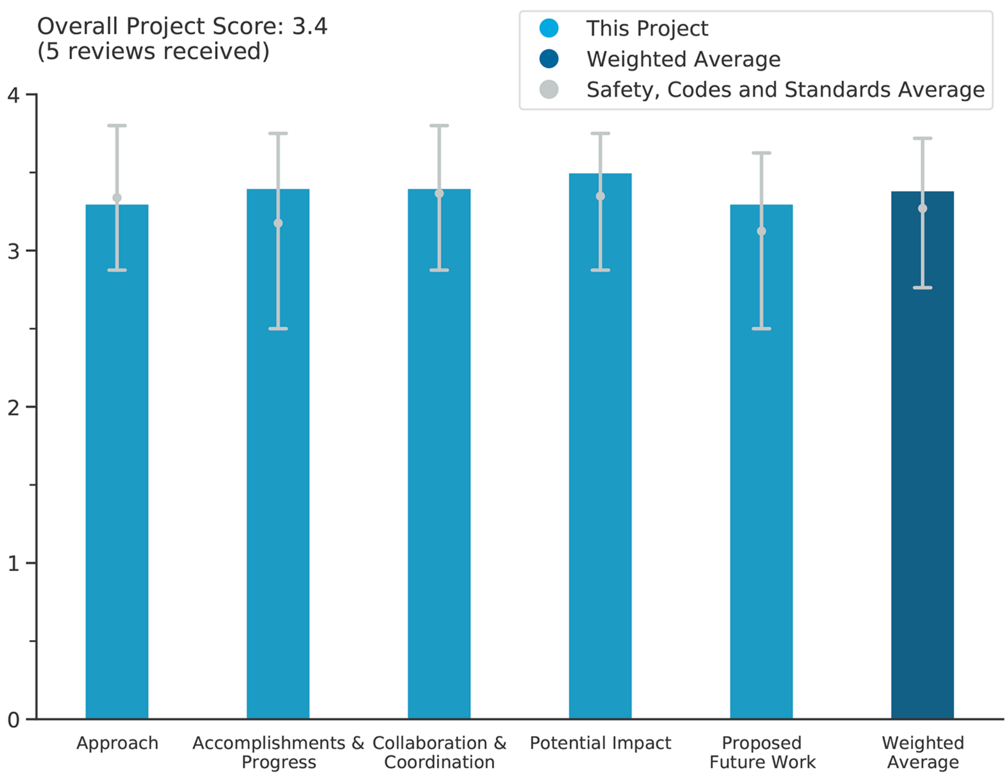
|---|---|
| **DOE Contract #** | WBS 6.2.0.502 |
| **Start and End Dates** | 10/1/2018 |
| **Partners/Collaborators** | University of Maryland, A.V. Tchouvelev & Associates Inc. |
| **Barriers Addressed** | • Limited access to and availability of safety data and information<br>• Safety not always treated as a continuous process<br>• 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 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




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### 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.

- The project team's approach for the component reliability database is well-defined, with reasonable inputs and outputs that will yield valuable industry information to support safer and more reliable hydrogen installations. Although the effort is not required to include a Hydrogen Safety Panel review, the project proponents do a great job of outlining and emphasizing the project's safety planning and culture. The diversity, equity, inclusion, and accessibility plan seems reasonable and complete for the effort.
- The approach was clear and concise, with the project team setting goals to (1) deploy the HyCReD database to track hydrogen-specific failure rates and failure modes, (2) develop a better understanding of leak behavior and leak size for a variety of components and failure modes, and (3) introduce new models and data into a QRA.
- The project appears to be well-organized, with stated goals. The goals could be made stronger by including specific measurable metrics to help gauge the extent to which the goals have been accomplished.
- It is great to see the inputs planned and potential outcomes. Industry data can often be difficult to access in full detail, owing to concerns about liability. This may be an ongoing issue that will require addressing.
- The project is addressing the challenges via data, modeling, and experimental approaches. More experimental results to compare with data collected and modeling results would be welcome, as well as selection and design of experiment conditions based on the data and models.

### Question 2: Accomplishments and progress

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

- The project has made some significant accomplishments this year, which are well-documented and include developing the HyCReD online platform, completing the in situ leak detection system design, and launching a technical seminar, which yielded valuable insights for the project. One of the key deliverables this year was the commencement of analysis of the incident database.
- A tremendous amount of work has been done in developing and populating the HyCReD database. Also, the development of the leak rate quantification apparatus was a significant effort, and the team is to be commended for making the jump to the in situ leak rate quantification approach, which should yield significantly higher-quality information about the source and size of leaks.
- The project team made significant contributions to achieving DOE goals in terms of identifying leak detection from hydrogen, as well as modeling the risk of hydrogen.
- The technology platform looks simple and easy to use with regard to the interface. There is good interest in the database globally, with opportunity to expand the database to other areas.
- Based on the budget level, the project has made good progress, especially the industrial non-disclosure agreement (NDA) to obtain more data. The reviewer looks forward to seeing the data comparison and reconciliation between industry data, modeling, and experimental data.

### 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.

- Industry collaboration is a must and should be pursued as much as possible to provide sound information to the database. The outreach opportunities taken in the past year are excellent, and the team should continue to attend such venues, including codes and standards meetings where possible, to shore up industry participation in reliability/failure information-sharing for the database.
- The work to engage more outside collaborators to provide data to populate the HyCReD is a big effort and should significantly enlarge the database, thus making analysis conducted using the data more accurate and meaningful by increasing the amount of failure data.

- The project team is working with the National Renewable Energy Laboratory (NREL) Faculty-Applied Clean Energy Sciences program. The team is also working on hosting two female graduate researchers. Finally, the researchers are supporting Johns Hopkins' Summer Academic Research Experience program.
- The project has established industrial and other collaborations and successfully organized the HyCReD technical webinar.
- This project includes good collaboration and outreach.

### Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project is important because it offers the possibility of promoting safe and reliable hydrogen installations by supporting risk assessment tools. The project will also provide valuable feedback on codes and standards development activities. Hydrogen leakage data are needed to support risk mitigation strategies, and having a way to physically quantify leakage is valuable.
- Both safety and reliability of hydrogen equipment are significantly impacted by component failure and leakage. Poor reliability has been a significant problem for the U.S. light-duty fueling station network. Safety systems generally work effectively and "convert" the impact of leaks from safety problems into reliability problems (e.g., equipment gets shut down when a leak is detected). Therefore, to the extent that use of these tools improves component reliability, the impact will be large and positive.
- The project addresses hydrogen performance goals and objectives as it addresses research and development to evaluate hydrogen performance rates and modes.
- Understanding component failure is critical in developing improved standards, regulations, and codes and will support more informed and better inputs to these discussions.
- The impact is to establish a common database for hydrogen component failures. This is very important in supporting broad hydrogen applications.

### Question 5: Proposed future work

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

- The proponents do a great job of identifying the barriers faced, including difficulties in utilizing the leak quantification device to measure leakage in affected components, as well as the challenges in obtaining sound reliability/failure data from incidents. The team should continue mining data from H2Tools' Lessons Learned database. The team should also consider participating in several component-level standards meetings at CSA Group, SAE International, etc. A continued push on obtaining industry data is a must.
- The team has identified several future work options, such as the following: (1) continued outreach with industry and other partners; (2) more experiments and testing, such as identifying failed components that can be tested and developing a plan for what support NREL can provide to component testing facilities; and (3) more modeling, continued ventilation study of leaks in hydrogen equipment enclosures, and use of QRA to model the system risk.
- Proposed future work aligns with the project goals and has addressed previous reviewer comments.
- The three areas of future work discussed are logical next steps. There is a good deal of work, and it is recommended that the proponents consider prioritizing the three areas, if they have not already.
- Design of the Leak Rate Quantification Apparatus (LRQA) is an important focus. The reviewer would have liked to have seen how the QRA model and simulations can be applied to at-scale (i.e., gigawatt) hydrogen facilities.

### Project strengths:

- Project strengths include the subject matter. The derivation of a database to support safe and reliable hydrogen infrastructure and to support codes and standards activities is very important to the hydrogen industry and therefore supports the DOE goal of reducing greenhouse gas emissions.

- The project addresses an important area in the design of future hydrogen equipment. Appropriately, safety has been the major concern in system design to date, but to the extent that "safe systems" rely on additional components to control isolation, venting, etc., they can suffer from system reliability problems if those components are not extremely reliable.
- Leak detection is one of the most critical topics in addressing climate change and reducing emissions. In addition, using a modeling system and QRA for hydrogen systems is critical.
- This project includes good data capture, as well as good information- and knowledge-sharing for additional inputs.
- The NREL team has established collaboration with stakeholders in the hydrogen field and has made progress in NDAs to obtain more industry data. The team has also successfully hosted the HyCReD Virtual Technical Seminar.

### Project weaknesses:

- The project needs to focus on obtaining high-quality failure and reliability data for the database. Perhaps the leakage rate apparatus could be used to quantify leaks using staged leak conditions that could include various mis-assembled high- and low-pressure fitting configurations, valve seat leakage, etc.
- It is not clear what the relationship is of the modeling part of the project to the failure database and leak quantification parts. It would be helpful to clarify how the three elements fit together and emphasize what the synergies are between them.
- Some of the weaknesses or challenges were related to recreating leaks in the LRQA following removal from the system due to a failure. Also, the LRQA did not accommodate all components of leak scenarios, such as for cold gas.
- The experimental and model results need more progress with clearly identified component failure, such as failure type, incident frequency, and mitigation strategies.
- The project relies on industry to share sensitive information for full capture of data.

### Recommendations for additions/deletions to project scope:

- The current scope consists of coherent approaches to address the objective, so there are no recommendations to add or delete.
- The database is only going to be as good as the data it contains, so it is recommended that the researchers continue the good work they have started to bring additional sources of data into the project.
- More support is needed in terms of data-sharing from industry, as well as sharing success stories and challenges. In addition, there should be more collaboration with industry on the HyCReD.
- Test modeling on large-scale hydrogen facilities is needed to ensure relevance and reliability.

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

Joe Ronevich, Sandia National Laboratories

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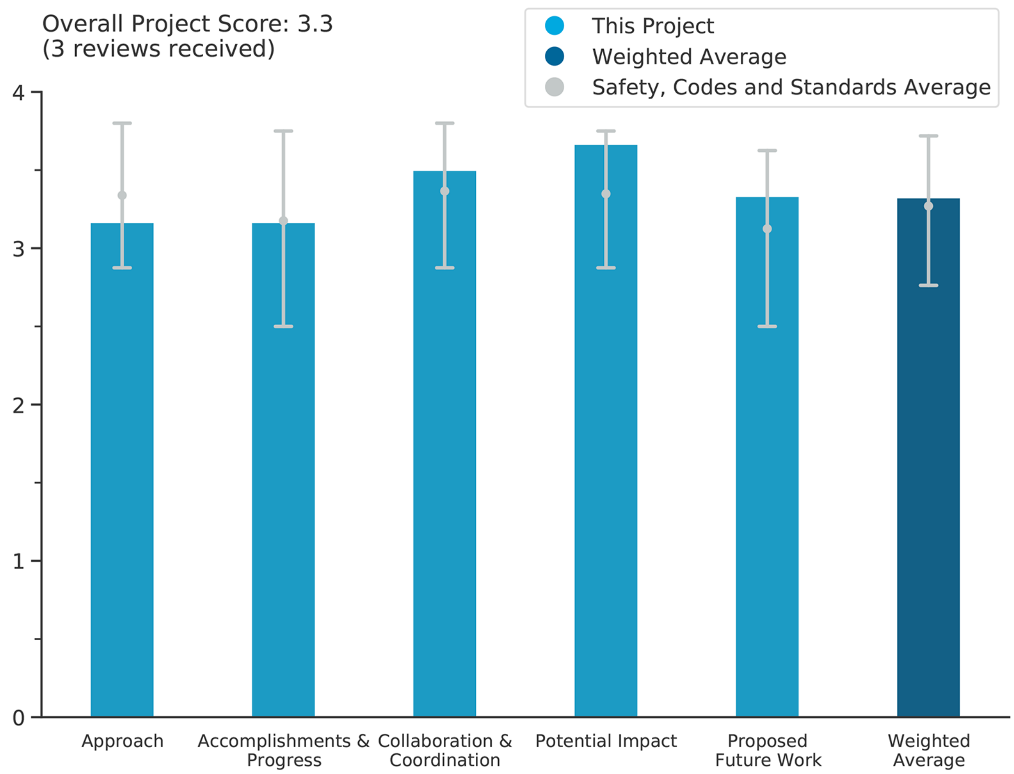
|---|---|
| **DOE Contract #** | WBS 6.2.0.801 |
| **Start and End Dates** | 10/1/2003 |
| **Partners/Collaborators** | CSA Group, ASME, SAE International, International Organization for Standardization (ISO), FIBA Technologies, Inc., Tenaris Dalmine S.P.A., JSW Steel, Swagelok Company, NASA White Sands 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** | • Limited access to and availability of safety data and information<br>• Consistent regulations, codes, and standards needed to enable national and international markets<br>• 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



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### 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 high-level goals of the project are clearly stated. It would be helpful to state the metrics used to show whether the goals are being achieved. The general approach to experimentation appears consistent with established practices for testing material samples for fatigue and cracking. The project reports great progress in demonstrating methodology specific to the behavior of samples in a hydrogen environment.
- The approach is good for looking into research and development for safety codes and standards materials and compatibility. Even though there are several research projects conducting research on this topic, it is good to get a different perspective.
- A large separate poster for describing work is appreciated; however, since slides were also posted on the poster wall, this would have been a good opportunity to present expanded data results and show links to codes and standards gaps and the current state of the data, rather than just copy and paste slide data. Sandia National Laboratories has an extensive safety culture; however, presented data did not describe hazard/ safety analysis for specific experimentation. Adding a reference to the specific safety analysis document reference would have been valuable (e.g., on slide 25).

### Question 2: Accomplishments and progress

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

- A good deal of material related to the project has been published by the principal investigator and project participants, and much of that material has contributed to the body of knowledge being used to improve, particularly, the relevant ASME code cases and codes. While it is true that the project was not required to submit a formal safety plan for review, it is nevertheless important to see the safety approach used by the lab, as the Hydrogen Safety Panel has observed that labs, even those using small quantities of hydrogen, tend to have a higher incidence of hydrogen incidents and near misses.

- The scope qualified investigation of "precipitation hardened 17-4 stainless steel," two grades (Slide 7) and multiple steel grades (Slide 9). The presentation could be enhanced by showing a matrix of all steels used for hydrogen service and identification of weaknesses in current applications. This would qualify how experimentation is completing gaps in codes and standards bases.
- This is one of the overall DOE project goals.

### 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.

- This project is collaborating with various entities such as standards-focused entities—e.g., the International Organization for Standardization (ISO) and ASME—and industry partners such as Pipeline Research Council International and European Pipeline Research Group.
- A number of industry interactions were reported. It appears that most of the collaboration is focused on standards development organizations (SDOs), with the work with ASME being the primary interaction.
- There is an excellent interface with codes and standards organizations, industry, and other research organizations.

### Question 4: Potential impact

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

- This work is highly relevant and important in ensuring that standards continue to improve so that materials and components used with hydrogen are (first) safe and (second) reliable in service (which is a significant issue for hydrogen fueling stations, for example).
- The issues and data gaps being addressed have direct impact on development of optimized codes and standards. Multiple completed test activities demonstrate quality approaches.
- This project will provide more guidance regarding codes and standards and materials compatibility for hydrogen pipelines.

### Question 5: Proposed future work

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

- The project has done an excellent job identifying various testing method developments for welding standards and providing more guidance for ASME standards, which are key, especially working with the various stakeholders.
- The future work appears to be a logical progression based on the project progress so far.
- It is unclear what experimentation might be proposed for related liquid hydrogen piping and vessels.

### Project strengths:

- Project strengths consist of continuous testing experience, interface with codes and standards organizations, and significant efficiency in completing multiple test activities.
- The tie-in to specific SDOs and standards helps to efficiently get the results of the work reflected in updated standards as quickly as possible.
- While there are various research projects on this topic, it is beneficial to have another one to get a different perspective on hydrogen codes and standards.

### Project weaknesses:

- This project has an extensive history, clearly understood by the consistent project team; however, it is difficult for new reviewers to obtain an overall programmatic perspective for a project begun in 2003.

Obviously, presentation space is limited, but including a historical matrix related to the various materials covered by codes and standards or identified as gaps would be valuable, especially to understand future planned experimentation.

- While the future work proposed describes a suite of logical continuations of what has been done, it is a little hard to tell when the project objectives have been achieved and the work is done.

### Recommendations for additions/deletions to project scope:

- The project team has extensive interface with ASME. It would be valuable to identify experimentation dealing with an expanding current issue and promulgation involving ASME requirements for pressure stamping of electrolyzer vessels. Issues requiring pressure stamping are unclear. If criteria are related to electrolyzer fatigue or corrosion, experimentation to show over-conservatism in ASME criteria would be extremely significant.
- It seems that most of the projects have the same concerns with lack of access to technical and safety data from the industry. It is recommended that this be evaluated through a webinar/seminar with the industry to determine next steps that would benefit everyone.
- It would be helpful to state the metrics for the project goals and the definition of project completion.

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

Ethan Hecht, Sandia National Laboratories

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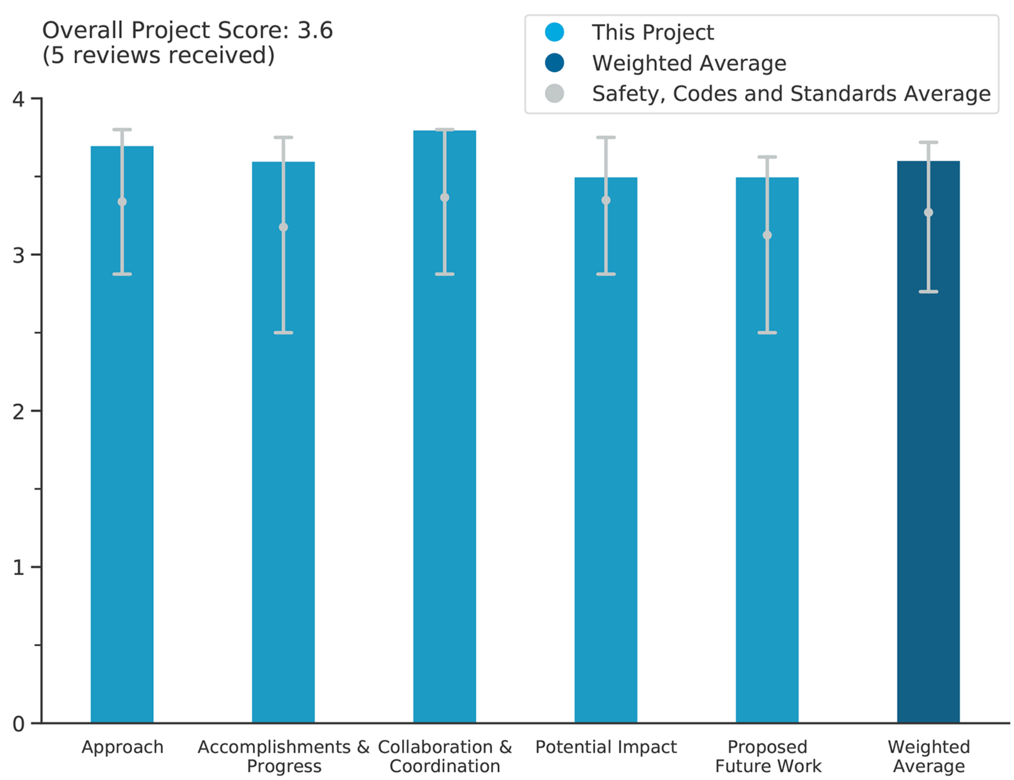
|---|---|
| **DOE Contract #** | WBS 6.2.0.801 |
| **Start and End Dates** | 10/1/2003 |
| **Partners/Collaborators** | National Renewable Energy Laboratory, Chart Industries, Inc., Air Products, National Fire Protection Association (NFPA) 2 Technical Code Committee |
| **Barriers Addressed** | • Conduct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

## Project Goal and Brief Summary

Sandia National Laboratories (Sandia) is working to address the lack of safety data and technical information relevant to the development of safety, codes and standards 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 (QRA) 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




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### 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 project barriers and objectives have been well-identified, and the project has a sound approach to developing and validating scientific models to predict hazards from liquid hydrogen (LH2) releases, including impinging flames. This project, coupled with the efforts of another one focusing on the development of QRA tools, with both outputs supporting codes and standards development activities, is outstanding. Significant risks can be anticipated in the experimental LH2 release efforts, and the team has done a good job of outlining safety planning and safety culture. Kudos to the team for involving a review of the test procedures from in-house national lab and external industry safety experts.
- The approach is excellent. The Sandia team has continued to make steady progress to safely meet objectives. The work is valuable to the industry and is very useful for code work, especially National Fire Protection Association (NFPA) 2. The focus on both LH2 and compressed natural gas (CNG)–$H_2$ blends is timely, given the rapidly growing interest in its use as a fuel, as well as the increase in use for hydrogen supply to fuel stations. No safety plan was required, but a good summary of safety was provided. No community benefits plan or diversity, equity, inclusion, and accessibility plan was provided, but it is not clear that one is needed—or really applicable to the work being performed.
- The presentation (slides 1–6) clearly linked the three specific experimental activities to the two defined subprogram goals and project goals, while clarifying interface with other projects (SCS-011). Safety culture was well-represented through evaluations, completed testing liquid hydrogen hazard and operability (HAZOP), and safety case development. One area that could be improved is clarifying how experiments and resulting model improvements (along with interface from SCS-011) is enabling codes and standards challenges for “real problems” (bottom left scope on slide 5). While the uncertainty and inaccuracy of existing models is presented, details about how model improvement will address codes and standards gaps and over-conservatism could be made clearer.
- The approach seems clear. At a high level, it would help to understand how this scenario was selected and prioritized among the possible hazardous scenarios. It was not clear whether a QRA informs the selection of this scenario. This seems challenging in the absence of really widespread infrastructure to prioritize among “real problems” that have not happened, or maybe even been envisioned, as of yet. Overall, however, the experimental approach and goals seem strong.
- The use of a wind tunnel makes sense. The team might inquire as to whether there is an ability to vary the wind for more turbulence, as might happen in the real world on a blustery day. This could impact the release boundaries of the differing mixes.

### Question 2: Accomplishments and progress

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

- The team is to be congratulated for completed safe and quality experimentation. The LH2 tests provided excellent data toward model improvement. Experimentation appears well-thought-out and well-executed. The display in slide 9 of real-time integrated video and data/chart generation was outstanding.
- The project team has made considerable progress on the experimental campaign related to LH2 spill characterization and the analysis of the experimental data. The team struggled to make progress on the assessment of an impinging flame on a surface but planned to perform computational fluid dynamics to design the experiment this year.
- The accomplishment of the LH2 spill tests was significant. It is notable that Sandia performed this test using a thorough approach to safety and should be commended for executing the testing with no incidents or ignitions. One negative comment is the speed of execution. It is clearly understood that safety is of absolute importance and that the work should not be rushed, but the timeline for work completion still seems to be longer than it should be.
- The ignition boundary data were informative and useful for initial transition of blended gases. The project has good safety preparations.
- The wind tunnel test seemed to provide good data and insights and a starting point for predictive models.

### 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.

- Sandia does an excellent job of engaging other organizations and stakeholders. An impressive list is provided that includes industry, academia, consortiums, and government labs. The liquid spill tests were a good example of cooperation among partners to accomplish the task. One area that would be good is a summary of similar work being performed by other organizations for LH2 and CNG–$H_2$.
- Industry, codes and standards, and fellow research organizations are well-represented. Use of Hydrogen Safety Panel members during the test experimentation HAZOP effort is a great example of safety collaboration. Description of their involvement, as well as project interface with LH2 trailer delivery personnel, would enhance the presentation. It is unclear how the Compressed Gas Association (CGA) interfaces are supported or impacted by experimentation (slide 13).
- The project successes are a result of the outstanding collaborative efforts of the project team involving key codes and standards groups (NFPA and CGA), other research institutions (university and national labs), and industry.
- The reviewer appreciated the list of collaboration activities and engagement with industry partners—the list seems strong.
- The project has good collaboration globally and with known leaders in the field of LH2.

### Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project seeks to provide a science-based foundation for the development (and revision) of critical codes and standards as related to separation distances for LH2 installations. This effort is key to promoting the safe and efficient development of LH2-based fueling infrastructure to meet DOE goals of reducing greenhouse gases by promoting the use of heavy-duty applications.
- The project has an important impact on the development of better-informed codes/standards/regulations on LH2 and also natural gas (NG):$H_2$ blends. This is especially useful, given the expected increase in use of these forms of hydrogen.
- This work is foundational to codes and standards efforts to develop regulatory requirements. This work is highly impactful.
- Tests excellently align to improve models. However, detail is missing on how experimentation planning and test results affect codes and standards. The reviewer is aware of conservatism in codes and standards and how standards are lacking or actually missing (for most liquid hydrogen applications). A couple bullet points or discussion qualifying the need for model improvements to these specific codes and standards issues would improve the presentation and experimental focus.
- It was hard to tell, at times, how much was enough to inform a code or standard and when something could be considered complete (and when a scenario of greater concern should instead be studied). However, the team seems heavily engaged with codes and standards work and publishing to ensure that their results reach the next intended audience.

### Question 5: Proposed future work

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

- The proposed future work looks relevant to the project goals and is needed by the market. Of particular interest is testing potentially forming liquid or solid air within a liquid hydrogen spill. Other items that could be added in the future are (1) the consequences of spilling LH2 onto water, such as at a river or harbor, and (2) assessment of three- and four-wall courts for both LH2 and gaseous hydrogen (GH2), which would be very useful since these are used widely and there are questions about potential overpressure created within the walls with a delayed ignition. There is a need for guidance on how far apart confining walls need to be for safety, as well as the effect of height.

  - It is not clear whether the work for "ignited LH2 by walls" is for a vapor cloud fireball, explosion overpressure, or a subsequent jet fire. This could be clarified.
  - Slide 14 mentions that the mitigation of liquid hydrogen leaks/flames by walls (to determine the effect on unignited clouds and reduction in heat flux/overpressure) would be a remaining challenge. However, this work is not shown in 2024, and only the effect of walls on ignited LH2 clouds is listed on future work for 2025. It would be helpful to accelerate this work. Evaluating the effect of walls to protect against unignited clouds is arguably more important since the behavior differences between GH2 and LH2 are likely larger than for ignited clouds.
- The project team has identified several barriers and challenges to the work effort, but the team has also identified future work activities to address these barriers, namely studying phenomena related to heat related to flame impingement in tunnels, examining the effect of walls as a mitigating strategy for releases, and studying the effect of air condensation in LH2.
- Slide 15 describes future experimentation to study "mitigation of ignited LH2 hazards by wall." The project appears to jump past studying "unignited" LH2 plumes impacted by walls or constrained by barriers/berms/equipment. It is unclear whether impingement testing evaluating incident impacts related to tunnels will attempt to recreate unique tunnel conditions (other than impingement against a flat concrete wall), such as curved surfaces, various tunnel interior materials (concrete, ceramic tiles, insulated coatings), and unique tunnel airflow patterns and moisture concentrations.
- It will be interesting to see the modeling around vapor barriers, walls, etc. to support hydrogen safety knowledge and adoption to RCS. It would be interesting to see LH2 testing incorporate replication of rainy-day conditions and any potential impacts on dispersion and data.
- The project has been responsive to prior input (for instance, concerns over air condensation into LH2) in considering future work.

## Project strengths:

- Project strengths include the highly relevant nature of the work effort to promote codes and standards development/modification in a subject matter that is critical to support the rollout of heavy-duty applications. The project team is extremely well-qualified, and the collaboration with other institutions and organizations is outstanding.
- The project is supported by a strong safety culture. The project also includes quality data gathering and analysis. The identification of barriers and test challenges is a significant strength.
- LH2 and NG:H2 blends are not as well-known in their behavior, and the increase in potential use of these forms of hydrogen will require good data and modeling to inform RCS and ensure the right blend of safety and risk management.
- The project seems well-organized, continues to perform valuable work, and operates safely.
- There is a good blend of analytical capabilities; the safety focus is appreciated.

## Project weaknesses:

- There seems to be a good deal of global activity around LH2 spill testing and hydrogen releases. It would be helpful for the project to develop a summary of that work in one location to ensure that global activity is not over- or underlapping and is done efficiently and quickly.
- The project needs to identify codes and standards gaps or over-conservatisms directly linked to Hydrogen Risk Assessment Model gaps, then qualify these to experimentation.
- It is suggested that the project deprioritize the blended fuel release assessment, as it is unclear what industry or application is driving this need.
- The wind tunnel is good; however, it may not provide real-world information on performance in variable weather conditions.

### Recommendations for additions/deletions to project scope:

- The team should consider LH2 spill tests on water. It is not clear why a safety plan is not required. Sandia seems to be self-managing safety well, but it still seems like a safety plan is a good way to document processes, particularly if there is turnover of personnel. The project should model and/or test overpressure that can be developed by three- and four-wall courts for both LH2 and GH2. The project makes a comment on the use of walls to reduce flame impingement, but it would also be useful to understand fire barrier walls' ability to block unignited cold clouds from vaporized GH2.
- The experimental set-up for the LH2 data established wind flow over an unconstrained pool. It would be valuable to establish flow patterns for wind flow constrained by various barrier/berm locations and heights. For example, an experiment could be designed with a 1"–6" front barrier face directly in the path of the wind and combinations of side and rear wall barriers. This would represent an increasing number of real-world LH2 incident conditions at fueling stations where pools are constrained by existing equipment, structures, and walls. Slide 15 notes testing ignited hazards "by walls" as potential future work. If this describes similar experimental approaches, then "well done" to the team.
- Including rainy-day testing would be informative for comparing data sets and firming the modeling up further for different weather conditions.

# Project #SCS-011: Hydrogen Quantitative Risk Assessment

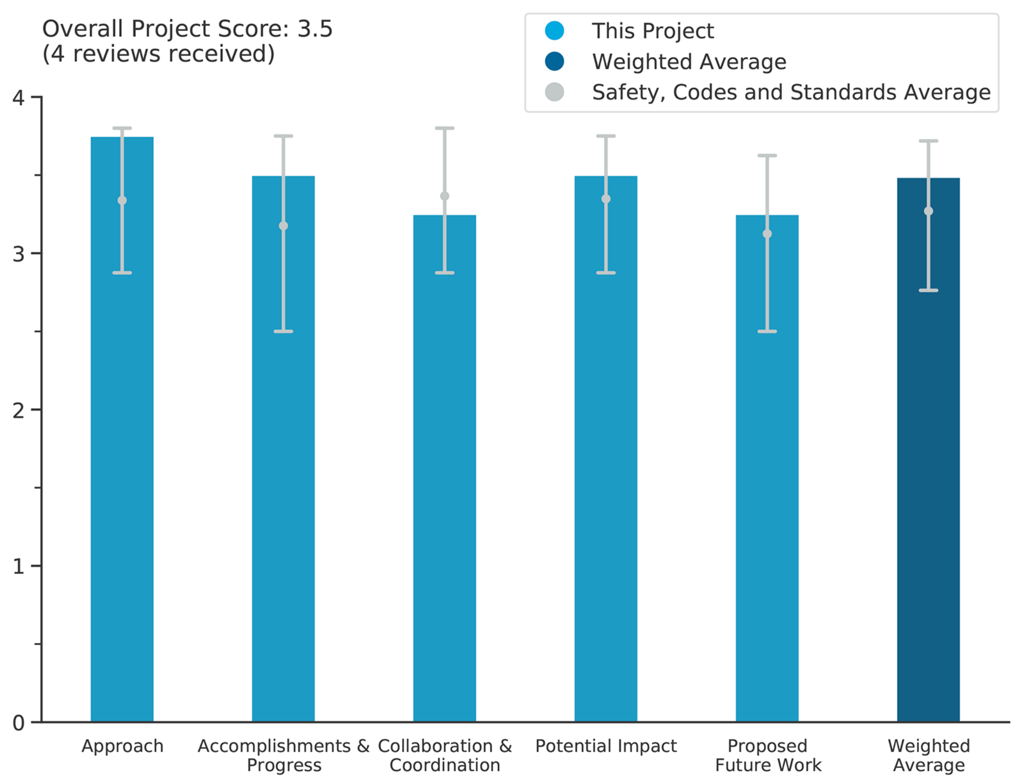
Brian Ehrhart, Sandia National Laboratories

| | |
|---|---|
| **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, International Electrotechnical Commission, International Organization for Standardization, International Energy Agency |
| **Barriers Addressed** | • Risk-informed codes and standards |

## Project Goal and Brief Summary

The primary objective of this project is to provide a scientific 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 (Sandia) 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




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### 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.

- SCS-011 presents an integrated approach that uses hydrogen behavior experiments to create the basis for science-based codes and standards. The work scope also includes development of the hydrogen-specific QRA tools, data, and methods, but this appears to be deprioritized in favor of applied work. The continued development of the models and data for HyRAM+ (Hydrogen Plus Other Alternative Fuels Risk Assessment Models) and the dissemination of HyRAM+ produces important scientific tools that can be adopted broadly by stakeholders globally to drive change in the standards. A significant portion of project resources are focused on developing standards, particularly National Fire Protection Association Code 2 (NFPA 2).
- The objectives of the research are application-oriented, and the approach to evaluating safety using HyRAM (Hydrogen Risk Assessment Models) and QRA is very good. This project would build confidence in the end user for adopting hydrogen technologies.
- The project has stated goals that are clearly related directly back to the Hydrogen and Fuel Cell Technologies Office and DOE goals. The project continues to build on much previous work. The goals, however, are quite broad, so it is difficult to assess progress at that level.
- The project objectives and barriers are very well-explained. The presentation also clearly identifies the link with other relevant efforts on that topic.

### Question 2: Accomplishments and progress

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

- Progress and accomplishments since the last presentation were well-described. Overall risk assessment is key to development of codes and standards. The tunnel safety assessment and blended fuels advancement and processes were well-explained and are moving along.
- The accomplishments include risk assessment of tunnel design and subsurface storage, using HyRAM+ and QRA to assess blends of hydrogen and natural gas, as well as validate overpressure models.
- This year's strongest progress is on developing advancements in behavior and flame models for hydrogen and blends; this work is consistently strong and valuable to the broader community. This year, the project has made limited progress toward its stated goal of developing hydrogen-specific QRA tools, data, and methods. The accomplishments are vague claims about confidence and a questionable sensitivity analysis. The technical depth is missing, and the responses to the previous year's comments dismissed questions about technical depth. This work using HyRAM+ to conduct applied analysis of fires in tunnels is a good step toward enabling others to do the applied facility safety analysis while the national lab focuses on innovating the tools, methods, and data to enable the industry.
- It would be helpful if the authors/presenter could somewhat simplify the presentation of accomplishments and progress. Some of the explanations are hard to follow for those not already familiar with QRA. The project clearly has important applications in areas such as risk of hydrogen vehicles in tunnels, but it is difficult, from the presentation, to understand how the methodology is applied.

### 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.

- The researchers have collaborated with industry, codes and standards organizations, and national labs.
- Many collaborators are listed, but it is unclear how deeply they are engaged in the work based on the limited details provided in the presentation. It listed collaborations with other DOE labs and mentioned four companies seeking technical assistance but did not describe the depth of collaboration, so the collaboration appears relatively superficial. It appears that Sandia is doing most of the work in-house and then informing code committees. Sandia is encouraged to engage in two-way collaboration, work with subcontractors, and engage those partners more deeply.

- A list of collaborators and their roles is provided at the end of the presentation. It would be helpful if more information about specific work by and with collaborators was embedded in the presentation when discussing, for instance, accomplishments and progress.
- The project could benefit from additional collaboration with institutions and feedback.

### Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This research will help end users develop confidence in the safety of hydrogen technologies. The project could, thereby, accelerate the introduction of hydrogen vehicles into the fleet and further development of hydrogen infrastructure.
- This project is key in advancing the Hydrogen Program's objectives.
- Being able to correctly identify the risk in a given situation/installation is extremely important, as is the ability to quantify the change to (improvement in) risk by making a design or process change when a risk has been identified. It is not clear how the tools presented are used to do that.
- The milestones are relevant to the Hydrogen Program goals. However, given the budget allocated to the project and the 20 years of work toward these goals, it should be producing more impactful results by enabling more stakeholders to do these analyses. Sandia has the means to create the tools that support industry across a broad spectrum of engineering standards but is too narrowly focused on doing routine analysis.

### Question 5: Proposed future work

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

- Future work includes uncertainty/sensitivity analysis, heat flux effects versus temperature for quantification of risk, and comparison of jet explosion models to vapor cloud explosion models for risk assessment. All of this work is needed to further enhance the models for risk assessment.
- The project demonstrated its next steps very clearly. Explaining the prioritization process for new risk assessment would benefit the project. Sandia might coordinate with labs and researchers to verify and obtain validation data on, for example, fuel blends.
- The future work discussed seems to represent logical extensions of the work to date. It would be helpful if the ultimate destination of the work planned could be articulated. It is not clear how anyone will know when this work is done.
- Proposed efforts on sensitivity and uncertainty are questionable. Sandia is encouraged to emphasize technical depth and transitioning capabilities. More effort should be placed on expanding capabilities of HyRAM+ and making it usable by external organizations for a wider range of analyses. The project could survey users about their needs.

### Project strengths:

- The development of computational tools rooted deeply in physics- and data-informed methods is the strongest possible strategy for enabling harmonization of international standards. The combination of experimental and computational work and the HyRAM+ platform of the national labs provides a much-needed scientific approach to safety, codes, and standards development.
- The strengths of the project are the tools developed through research and knowledge to evaluate safety risks associated with hydrogen or blends of hydrogen. The results of this research are also coordinated with standards organizations that would provide guidelines for safe designs.
- The project tackles an area that is both very important and very difficult because of the potential high consequences of various risks and the large variation in probability of their occurrence.
- The project is essential for codes and standards validation. Key modeling aspects are covered and discussed in the project.

### Project weaknesses:

- The reviewer did not find weaknesses.
- The work shies away from the hard problems that national labs are uniquely positioned to address in favor of routine analysis. This project has a large amount of funding and a 20-year history. Revising NFPA 2 separation distances has been part of Sandia's scope for 20 years. It raises the question of whether the national lab is doing enough to transition the routine work to others. There is significant vagueness in the milestones and outputs that is potentially disguising lack of technical depth. The collaborations appear superficial. The project could benefit from expanding the network of collaborators and engaging in deeper collaborations.
- It would be helpful to articulate how a QRA does not always end up with an extremely conservative answer in the face of large uncertainty. As presented, it is difficult to follow how the QRA process/tools should be used to communicate risk and demonstrate that a project/situation has been properly evaluated and the risk communicated in a way that is clear to non-expert stakeholders.
- Although it has been noted that the team is working to gather validation data, some of the assessments are models and will still need to be validated before being used in codes and standards. Presenting a decision tool for prioritization next year could be beneficial in explaining how the next risk assessment is launched.

### Recommendations for additions/deletions to project scope:

- The project scope, as presented in the stated project goals, is broad. At least from the point of view of trying to review the project based on a 20-minute presentation, it would be helpful if the goals and activities could be prioritized to give reviewers a better feel for whether the project made progress on the three most important things.
- There should be increased focus on enabling the stakeholders to conduct QRA, as well as on adding data and modeling capabilities that can inform a broader set of risk mitigations beyond separation distances. The project should focus on creating and disseminating unique capabilities rather than doing routine analyses.

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

Nick Barilo, Pacific Northwest National Laboratory

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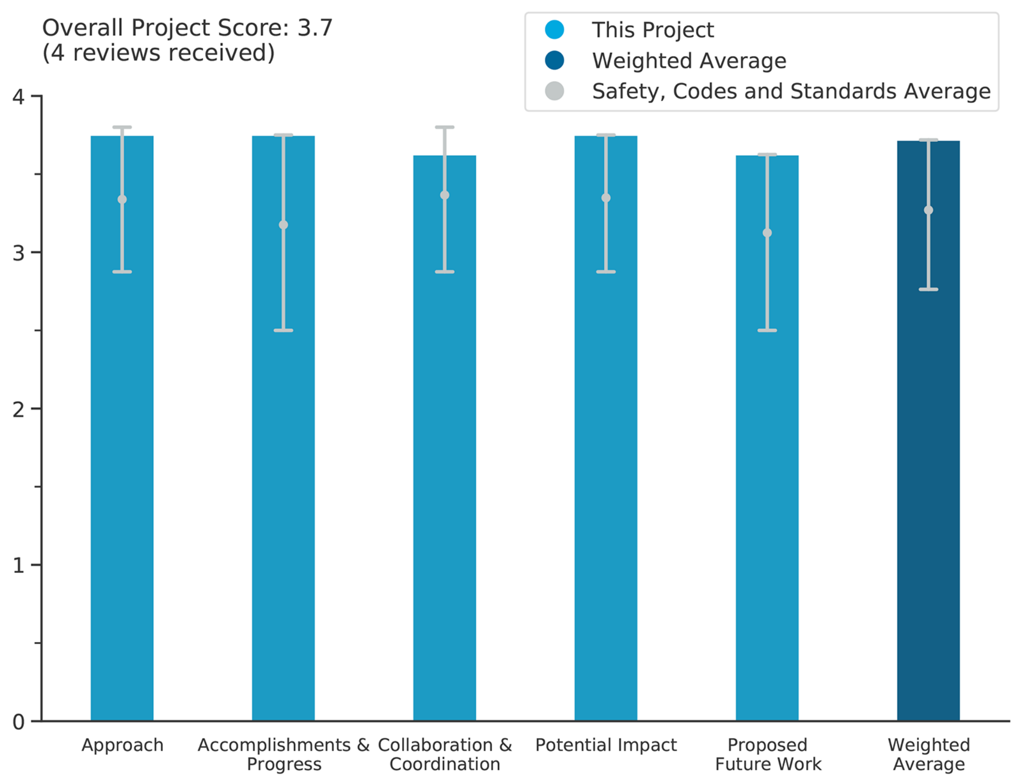
|---|---|
| **DOE Contract #** | WBS 6.1.0.702 |
| **Start and End Dates** | 3/1/2003 |
| **Partners/Collaborators** | California Energy Commission, American Institute of Chemical Engineers' Center for Hydrogen Safety |
| **Barriers Addressed** | • Safety not always treated as a continuous process<br>• Limited access to and availability of safety data and information<br>• 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 to 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




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

## 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.

- Nick Barilo and the Pacific Northwest National Laboratory are providing outstanding leadership in this project. It is truly a global resource that makes others jealous. The HSP is one to be mimicked (the European Union is trying); the incidents database is extremely valuable, and the cooperative research and development agreement (CRADA) with the American Institute of Chemical Engineers (AIChE) has turned into an extremely valuable resource. The first responder training is to be copied—indeed, others are trying to do exactly that. The presentation did not mention diversity, equity, inclusion, and accessibility (DEIA).
- This project clearly outlines its objectives and is essential for the hydrogen economy deployment. Gaps and barriers are identified, although access to data will remain an issue for the HSP.
- This project has been in operation since 2003. Its focus is to develop safety culture for hydrogen technologies and build public confidence in these technologies. The approach used through HSP, H2Tools, and the Center for Hydrogen Safety (CHS)–AIChE CRADA is helping meet the objectives, but perhaps more is needed in the coming years to develop hydrogen infrastructure.
- HSP, safety knowledge tools, and first responder training resources are all robust projects, each with different goals. It would be good to hear more in-depth reporting on each, which may require more than one presentation slot. Although not strictly required, there may have been a missed opportunity to address the benefits of the project on DEIA activities. It would be good to see this specifically highlighted next year, perhaps with training and knowledge resources being provided to projects and communities addressing DEIA initiatives.

## Question 2: Accomplishments and progress

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

- This project continues to excel in its accomplishments and the progress made. The HSP is a global resource, the first responder training is outstanding, and the AIChE outreach is outstanding. The H2Tools Portal provides an open user tool to help educate on hydrogen behavior, properties, and other hydrogen safety issues. The work is outstanding.
- The accomplishments from HSP include providing education and expertise to industry and authorities having jurisdiction, as well as providing lessons learned from detailed review of field incidences and updating codes and standards for safety improvements. In general, the HSP is progressing well. H2Tools is a good resource for industry to gather information needed. The Hydrogen Safety Codes and Standards Applicability Navigator (HySCAN) tool is a good resource that was released last year.
- The project's, and particularly the HSP's, progress is clearly listed, measurable, and demonstrated. The trainings numbers are also provided and clear.
- The team might consider a suggestion to improve the project's effectiveness in addressing DOE multi-year research, development, and demonstration plan (MYRD&D) Barrier G. There is insufficient technical data to revise standards—perhaps the team could engage active standards development working groups (WGs) regarding incidents that may provide opportunities for improved standards. For example, incidents pertaining to components in hydrogen fueling stations could be shared with the International Organization for Standardization (ISO) Technical Committee (TC) 197 WGs or Canadian Standards Association (CSA) WGs covering standards for the failed components. Specific data, incident information, and hazards analysis are critical to those WGs and nearly impossible to get through WG members directly.

## 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.

- This well-coordinated effort has been continuing since 2003. The collaboration with other research organizations, AIChE, and others to build the knowledge base and then disseminate the knowledge through webinars, etc., and the H2Tools website is helpful.

- Through the AIChE's HSP, the collaborations and coordination with the larger hydrogen community cannot be any better.
- The project has key collaborations in the United States and North America. Although major efforts are made to hold CHS meetings in different time zones to include various regions, the number of international collaborations could go beyond current activities. For example, the team should review incidents from other locations, when feasible.
- The CRADA with AIChE is certainly an important partnership. Some output and even, in some cases, participation at any level in key aspects of the work is limited to CHS members. The team should consider direct outreach with relevant regulations, codes, and standards (RCS) WGs to discuss lessons learned and issues encountered relating to components or systems.

### Question 4: Potential impact

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

- The impact of this work is well-stated in its output and results—outstanding.
- This project is essential to the safe deployment of hydrogen and clearly supports the DOE objectives.
- The potential impact of this work would be more acceptance of hydrogen technologies by the industry and the public.
- This project directly supports and advances progress toward stated goals and objectives. One area of potential improvement relates to MYRD&D Barrier A. Regarding safety data and information, access and availability are limited. Perhaps the impact could be improved with more direct coordination with relevant RCS WGs.

### Question 5: Proposed future work

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

- The team should keep it up.
- The future plans for the HSP and CHS CRADA are excellent. The HSP will continue safety reviews for DOE-funded projects, though the future support of DOE hydrogen hub projects' safety planning will occur outside of this project. The team should consider engaging with the broader community on the stated plan to continuously improve H2Tools with easier access to key information and new best practices. One proposed future activity could use further elaboration: developing an international section on H2Tools. The team should also highlight codes and standards from around the globe, including ISO codes. The Fuel Cell Codes and Standards Database hosted on H2Tools already includes international standards. Efforts to improve usability are awaiting the impending user interface update.
- The work by HSP is still needed and should continue. As hydrogen vehicles are introduced into the fleet, new issues may arise, which an established program such as the HSP can evaluate and address. However, more needs to be done to engage the public in hydrogen safety. Perhaps then the resistance to hydrogen infrastructure development will be reduced. More work is also needed for first responder training and for identifying fuel types. Research on approaches to identifying fuel used in vehicles would help first responders.
- With this project's importance to the industry, clearer explanations of future work would be of benefit.

### Project strengths:

- The project has outstanding outreach, outstanding engagement, and outstanding performance.
- This project's success relies on a collaborative approach and shared knowledge and experience. The team is doing a great job.
- The HSP and CHS CRADA effectively address many of the challenges of the work and contribute directly to project and DOE goals.
- This well-established project has a focus on safety.

### Project weaknesses:

- Improvement is encouraged in ensuring that key learnings are transferred directly to RCS WGs. This endeavor could be addressed to some degree through the planned work on expanding H2Tools for role-based dissemination.
- The project lacks sufficient public outreach on hydrogen safety. More engagement is needed to dispel fears about well-designed fueling stations. First responder training is needed on fires involving hydrogen or a blend of hydrogen and natural gas. Some research is needed on approaches for first responders to identify the type of fuel used.
- The H2Tools website is sometimes not easy to navigate, especially with so much information.
- There is no mention of DEIA.

### Recommendations for additions/deletions to project scope:

- The principal investigator did an excellent job. This presentation really needs a longer presentation slot at the Annual Merit Review. The author was forced to skip over much of his presentation material to get to the meat of his presentation, which in and of itself was raced through. The project's outstanding level was still obvious, but it would have been much better for the presenter to have had more time to articulate. The presentation should include a discussion on DEIA.
- The team should consider one or more workshops on incidents, failure analysis, and lessons learned in conjunction with relevant RCS meetings, such as ISO/TC 197 plenary week or one of CSA's conferences.
- Because the project is so broad, it is not easy to keep track of all the year's achievements in 20 minutes. It could of benefit to showcase how the work interacts with codes and standards improvements and development.
- The team should disseminate information to the public on hydrogen safety so citizens do not think all hydrogen applications are unsafe. First responder training is needed for hydrogen–natural gas blend fires, and research is needed on approaches (regulatory and industry standards) to aid first responders in correctly identifying fuel types in vehicles.

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

William Buttner, National Renewable Energy Laboratory

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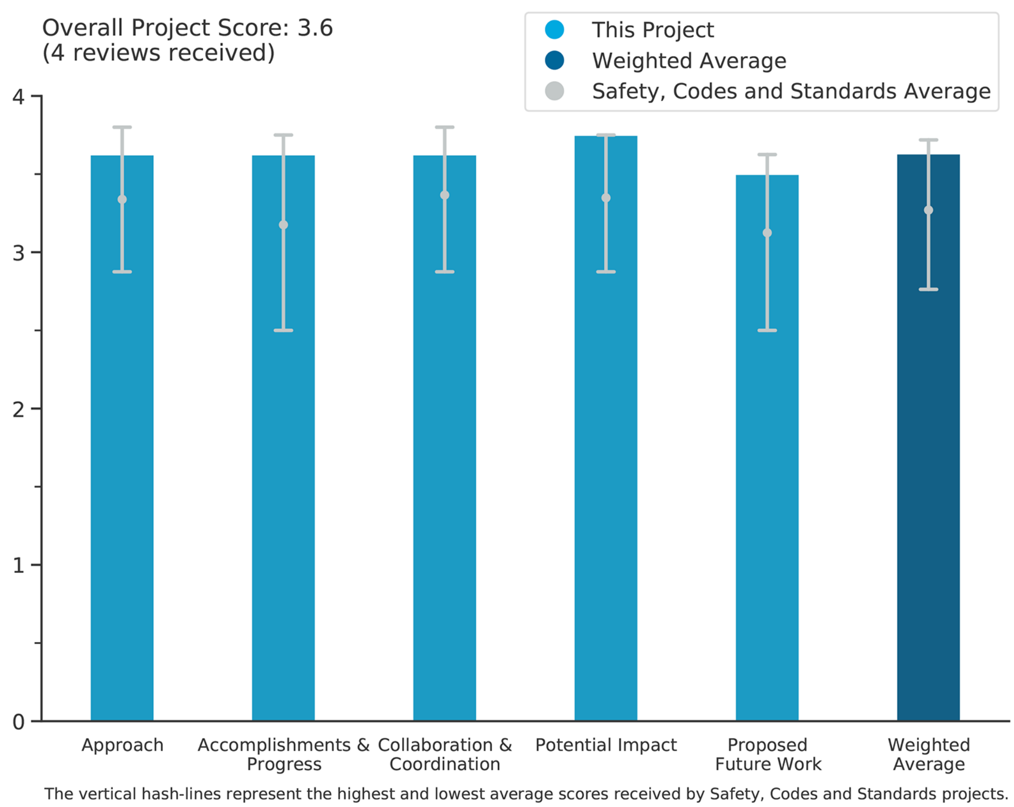
|---|---|
| **DOE Contract #** | WBS 6.2.0.502 |
| **Start and End Dates** | 10/1/2010 |
| **Partners/Collaborators** | AVT and Associates, Element One, Inc., University of Maryland, KWJ Engineering, Inc., Los Alamos National Laboratory, Shell, Amphenol, California Air Resources Board, GTI Energy, Electric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

## 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.

- The NREL sensor facility is truly a gold mine of capability and talent. It needs to be kept alive and stable to continue to achieve the greatness it has already demonstrated. The domestic–international interactions spread the knowledge and keep the project globally relevant. Hosting student interns enables the education of those students, preparing them for future work. The project includes a nice discussion on diversity, equity, inclusion, and accessibility (DEIA). The project is outstanding.
- The project objectives and barriers are clearly defined and are being addressed through the development and maintenance of a comprehensive hydrogen sensor testing laboratory, which provides a controlled environment and standard methodologies for onsite testing and validation of new sensor technologies for safety and emissions quantification. This facilitates the development of advanced hydrogen detection methodologies for early leak detection (e.g., hydrogen wide-area monitoring [HyWAM]) and high-sensitivity sensors that are able to detect hydrogen leaks for environmental monitoring and quantification. In addition, the facility allows for process monitoring testing through its hydrogen contaminant detector (HCD) program. The outdoor Advanced Research on Integrated Energy Systems (ARIES) facility is excellent for controlled release to better understand and model the dispersion of hydrogen in the atmosphere. which will improve quantification methods and is important for environmental monitoring. In addition, the laboratory has capabilities to validate hydrogen sensors with sub-parts-per-million (sub-ppm) detection limits, which is needed for environmental monitoring. One point to note is that offshore hydrogen sensors may have unique requirements due to the unique marine environment and infrastructure. Sensors may not be resistant to the corrosive, salty air, and the dispersion plume from hydrogen releases will have different characteristics from onshore. In the future, it would be good to see offshore-specific needs addressed as well.
- The project clearly contributes directly to DOE Multi-Year Research, Development and Demonstration (MYRD&D) Plan Barrier 3.7.5.G – Insufficient Technical Data to Revise Standards, as well as 3.7.5.H – Insufficient Synchronization of National Codes and Standards. The presentation lists DOE MYRD&D Barrier 3.7.5.J – Limited Participation of Business in the Code Development Process, but the project does not address this barrier nor progress in addressing it. While the project assists businesses in evaluating the performance of sensors, this does not necessarily involve those businesses participating in the code process.
- The lab clearly plays an important role across several functions in a rapidly evolving industry. The component and sensor testing capabilities were clearly communicated. Also, it would be good to see a little more clarity on how each of the testing facilities/locations covers the range of anticipated layouts that we could expect in the emerging hydrogen economy.

### Question 2: Accomplishments and progress

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

- This project continues to exhibit a high degree of progress and accomplishments focused on the DOE goals of deploying hydrogen technologies in a productive and safe manner. Pioneering work with HyWAM is a prime example of out-of-the-box thinking that is relevant to leak detection in large facilities. Continuing to improve on the capabilities will prove very valuable in the future, for example. The work is outstanding.
- Significant progress has been made, in particular toward developing and testing sensors and methods for the detection, monitoring, and quantification of hydrogen losses for environmental purposes. An example of this progress is the verification of sensors at lower levels and methods for wide-area monitoring, which is important for environmental purposes. These efforts (i.e., more sensitive sensors and understanding the dispersion characteristics of hydrogen plumes under a variety of conditions) should continue. There has also been progress in the development of HCDs for process control.
- Progress is clearly demonstrated for DOE MYRD&D Barrier 3.7.5.G – Insufficient Technical Data to Revise Standards, as well as 3.7.5.H – Insufficient Synchronization of National Codes and Standards. The project also demonstrates progress on DEIA objectives.
- Overall, the project’s accomplishments are clearly stated.

### 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.

- This team continues to work with others on project improvement and execution. For example, the project team makes excellent use of Argonne National Laboratory for techno-economic analysis, Sandia National Laboratories for laser detection and materials interaction, and Pacific Northwest National Laboratory for polymer interactions. In this review, the presenter specifically called out activities related to DEIA. With such a focus, the impact on DEIA will be excellent.
- This project is well-coordinated with several universities by providing a testing site for sensor performance validation. The project team is also leading a project with partners from private industry to implement wide-area monitoring and hydrogen leak detection, as well as to advance computational fluid dynamics (CFD) modeling.
- The project coordinates with an impressive list of collaborators. It may be time to re-engage with the International Organization for Standardization Technical Committee on Hydrogen Technologies (ISO/TC 197) work on hydrogen detection for fueling stations. Results from this project have the potential to solve some of the detectability issues identified back in 2010 while developing ISO 26142: Hydrogen detection apparatus.
- There is an extensive list of project partners, and the lab is connected with critical industry, governmental, and codes organizations. It is good to hear of the California Air Resources Board collaboration. The project team is encouraged to consider what other collaborations might be useful.

### Question 4: Potential impact

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

- This project has already had a positive impact on hydrogen deployment safety. As hydrogen systems are deployed, the sensor activity will be paramount to ensuring safe deployment. The progress made thus far is outstanding.
- The Annual Merit Review had a number of presentations on hydrogen safety, and it is right to recognize the critical impact of safety and sensor enablement of safety (that the lab supports) on hydrogen's having any sort of meaningful deployment. It was also clear that the lab likes working with interns and having education be a part of the lab, which, as was noted, helps contribute to industry-wide growth in education and professional capabilities.
- In addition to the progress demonstrated on the technical aspects of hydrogen detection, the project has impressive DEIA/community benefits plans and activities, including course material development and hands-on experience.
- This project supports the DOE mission for the safe and efficient implementation of hydrogen as an energy carrier by providing a unique and indispensable environment for the development and use of hydrogen detection technology for safety, process control, and emissions quantification and mitigation.

### Question 5: Proposed future work

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

- Continued improvement is critically needed in sensor technology at sub-ppm levels for environmental application and improvement of HyWAM. The project team is encouraged to continue in this direction.
- The project has some specific plans that align well with advancing sensor technologies and reducing unintended hydrogen releases. The project also offers the flexibility to address needs identified by the industries being supported. There is one barrier identified that needs more specific future work to address it: the need for lower detection limits to inventory operational and unintended releases to optimize operational efficiency and minimize potential environmental impacts. It would be helpful to know whether, based on the work so far, there are any recommendations for future work to help address this barrier. Regarding DOE MYRD&D 3.7.5.G – Insufficient Technical Data to Revise Standards, the project team is encouraged to consider applying the lessons learned from this project directly to the ISO/TC 197 work on

hydrogen detection for fueling stations. ISO 26142: Hydrogen detection apparatus, published in 2010, sets out the requirements applicable to a product standard for a hydrogen detection apparatus; such requirements include precision, response time, stability, measuring range, selectivity, and poisoning. The reviewer was engaged with the work as it was developed. In the 14 years since then, this project has resulted in significant learnings regarding detection technologies, which could be invaluable in updating detection standards.

- The proposed future work addresses challenges and barriers through efforts aimed at improving the understanding of released hydrogen behavior through wide-area monitoring and CFD modeling. The work also addresses detection strategies for hydrogen leak detection for large-scale and emerging markets, as well as lower detection limits to monitor and minimize environmental impacts.
- It was hard to determine what the role of the lab was in modeling. For example, it was unclear whether the lab intends to be an impartial evaluator of modeling capabilities or a developer of these capabilities. Relatedly, it was also unclear what the nature of the gaps is for the industry in this space, as well as what the most effective role for the lab is. The laboratory makes itself useful, but it can be hard to differentiate what the roles are across the entirety of the hydrogen ecosystem. For example, more consideration is due to supporting the conversion of equipment (such as boilers) from methane to hydrogen. Perhaps such efforts fit in the project for the lab, or perhaps they would be duplicative with the Center for Hydrogen Safety and the Southern California Gas Company.

## Project strengths:

- This project includes outstanding outreach, outstanding engagement, and outstanding performance.
- Inline hydrogen contaminant detection is critical to meeting the fuel quality needs of the future. Evaluation of hydrogen sensors is contributing to better detection capability. HyWAM work is important to informing models, as well as codes and standards. Education and outreach efforts directly support DEIA/community benefits plans and activities.
- This project provides an extremely valuable resource (controlled onsite outdoor testing) to help in understanding how hydrogen plumes disperse in real conditions, allowing for improvements in modeling, monitoring, and quantification. Testing done at the facility will increase the technical data needed to revise standards and better estimate hydrogen losses.
- There are clear strengths in staff, facilities, and responsiveness to opportunities.

## Project weaknesses:

- It is not clear how the project will contribute to increasing participation of businesses in the code development process. It is also not clear how the project will address the need for lower detection limits.
- The principal investigator (PI) has listed a few of the project's DEIA/community benefits plans and activities, which are encouraging but could be developed in a more concrete way in the next year.

## Recommendations for additions/deletions to project scope:

- The PI is very good at running this project. The PI's facilities, out-of-the-box thinking, mentoring, etc. all fit very well into what is needed for the growing deployment of hydrogen technologies. The project team is encouraged to continue pursuing this effort.
- There are no suggestions for additions or deletions. The project scope is sufficiently broad and flexible.
- In the future, it would be good if this project would consider offshore-specific needs for hydrogen sensors and modeling of hydrogen releases, if they are different from those for onshore. For methane, onshore sensors are not suitable for the harsh, salty marine environment, and the dispersion of gaseous plumes have different characteristics from onshore due to differences in infrastructure and meteorological conditions (e.g., stable marine boundary layer).

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

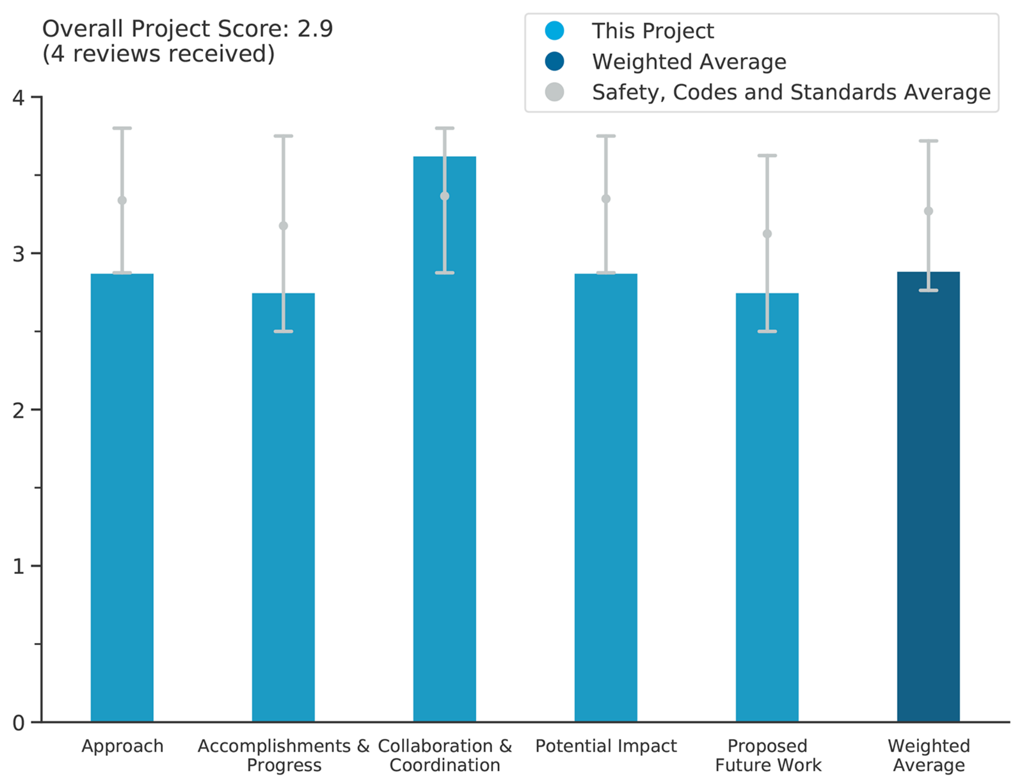
Karen Quackenbush, Fuel Cell and Hydrogen Energy Association

| | |
|---|---|
| **DOE Contract #** | DE-AC05-00OR22725 |
| **Start and End Dates** | 04/15/2023-04/14/2024 |
| **Partners/Collaborators** | National Hydrogen and Fuel Cells Codes and Standards Coordinating Committee, Pacific Northwest National Laboratory, Oak Ridge National Laboratory |
| **Barriers Addressed** | • Consistent regulations, codes, and standards required to enable national and international markets<br>• Insufficient synchronization of national codes and standards<br>• Limited business participation in the code development process |

## Project Goal and Brief Summary

The project goal is to facilitate widescale adoption of fuel cells and hydrogen energy systems through 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 (AHJs), and other key stakeholders.

## Project Scoring




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- The project convenes working groups comprising hydrogen-related businesses. The project creates and freely disseminates bimonthly online newsletters and websites focused on RCS progress. The project also connects businesses to the needs and progress of standards development organizations.
- The approach is good, although the ability to influence RCS remains a little more arm's length—however, with solid representation from industry members.
- The project goal and impacts are clearly identified. While a safety plan is not relevant to this project, the safety slide could have mentioned the 2023 interface with the Hydrogen Safety Panel for engagement on scope and issues. A growing client base for understanding codes and standards is highlighted: AHJs and fire marshals. This presentation could expand the interface description for how it is involved with these two key stakeholders. For example, it is unclear what specific AHJs and fire marshals are connected with the organization and how, specifically, the FCHEA identifies and reaches out to these entities.
- The work to address the fuel cell stack ASME issue is a good example of the type of work that might be useful. However, it is still not clear if FCHEA is critical to the effort. If this work is important, as it seems to be, then it would still be done without the need for government funding. The objectives and barriers are clearly stated, but there is limited support for why this project is necessary to obtain those objectives. The approach of this project is most effective when FCHEA takes a chair or convening role on a given task. Otherwise, the support is generally not effective. It is also not clear why the FCHEA support requires DOE project funding. There is no safety plan or diversity, equity, inclusion, and accessibility/community benefits plan, presumably since they are not required and are not really applicable to this project.

### Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- RCS is not a particularly "sexy" topic; however, the output of the quarterly newsletter and its availability on the website, along with code coordination and feedback from FCHEA members, are important functions. This communication is increasingly important as the world looks to harmonize RCS and deliver lower-cost and safer outcomes. The government will need to continue to play a role in supporting this forum to deliver global best practices and public access.
- The specific examples identified throughout the presentation support the project's value to the DOE Hydrogen Program. Extra slides at the end of the presentation, solely for reviewers, are helpful. Quotes from users and new/smaller firms would be valuable to document the value of interfaces. Web analytics (slide 14) are unclear, especially how analytics identified were accessed by AHJs and first responders. Just posting presentation slides as a "poster" limits the communication of the value of FCHEA and its impact. The team should consider preparing an actual poster for future poster sessions, while still including the slides on the side of the presentation space. The team should also use the poster to highlight significant accomplishments and issues and include quick response (QR) coding for visitors to access the database and matrix.
- The project lists accomplishments such as the progress and completion of several International Organization for Standardization (ISO) standards. However, it is not shown how the specific input of this project was impactful to that result. It is unclear whether specific input from this project enabled the progress or this effort is mostly monitoring and reporting. It is difficult for an effort such as this one to have meaningful quantifiable results, which makes assessing its usefulness difficult. For example, while the breakaway harmonization was useful, this work could also have been done by other groups, such as members of the National Fire Protection Association (NFPA) 2 Fueling Task Group. Groups such as this one do this work for many other issues and also operate basically on a volunteer basis.
- Maintaining and freely disseminating information about RCS progress across many standards development organizations is an important activity. However, it is important to show that this information is actually being used. The slides claim a broad range of accomplishments on standards. However, these accomplishments are not directly attributable to FCHEA. These standards are developed by myriad groups.

The poster does not clearly articulate what FCHEA achieved. Specific milestones are not articulated; thus, it is difficult to assess what is being accomplished. It is concerning to see meetings as a surrogate for accomplishments. It is unclear what technical information is informing the decisions. Reports are ad hoc. There is no discussion of sources or methods used to produce briefs based on best practices or research and development (R&D). Slide 15 shows only 8,000 per year, with a 72% bounce rate. This bounce rate is extremely high, which suggests that visitors are not finding useful information on the website.

### 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.

- The collaboration goal of the FCHEA is clearly presented. The organization exists to inform and connect firms with multiple codes and standards organizations and identify issues before they seriously impact company planning.
- The collaboration is outstanding. This project could be worthy of funding entirely based on collaboration alone. Centralizing the collaborations in one project would provide a more efficient use of limited DOE resources, and FCHEA stands out as a highly collaborative organization.
- The very strong membership base for FCHEA provides a strong and experienced voice for RCS updates and changes. Potential exists for broader engagement on RCS work with other countries/international bodies in the future, if desired.
- The nature of this project inherently requires collaboration and coordination with other institutions. FCHEA, through its large membership roster, will naturally involve a number of varied participants. It would be helpful to understand participation in the monthly calls and whether that participation is increasing, decreasing, or flat.

### Question 4: Potential impact

This project was rated **2.9** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- A key project goal is the harmonization of related codes and standards. There is minimal information as to how this harmonization is happening. The identification of specific issues addressed in 2023 was valuable. This information could be expanded as a table for all major national and international codes and standards. The table could also highlight company responses to indicate how the advanced information and interfaces are impacting hydrogen project planning.
- RCS adoption and development is often a slow process, and considerable compromise can be required. The impact of FCHEA on the final outcome of RCS development is not clear; however, there is significant industry involvement in the working groups, and their coordination of feedback is important to developing efficient RCS.
- The main progress is toward enabling the participation of multiple types of commercial businesses in the RCS progress. The project makes no impact on two of the claimed barriers: “Ensure that best safety practices underlie research, technology development, and market deployment activities supported through DOE-funded projects” and “Conduct R&D to provide critical data and information needed to define requirements in developing codes and standards.” The project does not have an impact on these identified barriers: “Enabling National and International Markets Requires Consistent RCS” and “Insufficient Synchronization of National Codes and Standards.” Slide 15 shows only 8,000 per year, with a 72% bounce rate. This bounce rate is an extremely high and suggests that visitors are not finding useful information on the website.
- The project supports the broad goals of the Hydrogen Program, but the question is whether the results warrant the resources. It is not clear that this is the case or whether nearly all of this work would be completed anyway. It seems as if FCHEA effectively abstains on many issues, thereby providing little impact on the results, with the exception of those activities for which FCHEA is a convenor. The year-over-year 19% drop in the viewership shows a significant loss of effectiveness, especially considering the significant increase in hydrogen activity last year due to growth in the market. Similarly, the number of unique visitors is almost as high as the total number of visitors, which shows that most viewers are accessing the site only once per year—indicating that people are not inclined to return to the site for regular

updates. Similarly, metrics on attendance as the National Hydrogen and Fuel Cells Codes and Standards Coordinating Committee would be useful to gauging the overall direction of the project.

### Question 5: Proposed future work

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

- The project has a good focus from the various working groups to try and harmonize local, state, and federal RCS, which will be important for simplifying this harmonization for regulators, communities, and industry alike.
- The future scope is primarily to continue with current interface plans. Focus on working group planning indicates the value of these groups. There is no significant discussion on barriers to project scope. Slide 21 mentions connecting (“bring[ing] to the table”) hydrogen experts to codes and standards scope. This scope is indeed a great focus, but it is unclear what the barriers and future planning are to making this activity fruitful.
- The proposed work seems to just be general comments of continuing to “support,” “address,” or “work” with various task groups and committees. There are no significant detailed issues provided for the project to work on this year, which might be used as an objective method to measure the success of this project.
- It would be preferable to see more focused, specific approaches and accomplishments rather than the current approach, which is scattershot. Focusing on the RCS matrix and the newsletter is valuable. The team should conduct an independent review and solicit feedback from members regarding the effectiveness of FCHEA activities and target resources to the most high-value of the many activities in which this project engages. It seems spread too thin right now, so some of the work is not making the impact that it could be making.

### Project strengths:

- The project strengths include wide industry interest, an excellent database, and scope and availability of working groups. Additional detail on the activities and effects of the working groups (e.g., current-year accomplishments, future plans, members) would be valuable.
- The main strengths are those activities in which FCHEA has a specific role (chair, convenorship) or a specific task identified for completion.
- The project strengths are the depth of industry engagement in FCHEA and the involvement in review of RCS.
- The collaboration is outstanding.

### Project weaknesses:

- Reporting effects of maintaining data resources and connecting users to information are always challenging. The project needs to improve its identification of communication issues and better highlight the effects of its resources to real-world projects. Web analytics are important but do not tell the story very well. The team should consider other ways to display the positive effects this organization’s interfaces have had in helping solve real-world problems. On example is specific quotes by user organizations on the effects on their designs and projects.
- The main weakness of the project is that, other than convenorship, the project does not add much value to the actual content or progress of the standards. FCHEA does not tend to drive the conversation on material and is in more of a monitoring role. It is better for a project to have a specific goal with an identifiable objective and timeline. Then, when complete, another project could be initiated to complete the next task. The reviewer comment shown from last year still seems appropriate, despite the response: “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.”
- It is concerning to see meetings as a surrogate for accomplishments. Perhaps some of those efforts could be guided toward more high-impact work.
- Given the significant industry involvement, it is unclear why the government is funding this effort.

### Recommendations for additions/deletions to project scope:

- The collaboration is outstanding. This project could be worthy of funding entirely based on collaboration alone. Centralizing the safety, codes, and standards collaborations in one project provides a good deal of efficiency for DOE, and FCHEA is positioned as a highly collaborative organization.
- The project should consider developing a methodology (or report on it, if one is in actual use) for high-profile and/or emergency alerts associated with codes and standards promulgations or working topics. While code promulgation is often a slow process, qualifying barriers and approaches to understanding and connecting resources to impactful issues would be significant. For example, the information on the ASME pressure stamping requirements for electrolyzer stacks may have a significant impact on rollout of these units, as noted, but it is unclear if a standard process exists for communicating these issues to those with the expertise needed for a cost-effective resolution.
- This project should poll the large list of organizations on slides 25–27 to validate their continued support for this effort. The team should consider discontinuing the Fuel Cell Safety Report if its year-over-year usage continues to drop, especially if there is no indication that users are seeing value, which could be shown by having a much larger number of overall visits compared to unique visitors.

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

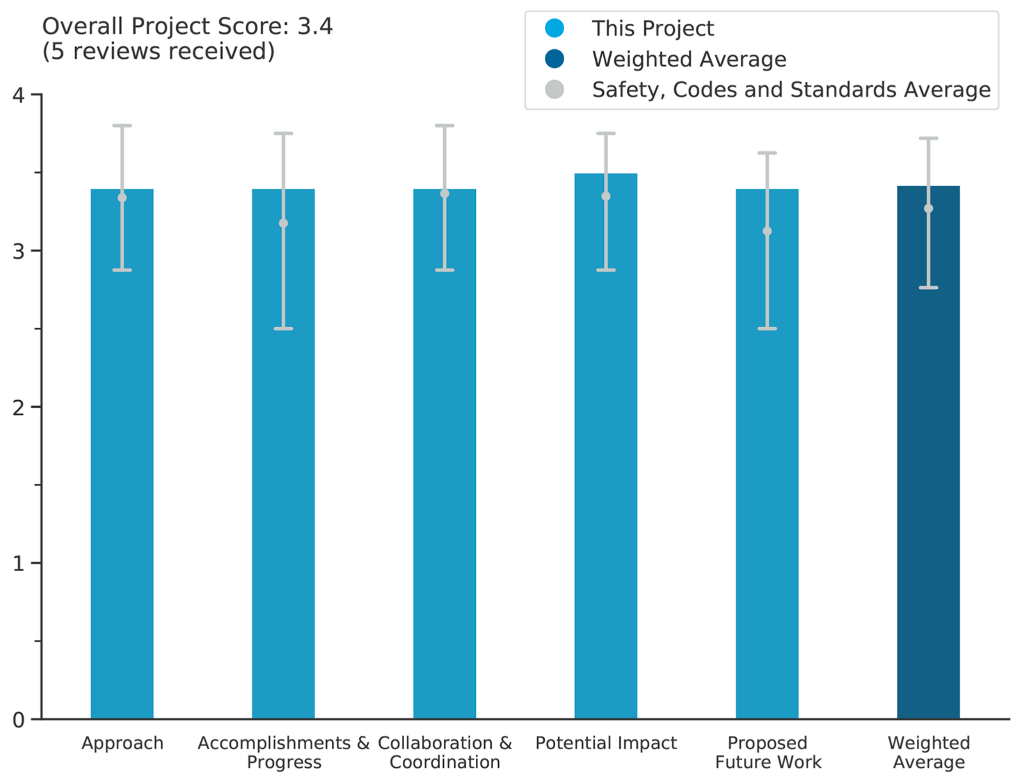
Eladio Knipping, Electric Power Research Institute

| | |
|---|---|
| **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



The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### 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 project directly addresses the DOE goal for workforce planning of the hydrogen economy. Targeting universities' technical programs and courses and involving industry is a great approach.
- The general approach is well-considered and has delivered very good outcomes and ratings—more than what was targeted. The project has good engagement with a broad range of partners and contributors.
- The project includes a multifaceted, coordinated approach with clear metrics.
- The approach is well-explained; however, it might favor one aspect of education over another. Gas fitter and current workforce are not prioritized. It might be due to the very broad scope of the project. The targeted audience is listed as "workforce," but this is not fully covered.
- Overall, the project has a nice approach that has improved in the last year; however, there are some efforts that do not seem to align with other activities occurring with the hubs and their community benefit plans. There could be duplication. The course on fuel cells is an area that has already been funded by DOE in the past. It is not clear if the quantitative metrics in terms of potential job creation are reasonable for this effort. A main need for hydrogen to be successful is the construction jobs, and obviously at this level, this training will not align.

### Question 2: Accomplishments and progress

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

- The project has very good results (delivering more than what was targeted in some instances), particularly with enrollments and satisfaction surveys. It is pleasing to see the focus on historically black colleges and universities.
- Significant progress has been shown on developing courses that meet the needs of the future workforce and reassessing needs and gaps.
- Significant progress has been made in the last two years, and it is well-explained and well-demonstrated/ quantified.
- The project has had vast improvements since the last year in terms of adding additional diverse partners and beta testing some of the initial training modules.
- The project completed the first set of courses and received university feedback—an important first step; however, it is not clear how much feedback has been received from industry, which strongly dictates the course content needed to prepare students for entering the hydrogen workforce.

### 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.

- Collaboration and coordination with partner institutions are excellent.
- Collaboration and coordination are greatly improved.
- The project has an overall great collaborative approach with the universities; however, it is lacking connection with other schools providing science, technology, engineering, and mathematics (STEM) programs, for example.
- Collaboration with universities and industry is strong but surprisingly more heavily weighted toward the eastern United States. This is surprising, given that a significant portion of the country's hydrogen infrastructure (hydrogen refueling stations) today is in California.
- The project has great partnerships; however, not all hubs in the Regional Clean Hydrogen Hubs Program have universities represented in the partner group. It would make sense to target these areas, given the increased demand for local workers in the hydrogen space. Short courses could also be rolled out to target trades and maintenance groups that will be dealing with hydrogen in the future, which would require further engagement and collaboration.

### Question 4: Potential impact

This project was rated **3.5** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project has incredibly strong potential to be foundational to developing the future hydrogen workforce and advancing the overall economy. Having a unified framework across the country could streamline the way industry onboards new employees across many facets (engineering, research, business development, policy, etc.).
- Workforce availability and skills are critical to the rapid adoption of hydrogen in the economy. By ensuring it is delivered in an educated, safe, and well-understood manner to lower risk of incidents and build community trust and knowledge, the program delivers accordingly.
- The project focuses on developing engineers, which is very important and appropriate at this stage of workforce development. Consideration should be given to expanding the reach, perhaps by developing courses for trainers in trade schools, so that hydrogen technologies and safety are taught there in the future. This would require a change in scope.
- The impact could be very high. Training of the workforce is essential.

### Question 5: Proposed future work

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

- The five areas of future work described on slide 20 are outstanding and sharply focused on the barriers identified.
- Good work is proposed for the last few years of the effort.
- The proposed future work addresses previous feedback well.
- The project has good plans for expansion and delivery of content in Fiscal Years 2023–2024. It would be good to see the plan through to the end of project funding.
- The future work listed is ambitious and relevant; however, it might not cover all the aspects of workforce training, especially when reaching out to educational organizations outside of universities.

### Project strengths:

- The project demonstrates a robust and well-thought-out approach for developing the future hydrogen economy workforce in a very impactful way. Directly engaging both academia and industry will help secure necessary skillset development for safe future hydrogen deployment at large scales.
- The project creates a workforce development program that is actively used by students and professionals. Other project strengths include very good collaboration and an advisory board to provide stakeholder feedback and information.
- Project partners are a key strength. Involvement of industry is crucial. A gaps assessment and development of a training roadmap will help ensure project success.
- Education of the current and future workforce is key to the safe deployment of hydrogen. Collaboration between universities is also essential to move the project faster.

### Project weaknesses:

- The project focus is reasonably aimed at university students and professionals in the hydrogen industry; however, the project misses out on trades that will often be dealing with installations and maintenance in the future.
- Expanding partnerships beyond universities should be covered. Training of the current workforce should be promoted.
- Industry involvement is currently small and not necessarily focused on the need for future engineers.
- The project lacks partner universities in the western region of the United States.

### Recommendations for additions/deletions to project scope:

- It would be good to see some of the content tailored for the people who will be working on maintenance of equipment and technology in the future to build capability in these areas in the long term. Tradespeople will require some more specialized training; however, high-level education will support the development of their skills now.
- Consideration should be given to expanding the reach, perhaps by developing courses for trainers in trade schools so that hydrogen technologies and safety are taught there in the future.
- More universities in the western region of the United States should be identified and onboarded, particularly in California, where much of the country’s hydrogen vehicle refueling structure exists today and continues to expand.
- This project has a very broad scope, and it might benefit from establishing a clear workplan based on different 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** | 10/1/2021–3/31/2024 |
| **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 |

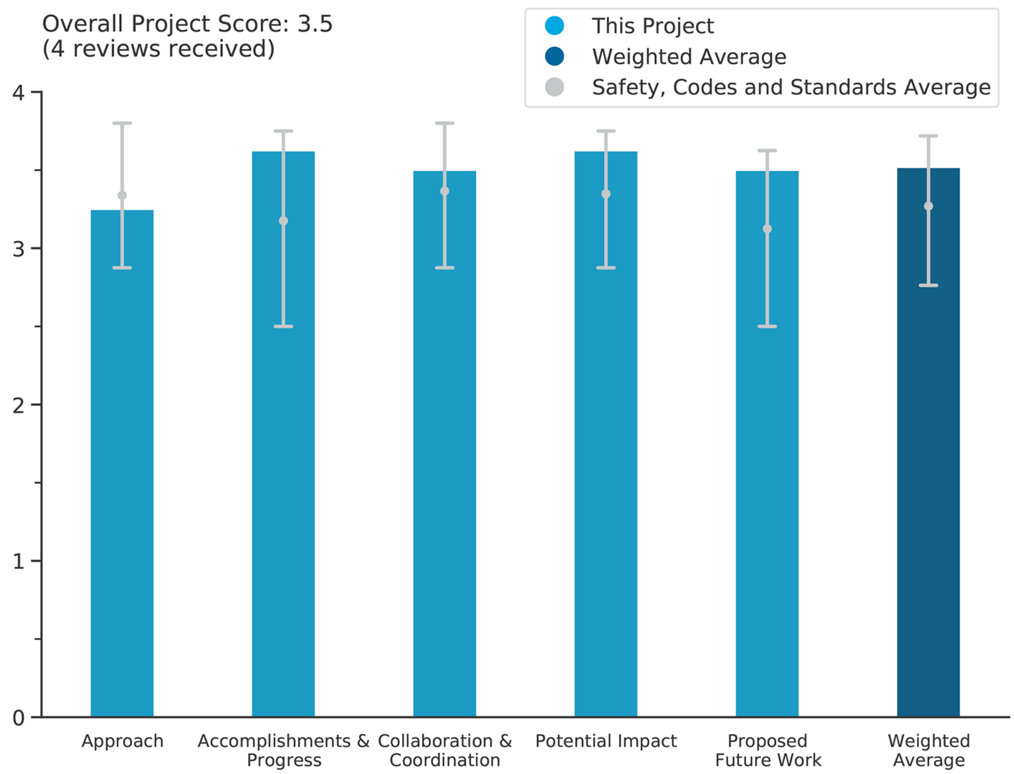
## Project Goal and Brief Summary

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. MC represents total heat capacity.

## Project Scoring




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

## 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.

- The approach is well-defined and consists of a reasonable strategy to successfully develop an H35HF fueling protocol, namely, the use of a survey to define the boundary conditions for the protocol, the adjustment of the H2Fills model to accommodate H35, testing at NREL's facility, and documentation for incorporation of the fueling protocol into SAE J2601-5. Safety planning and safety culture are incorporated into the project effort for the fueling tests to be conducted at NREL. Presumably, the Hydrogen Safety Panel safety plan review is not required. Some additional details regarding how and what aspects of the safety plan have been implemented would be helpful. There was no mention of a diversity, equity, inclusion, and accessibility (DEIA) plan or community benefits plan, so those plans were presumed not to be required for this effort.
- The issuance of Technical Information Report (TIR) J2601/5 is a major milestone. The project goals and barriers were clearly stated. The project team also was diligent in providing answers to the previous year's comments but acknowledged the limitations caused by the barriers. The project has shown progress with the Zentrum für Brennstoffzellen-Technik (ZBT) testing, but the NREL testing continued to slip. There was no comment about a safety plan. It is good that a process hazard analysis was completed for the testing at NREL, but the "safety slide" was insufficient to evaluate the safety of the project.
- The approach used for this project is a good one; it is systematic and methodical. There was no mention of DEIA.
- The objectives, goals, and scope are very clearly stated.

### Question 2: Accomplishments and progress

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

- The project has accomplished its goals, with the exception of a few remaining tests at NREL. The project has effectively concluded, and the work product (H35HF) fueling protocol has been submitted for publication in SAE TIR 2601-5.
- The project struggled with its own barriers but was able to make progress on the barriers within the H35HF fueling industry. The development of the calculator, the modeling, and the testing at ZBT were significant milestones.
- This project is making good advancement toward completing its goals. There are some difficulties, however, in that NREL does not have H35 fill hardware to more correctly test the protocol. The German partners do have H35 fill hardware but not the receiving tanks, presenting a bit of a challenge.
- The accomplishments are well-outlined and -explained and in alignment with the objectives. However, it is unclear whether the task to perform H35HF protocol fueling (and confirm the vehicle tank temperature and pressure stay within the safety boundary conditions set by the protocol) will be completed. The project ended, but it is noted as "incomplete" in the report.

### 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 were a significant number of organizations that collaborated with the project and represented a good cross-section of interested parties. Of particular note were the cooperation and coordination with the SAE J2601 committee.
- The project team has yielded successful results, partly thanks to a well-rounded collaborative/cooperative approach with key industry stakeholders, including end users, codes and standards organizations, government agencies, station providers, and research institutions.
- The partners are appropriate to execute this project. The project must, however, resolve the need for the correct fill hardware.
- The partners are aligned with the project. However, it is not clear if there is enough testing on both buses and trucks.

### Question 4: Potential impact

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

- This project is addressing a serious issue with the standardization of H35 fueling. J2601/2 is a performance standard that does not lend itself well to ensuring compatibility of vehicles at fuel stations and is better used for small demonstration projects. It may sound redundant, but a "uniform" standard is needed for operational safety for a large number of stations and vehicle manufacturers. Otherwise, the industry would develop a plethora of potential non-compatible fueling protocols that could lead to safety issues for fleets with multiple vehicle types and models.
- The project is impactful and relevant because it addresses the need for the development of an H35HF fueling protocol to support MD and HD fuel cell vehicles. As a result, the project achieves the DOE goal of reducing greenhouse gas emissions.
- The development of an H35 fill protocol will help deploy hydrogen fast-fill hardware (buses and HD trucks). This is a value-added project.
- Confirming fueling protocols with accurate data is essential for codes and standards. The project is very supportive of hydrogen deployment.

### Question 5: Proposed future work

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

- The proposed future work is consistent with ending the project, provided that it is completed satisfactorily.
- The proposed future work is nominal and includes the finalization of a few H35HF tests at NREL and the creation of the final report.
- Adding the correct fill hardware and completing the test evaluation, culminating with the final report, is a good direction for this project to go.
- Future work is essential (such as finalizing validation/testing). However, it is unclear if funding will be provided to do so.

### Project strengths:

- The issuance of TIR J2601/5 is a major step forward for the industry. Completion of testing to help validate the protocol and modeling is also a significant strength.
- The project has successfully met its goal of developing and validating an H35HF fueling protocol, which has now been adopted into SAE TIR J2601-5. This is well done.
- This project will help deploy MD and HD fueling, which is a key area for hydrogen deployment.
- The project team is on track to finish the testing and write up the report.

### Project weaknesses:

- The testing and hardware barriers presented a challenge to fully validating the protocol. The project has not provided a clear discussion about future resolution of J2601/2 and J2601/5 co-existing. This oversight may create a confusing situation for the industry and may still lead to incompatible stations.
- Not having the correct fill hardware is an obvious drawback. The project team needs to fix that before completing the testing.
- Some of the validation processes indicate "disadvantages," but it is unclear how the team worked around these. Validation was not finalized.

### Recommendations for additions/deletions to project scope:

- Additions and deletions are not applicable since the project is essentially complete. The need for additional testing in the future by another project or by independent entities should be evaluated, especially when the correct hardware is available.
- The correct fill hardware for the NREL station should be procured and a discussion on DEIA included.
- The validation testing should be finalized, as proposed in the presentation.

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

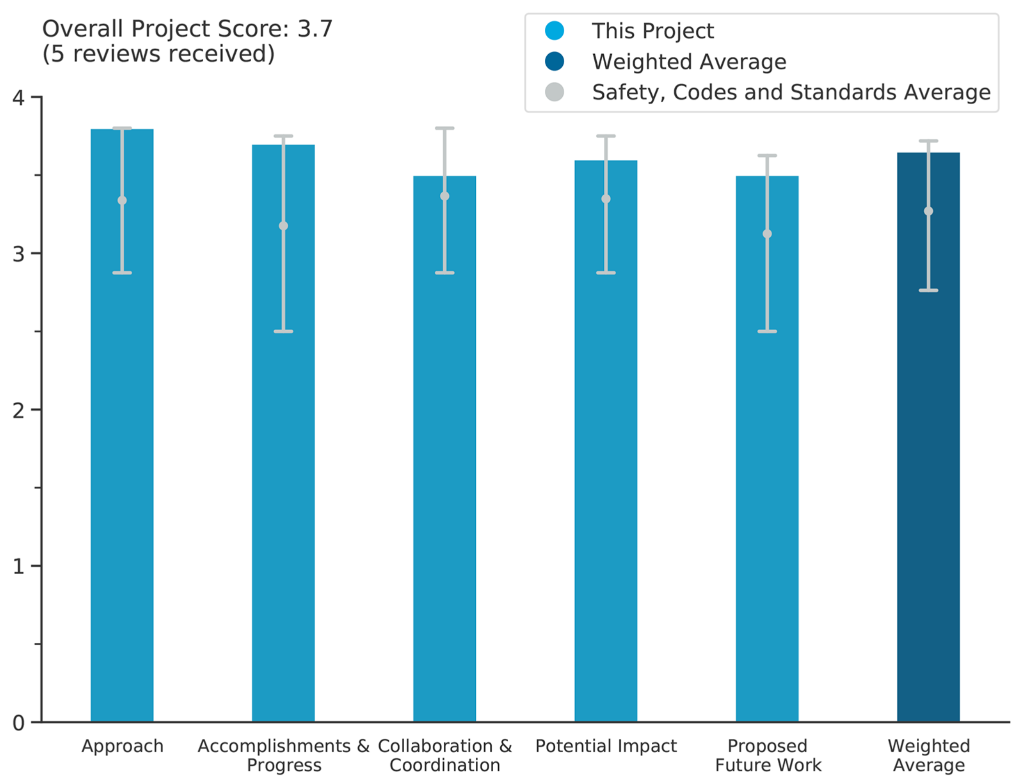
Shaun Onorato, National Renewable Energy Laboratory

| | |
|---|---|
| **DOE Contract #** | WBS 6.2.0.504 |
| **Start and End Dates** | 2/2/2022–2/1/2025 |
| **Partners/Collaborators** | Argonne National Laboratory, NextEnergy, Chevron |
| **Barriers Addressed** | • Limited availability of heavy-duty hydrogen fueling infrastructure (globally) to evaluate the performance of fueling protocol concepts and hardware<br>• Limited understanding of how heavy-duty fueling concepts will influence infrastructure and vehicle design, specification, and cost<br>• 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 (NREL's) research station. The project will also conduct modeling and analysis using computational fluid dynamics (CFD) and perform techno-economic analyses (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




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### 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 SCS-031 project intends to develop a comprehensive assessment of HD FCEV fueling protocols and fueling hardware to understand the different effects of these in a real-world environment. Fueling protocols' influence on station design, vehicle design, and functional safety requirements and the implications on the TCO are evaluated. The project is therefore divided into three different sub-tasks: hardware (assessing HD fueling hardware and protocols), modeling (modeling and validation of HD components and fueling protocols with experimental results and updating fueling models for public release), and analysis (performing TEAs to determine the TCO of HD station concepts and vehicle architectures). The approach to performing the work is well-structured and very detailed. The objectives are clearly identified and barriers correctly addressed. Three partner organizations with different scopes participate in the project. The diversity, equity, inclusion, and accessibility (DEIA) plan or community benefits plan and the safety plan are not applicable to this project.
- The objectives were (1) to assess HD fueling protocols, (2) to develop and enhance computational models for fueling, (3) to evaluate cost of ownership of HD hydrogen fuel cell vehicles and HD hydrogen fueling station designs, and (4) to coordinate with industry and standards organizations on the models and findings. All four objectives were met. This effort was well-coordinated and included industry participation. The target fueling times were achieved in the physical tests showing feasibility. Models were updated and validated against relevant data. The cost of ownership was evaluated using the new models, and information was provided to the industry. The researchers partnered with industry to obtain state-of-the-art devices for evaluating the fueling protocols with and without communication.
- NREL has a very good comprehensive approach to a much-needed topic. The team has a nice approach to compartmentalizing hardware, protocols, and communications across NREL subgroups for hardware, modeling, and analysis. The project has excellent coordinated work with other protocols in development, which provides a feedback method for formalizing research results for use in practice. A modeling approach that focuses on holistic (station-level) impacts and partial (dispenser–vehicle) impacts also provides nice segmentation.
- The approach used for this project is a good one. The team is systematic and methodical in its approach. Combining testing with modeling is very good. The presentation did not include a discussion of DEIA.
- The approach is well-thought-out and focuses on the data needs for codes and standards for HD refueling.

### 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 shown significant progress toward its goals in the three sub-tasks, as discussed below.
    - For the hardware task, the NREL fast-flow facility was upgraded and modified for integration of project hardware, including mass flow meters, flow control valves, and receptacle mounts. Two sets (Tatsuno) of each HD refueling component were successfully delivered to NREL for integration and testing. The Tatsuno components (nozzle, receptacle, and breakaway) were evaluated for operational safety by a third-party laboratory and installed and evaluated for pressure drop at NREL's HD dispenser. The Tatsuno components were then tested as baseline hardware for assessing the fueling protocols. The results from initial testing were shared with SAE International and the International Organization for Standardization (ISO) working groups (WGs). NREL intends to extend the testing to new components (from WEH and Staubli) to study and evaluate differences encountered, providing feedback to ISO WGs for critical standardization decisions. Tests were conducted to look at flow control algorithms, flow control valve positions, and different components causing pressure drops. No time lags were observed when performing the fueling protocols. Fueling tables were validated with test data to confirm assumptions made by SAE (pressure drop, temperature, etc.). Regarding vehicle-to-dispenser communications, a collaboration with Shell Techworks for the design and integration of the Shell HyConnect system was established, and this system evaluated performing fueling protocols.

- Regarding the modeling task, the partial model version that enables the evaluation of interactions between the dispenser and truck was released to the public one week ahead of the 2024 Annual Merit Review. The holistic version, which enables evaluation of the impact of individual station fueling components on fueling performance, will be released a month later. The fueling table generation capability successfully helped SAE publish its J2601-5 medium-duty (MD) and HD high-flow fueling protocols (fueling protocol document published on February 24, 2024). The SAE J2601-5 protocol (i.e., the MC Formula) was incorporated into a C++ code and integrated into the NREL dispenser for validation. It was verified that the SAE J2601-5 fueling was controlled based on the MC Formula control logic. Additionally, a slow-fill CFD simulation was performed with a Type IV tank and straight injector, revealing that thermal stratification occurs but the peak hydrogen temperature does not exceed the 85°C limit. It was also observed that if Type IV tanks are initially pressurized under fast-fill conditions, the pressure ramp rate can be reduced to 3 MPa/min.
- Regarding the analysis task, the project team used the Heavy-Duty Refueling Station Analysis Model (HDRSAM) developed by Argonne National Laboratory (ANL) to perform TEAs considering the effects of fueling protocols on HD station cost. Five main conclusions were observed: (1) refueling cost depends on the individual contributions of different station components; 2) station cost difference varies between fueling protocols with the precooling and ambient temperature; 3) levelized refueling cost is ~$2.0–$3.8/kg cheaper for liquid hydrogen stations vs. gaseous stations; 4) fueling profiles have a moderate effect (~$0.70/kg) on gaseous stations; constant ten-hour fueling demand is more expensive than two separated five-hour peaks; and (5) levelized cost decreases exponentially as fleet size increases. TCO analysis was also performed using the Transportation Technology Total Cost of Ownership model (T3CO) developed by NREL. Following are the main observations: (1) TCO depends on the station cost and vehicle performance; (2) fuel price is the largest contributor to the TCO; (3) TCO decreases if FCEV technology achieves proposed targets (approximately a $0.4/mile decrease); and (4) SAE J2601-5 TCO has a small cost variation compared to PRHYDE, specifically for higher ambient temperature and warmer precooling conditions (40ºC ambient, -20ºC precooling).

- A good deal of work was accomplished here; the principal investigator has done a good job managing and tying it all together for meaningful and useful results. It is unclear whether the two H2Fills models were validated with NREL's hardware on the built environment side, similar to the plans for the CFD. Initially, the TEA impacts from J2601-5 appeared to tell only part of the story and not to account for TCO impacts from improved operational efficiencies; however, the T3CO model appears to consider fleet size/scale impacts.
- Significant progress on fueling protocols has been made through this project. Collaboration with industry and standards development organizations is contributing to improvements in refueling hardware.
- The goals and approach of this project were well-defined. HD fueling with the HD fueling hardware, along with the fueling protocol, was done within the target fuel time. The CFD models of the fueling with the HD fueling were validated and used for the TCO study.
- This project is making good advancement toward completing its goals.

## 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 approach on collaboration—having a single partner organization responsible for industry liaison—is very good. There is good collaboration with the ANL team to incorporate learning with the HDRSAM model for TEA impacts.
- The project has effectively engaged with other institutions, in particular, with standardization institutions and working groups (SAE and ISO WGs) sharing relevant insights—for example, the fueling table generation capability developed that successfully helped SAE J2601-5 publish MD/HD high-flow fueling protocols (the fueling protocol document published on February 24, 2024).
- The project was coordinated well with industry stakeholders. The results of the study are being communicated to the industry and standards organizations so they can update based on the study's results.

- The project collaborates with NextEnergy, a relevant industry group and component liaison, as well as an energy company and modeling partner. These partners allow for excellent coordination to address issues as they arise. In the response to reviewers' comments from the previous year's Annual Merit Review, the presenter notes, "The project expanded to include two additional component suppliers and is performing specific testing to accelerate efforts under ISO TC [Technical Committee] 197 Working Groups 5 and 22 (connection devices and hoses)." However, ISO/TC 197 WG 22 has identified specific testing being sought for this effort to validate potential new test methods, as well as gather necessary data on failed hoses. With closer coordination with ISO/TC 197 WG 22, this project has the potential to answer these questions, which would make it possible to expand ISO 19880-5 to apply to hoses for HD refueling.
- The partners are appropriate to execute this project.

### Question 4: Potential impact

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

- The project indeed advances progress toward building a clean energy infrastructure. The project provides support to industry and to codes and standards groups to build out new HD hydrogen infrastructure for hydrogen trucks. The project is succeeding in performing a comprehensive assessment of HD FCEV fueling protocols and fueling hardware to understand the different effects of these in a real-world environment. Additionally, the work helps to provide pathways to private-sector uptake through the evaluation of HD fueling components and protocols under real-world conditions. The project is also contributing to lowering greenhouse gas emissions and pollution by enabling hydrogen infrastructure research and development to accelerate the use of hydrogen-powered vehicles.
- The potential impact from having a publicly available assessment of HD fueling station methods and components is significant. Achieved, demonstrated, and validated fueling speeds of 10 kg/min with peak of 27 kg/min are critical and represent a big success. A partial model has also been released and is available to the public. The contribution of fueling tables to J2601-5 was also critical and long-lasting.
- High-flow rate fills for HD trucks and buses are needed to deploy hydrogen-fueled vehicles to keep them competitive. This project seeks to address this issue. The shorter the fill time, the better, provided it is done safely. This project seeks to do exactly that.
- The potential impact of this study is to develop confidence in fast fueling for HD vehicles and confidence in the models used for evaluating cost of ownership of hydrogen fuel cell vehicles. The standards organizations would also update their standards based on the data provided from this research.
- The project aligns with DOE goals and objectives and is likely to increase the uptake of HD hydrogen vehicles.

### Question 5: Proposed future work

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

- The project has effectively planned its next steps to achieve its goals in the three sub-tasks and share the results with the relevant international standardization organizations and working groups.
- The proposed future work moves this project along appropriately. Completing that work will contribute to the high-flow rate space. The reviewer looks forward to that work being completed.
- Future work is to evaluate additional hardware, update the models, and perform cost of ownership analysis using the updated models. This work is needed to ensure the models used and the fueling protocols are robust.
- Future work appears to be according to plan and will continue to address industry barriers.
- The project team might consider discussing the hardware test plan with ISO/TC 197 WG 22 to ensure alignment with the testing needs identified by WG 22.

### Project strengths:

- The project is unique in contributing to the assessment and validation of innovative HD FCEV fueling protocols and fueling hardware. This work allows for understanding the different effects on station design, vehicle design, and functional safety requirements, as well as implications on the TCO. A really positive aspect is that the project tackles the assessment of fueling protocols by combining experimental hardware testing and validation with thermos–physical modeling and TEA.

- This is a great comprehensive project with many facets for studying and publishing the operational effectiveness of HD fueling methods and components. The project is barrier-focused and does an excellent job of tying together results between the topics and organizations.
- The strengths of this project are the coordination and research partnership with industry, the evaluation of fast-fueling protocols for HD vehicles, the work to enhance and validate fueling models, and coordination of the research findings with industry and codes and standards.
- The modeling combined with testing is a very strong approach. The reviewer looks forward to seeing the conclusion of this work.
- NREL has amazing testing and modeling capabilities. There is a direct application to developing codes and standards.

### Project weaknesses:

- No major weaknesses are observed for this project. However, the reviewer encourages the project team to give further visibility to the research by engaging further with industry internationally and providing further outreach of the models and TEAs developed for public use.
- No weaknesses were identified.
- Data on components may not be freely shared with relevant stakeholders. Component data are essential to inform codes and standards. It would therefore be highly beneficial to find a way to share the relevant data. This endeavor may necessitate inclusion of additional hardware so that the data is not attributable to a specific manufacturer.

### Recommendations for additions/deletions to project scope:

- During the research project, the team might consider whether there are any gaps or needs for other standards within the system to drive interoperability, safety, and/or cost reductions. There is a significant opportunity to validate the H2Fills models with simulations using the built hardware across many operating conditions. The coordinated effort of having a built test environment alongside model development is a rare opportunity, and someone should take advantage of that opportunity.
- The team could consider including failure analysis of hydrogen fueling components, including those for light-duty applications. These data are necessary to ensure standards include testing that can potentially identify components that may fail in service, as well as significantly advancing the inclusion of HD components into appropriate component standards.
- The project could expand collaborations with industry partners internationally to meet its objectives. The main industry partner is NextEnergy, but the information in the slides does not make it very clear which activities NextEnergy is involved in or its role in the project. It remains unclear how well this group is coordinated and tied into the effort. The project should give further visibility to the models and TEAs developed for public use/industry. Liquid hydrogen onboard solutions are a hot topic in other regions because they are ideal for semi-truck applications. A liquid hydrogen fueling protocol and the associated hardware are still barriers for industry, and further pre-normative research is needed. The addition of this scope is recommended to support adoption of fuel cell electric semi-trucks.
- A discussion on DEIA should be included.

# Project #SCS-032: Smart Hydrogen Wide-Area Monitoring for Outdoor H2@Scale Demonstration Sites and Enclosure

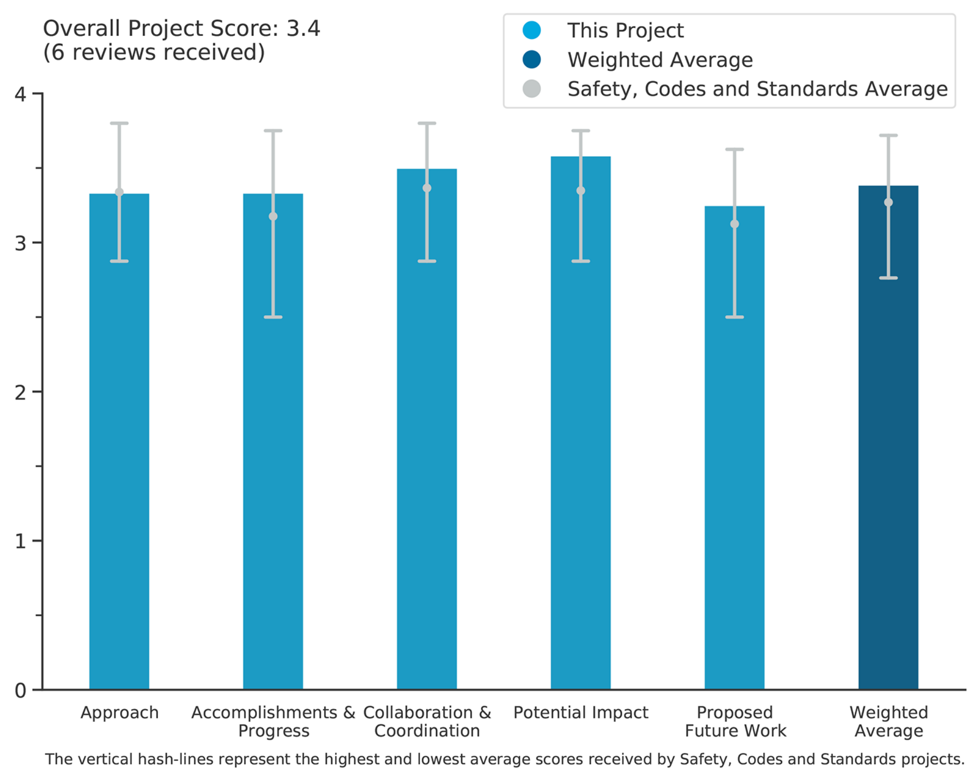
David Peaslee, National Renewable Energy Laboratory

| | |
|---|---|
| **DOE Contract #** | WBS 6.2.0.505 |
| **Start and End Dates** | 10/1/2022 |
| **Partners/Collaborators** | National Energy Technology Laboratory, Low Carbon Initiative, Paulsson, Inc., Boyd Hydrogen, GTI Energy, Electric Power Research Institute |
| **Barriers Addressed** | • Address the need for early hydrogen leak detection<br>• Identify and deploy emerging wide-area monitoring technologies within H2@Scale demonstration sites and commercial facilities<br>• Evaluate performance and limitations for both outdoor and indoor hydrogen detection applications |

## Project Goal and Brief Summary

The National Renewable Energy Laboratory (NREL) is addressing the critical challenge of early hydrogen leak detection to enhance hydrogen facility safety through this Smart Hydrogen Wide-Area Monitoring (HyWAM) project. The project focuses on developing and testing advanced hydrogen leak detection technologies for both indoor and outdoor applications. The HyWAM system, based on a distributed network of point sensors, serves as a control method for detecting hydrogen releases. The project incorporates detection methods, including Schlieren imaging for visualizing low-density hydrogen gas, ultrasonic leak detection responding to acoustic signals of gas releases, and fiber optic sensors developed by the National Energy Technology Laboratory (NETL), which offer remote, power-free interrogation. Measurements are being used to validate computational fluid dynamics (CFD) modeling of hydrogen leak behavior.

## 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.

- Project SCS-032 intends to identify and deploy emerging wide-area monitoring (WAM) technologies within H2@Scale demonstration sites and commercial facilities. Additionally, the project evaluates the performance and limitations for both outdoor and indoor hydrogen detection applications. The NREL HyWAM, which is a distributed network of point sensors, will serve as a control. The multi-approach of sensing strategies of the project was clear and well-presented. The objectives are clearly identified, and barriers are correctly addressed. The project is structured in different sub-tasks tackling different areas: (1) Advanced Hydrogen Detection Technology Identification and Evaluation (NREL, Paulsson, Inc.), (2) Hydrogen Monitoring of Outdoor H2@Scale Demonstration Sites (NREL, Electric Power Research Institute [EPRI]), (3) Hydrogen Monitoring in Enclosed Systems (NREL, Boyd Hydrogen), (4) Modeling of Hydrogen Releases (NREL), and (5) Hydrogen Selective Fiber Optic Sensor (NETL, NREL). The project's diversity, equity, inclusion, and accessibility (DEIA) activities include:
    - Educating the next generation of researchers and engineers in hydrogen by mentoring female intern researchers at NREL.
    - Supporting development of safety and monitoring plans for several pending large-scale hydrogen projects that include outreach to support hydrogen as a clean and safe fuel to community stakeholders.
- This project is excellent. It will assess several WAM technologies in two facilities: Advanced Research on Integrated Energy Systems (ARIES) and H2@Scale. The project will use the existing distributed point sensor array as the control. This approach is well-thought-out; combined with wide-area leak modeling, this approach will lead to a significantly improved understanding and presumably recommendations on wide-area optical mongering technologies. There was no DEIA discussion.
- It was clear that this project is a cooperative research and development agreement (CRADA) in which the team is working to identify and deploy emerging WAM technologies within H2@Scale demonstration sites and commercial facilities and also to evaluate performance and limitations for both outdoor and indoor hydrogen detection applications. The team members present a diversity of approaches that have been funded and were clear throughout the presentations and posters, with an emphasis on safety.
- Early detection of unintended hydrogen releases is critical to enhancing hydrogen facility safety. The NREL Hydrogen Safety Research and Development (HSR&D) program is conducting research in support of H2@Scale and the Hydrogen Earth Shot initiatives. For WAM applications, the Sensor Laboratory has evaluated emerging hydrogen leak detection strategies for both indoor and outdoor hydrogen applications. The Sensor Laboratory continues to partner with stakeholders in the hydrogen community to implement advanced hydrogen leak detection technologies. The Sensor Laboratory continues to evaluate emerging sensing technologies to address new low-level detection targets for emissions monitoring.
- This project conducts research in support of the H2@Scale and Hydrogen Earth Shot initiatives by evaluating emerging hydrogen leak detection technologies and strategies at two test sites. The project evaluates new technology for both hydrogen safety and low-level detection for environmental monitoring developed by project partners in private industry. The project evaluates a variety of emerging technologies to increase hydrogen monitoring capacity.
- Hydrogen leak detection technology is a valuable topic area, and this project is another example of valuable work.

### Question 2: Accomplishments and progress

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

- The team has made excellent progress toward project objectives that is demonstrated through the results obtained by the project's multi-faceted approach of sensing strategies and effective collaboration with project partners. Progress continues to follow the proposed schedule:
    - Collaboration is taking place with the CRADA project to model hydrogen dispersion at the Sandia National Laboratories (SNL) Thunder Tube. The HyWAM was used to profile liquid hydrogen

releases performed under the auspices of the Pre-Normative-Research for the Safe Use of Liquid Hydrogen (PRESHLY) project (European project): https://preslhy.eu/.

- Advances on Schlieren imaging were performed in the laboratory.
- Regarding ultrasonic leak detection (parametrization), the project is developing an understanding of the potential hazards associated with variable leak sizes and leak characteristics (e.g., noise).
- The project is conducting validation of sensor deployment at ARIES and validation of hydrogen leak modeling. CFD simulations are a first step, plus simulation of a hydrogen release to design location and height of the sensors.
- Fiber optic sensors work is still in progress, and data will be sent by a collaborator.

Another indicator of success is the fact that additional partners expressed interest in collaborating on parallel activities, such as validating new wide-area sensing systems and providing new technologies to meet wide-area sensing requirements.

- Excellent progress is shown on growing and assessing HyWAM, including technologies from the point sensor array to optical and acoustic. Some of the technologies are early in their development (the optical fiber hydrogen sensor, for example) but are still showing excellent results. The progress is very impressive. Combining the measurement results with modeling is excellent.
- Excellent accomplishments have been demonstrated so far. NREL has an experimental monitoring facility for hydrogen leakage, a wireless hydrogen monitoring facility, and the Schlieren imaging system, which is developing filters to allow for information capture in the presence of foreground disruption.
- The NREL HyWAM is based on a distributed array of point sensors for temporal three-dimensional profiling of hydrogen releases. HyWAM serves as the reference technology for standoff or wide-area detection methodologies explored under this CRADA. The HyWAM has been used to profile and model hydrogen (liquid and gas) releases. NREL supported the SNL experiment involving releasing liquid hydrogen within a controlled ventilated system (January 26 through March 2, 2024). The HyWAM was used to profile liquid hydrogen releases performed under the auspices of PRESHLY. Machine learning is used to recognize different cases of interference and has shown a 95%–100% success rate at categorizing three interference cases: gas, non-gas, and none. This work is deployed at the NREL Hydrogen Infrastructure Testing Research Facility (HITRF)/Fueling Station.
- This project has deployed a HyWAM system, which is used to profile and model hydrogen releases and serves as reference to evaluate other technologies. The project has also developed a wireless version of HyWAM and is testing several emerging technologies, such as Schlieren imaging for remote detection of hydrogen leaks, ultrasonic leak detection, and fiber optic sensors. The team has also tested and validated hydrogen leak modeling.
- Clarity on this work is varied. Some projects had more clearly defined goals and milestones (that were communicated) for the work. For example, with the Schlieren work, it is clear what the researchers are doing in terms of tasks and activity, but it is not clear what would be required to declare “success” or when the effort would be complete.

### 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 collaboration is effective and well-coordinated: (1) Advanced Hydrogen Detection Technology Identification and Evaluation (NREL, Paulsson, Inc.), (2) Hydrogen Monitoring of Outdoor H2@Scale Demonstration Sites (NREL, EPRI), (3) Hydrogen Monitoring in Enclosed Systems (NREL, Boyd Hydrogen), (4) Modeling of Hydrogen Releases (NREL), and (5) Hydrogen Selective Fiber Optic Sensor (NETL, NREL). Another indicator of collaboration success is the fact that additional partners expressed interest in collaborating on parallel activities, such as validating new wide-area sensing systems and providing new technologies to meet wide-area sensing requirements.
- Project partners include the following: Boyd Hydrogen, LLC; Fiber Optic Sensing Solutions (Small Business); Paulsson, Inc.; EPRI (not-for-profit); GTI Energy; and NETL.
- All the partners are experts in this field and complement each other well. This collaboration is nicely done.

- There is great collaboration and coordination with NETL, GTI Energy, EPRI, Paulsson, Inc., and Boyd Hydrogen.
- NREL has partnered with non-profits and small businesses.
- NREL has strong collaborations with representative industry groups.

### Question 4: Potential impact

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

- The project aspects align with the Hydrogen Program's goals and objectives in terms of advancing hydrogen sensor technology for WAM of hydrogen leakage and releases (for both indoor and outdoor hydrogen applications). The Sensor Laboratory evaluates emerging hydrogen leak detection strategies for this purpose. It also evaluates emerging sensing technologies to address new low-level detection targets for emissions monitoring. Additionally, the Sensor Laboratory continues to partner with stakeholders in the hydrogen community to implement advanced hydrogen leak detection technologies.
- Early detection of unintended hydrogen releases is critical to ensure the safety of hydrogen facilities. Detection of hydrogen is commonly performed using point sensors, which are often incorporated into a hydrogen safety system. The NREL HSR&D program strives to promote facility safety by ensuring the availability and proper use of hydrogen detectors. Other strategies for detection of hydrogen releases exist that may be able to provide earlier and more reliable leak detection than that afforded by point sensors. These are being investigated through a multi-step process that includes technical reviews and market surveys, laboratory assessments, and deployments in real-world facilities.
- This project has a large impact on advancing WAM and emerging technologies for hydrogen detection and monitoring, which supports the project's targets and Hydrogen Program goals.
- The impact of WAM sensing goes straight to the safety of large installations. The ability to survey the entire space to identify leaks is extremely valuable.
- Leak detection continues to be one of the most important research focus areas to impact safety and the environment.
- HyWAM is an important resource. The challenge for impact will be how to have the most impact in a rapidly developing technical space. The resource constraints are time-related as much as anything else.

### Question 5: Proposed future work

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

- The proposed future work for HyWAM is perfect: validating the CFD work, deploying at a demonstration site, advanced fiber optic sensors, and acoustic sensors. It would be good to see additional work refining optical techniques such as Schlieren.
- The proposed future work the team is looking into is very promising, with all the sensor characterization and modeling technologies and techniques.
- The future work presented is correctly mapped out and detailed, focusing on three areas: sensor characterization and model validation activities, advanced sensor demonstrations, and detection system guidance and final report.
- Regarding sensor characterization and model validation activities, HyWAM will be used to test and characterize the CFD models. Digital twin development will be derived from this work. Deployment at a demonstration site will follow. Regarding advanced sensor demonstrations, fiber optic sensors (Paulsson [acoustic, accelerometer, pressure, and temperature] and NETL [hydrogen reactive coating]) will be evaluated for integration into selected facilities. Advanced acoustic detection methodologies will be evaluated (following deployment). A detection system guidance and final report will follow. Additional work is needed for project completion.
- Future work involves improving the CFD modeling of hydrogen releases and advanced sensor demonstrations. Some testing sites still need to be identified.

- The digital twin work could be skipped unless the value can be well-communicated. If this work is included, some very clear milestones and measurements should be included that identify the limitations of supervisory control and data acquisition (SCADA) systems for leak detection (and quantification).

### Project strengths:

- This is a well-thought-out and well-executed project. The reviewer looks forward to the results as this project continues.
- The project has clear strengths in its relationships across industry partners and its breadth of familiarity with hydrogen sensing technologies. The project brings a range of facilities as well, from laboratory to outdoor demonstration.
- The project has effective collaboration with project partners, expertise on sensing technologies, and a multi-approach of sensing strategies.
- There can never be enough leak detection research projects, as each one brings in a different set of technical aspects and challenges.
- This project advances strategies for wide-area monitoring of hydrogen releases and is testing some novel sensors.
- This project has good partners to drive project success: Boyd Hydrogen, LLC; Fiber Optic Sensing Solutions (small business); Paulsson, Inc.; EPRI (not-for-profit); GTI Energy; and NETL.

### Project weaknesses:

- Considerable activity is proposed:
    - The NREL HyWAM: Based on an array of point sensors distributed around a hydrogen facility, the HyWAM will serve as a "reference" method within the scope of the CRADA.
    - Schlieren imaging: Schlieren imaging is based on variations in refractive index in a fluid medium. Schlieren imaging can provide a visual representation of a low-density gas (e.g., hydrogen) released into air.
    - Ultrasonic leak detection: Ultrasonic leak detectors respond to the acoustic signal associated with a pressurized release of a gas through an orifice or restriction.
    - Fiber optic sensors: Fiber optic sensors, accelerometers, acoustic, pressure, and temperature sensors developed and integrated as a system (by Paulsson, Inc., with support from DOE) allow for the deployment of sensing elements that can be interrogated remotely and without any electrical power at the sensing element. A fiber optic sensor with a hydrogen-selective sensing element is being developed by NETL, with support provided in part under this CRADA project.
    - Modeling validation: CFD modeling can be validated with field deployments of sensors at the NREL ARIES site.
    - DEIA: The team should strengthen the DEIA statement and partnerships.
- No major weaknesses are observed for this project. However, the project team is encouraged to give further visibility to the research results.
- The principal investigator has listed a few of the project's DEIA/community benefits plans and activities, which are encouraging but could be developed in a more concrete way in the next year.
- Further development of optical WAM technologies would be good.
- The project could have a little more clarity on how each of the testing facilities/locations covers the range of anticipated layouts that could be expected in the emerging hydrogen economy.
- One of the challenges or weaknesses is the lack of versatility with using the leak detection technology for hydrogen and/or natural gas.

### Recommendations for additions/deletions to project scope:

- In the future, it would be good if this project would consider offshore-specific needs for hydrogen sensors and modeling of hydrogen releases, if they are different from onshore. For methane, onshore sensors are not suitable for the harsh, salty marine environment, and the dispersion of gaseous plumes has different characteristics from onshore because of differences in infrastructure and meteorological conditions (e.g., a stable marine boundary layer). It would also be good to consider more emerging hydrogen sensor technologies with low detection levels designed for monitoring and quantifying hydrogen losses for environmental concerns.

- Regarding the pipeline space, the Subsurface Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA) project seems to be doing a good deal with storage. However, it seems like it would be valuable to conduct research and development relevant to regulations for hydrogen pipelines, some of which are being proposed by the Pipeline and Hazardous Materials Safety Administration. The team is well-situated, with its broad awareness of technologies and testing.
- If indoor facilities are a mature space with established codes and standards, then perhaps they no longer belong in the scope. It is unclear whether that role for NREL satisfies codes and standards testing or certification requirements. If this work is already done elsewhere, then perhaps a more exclusive focus on outdoor and WAM is more critical to advance the industry.
- Commercial point sensors based on thermal conductivity were used in the collaboration with the CRADA project to model hydrogen dispersion at SNL Thunder Tube. Perhaps a different collaboration could expand testing with other sensors with lower detection limits to ensure accurate monitoring of leaks (collaboration for monitoring leaks/hydrogen emissions at a demonstration site). Regarding advances on Schlieren imaging performed in the laboratory, an addition to the project scope could be evaluating the potential to use this technology outside of the laboratory (issue of selectivity).
- The project could be focused on one or two areas where success can be demonstrated. The DEIA statement and partnerships should be strengthened.
- There should be increased effort on WAM optical techniques such as Schlieren. A discussion on DEIA should be included.

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

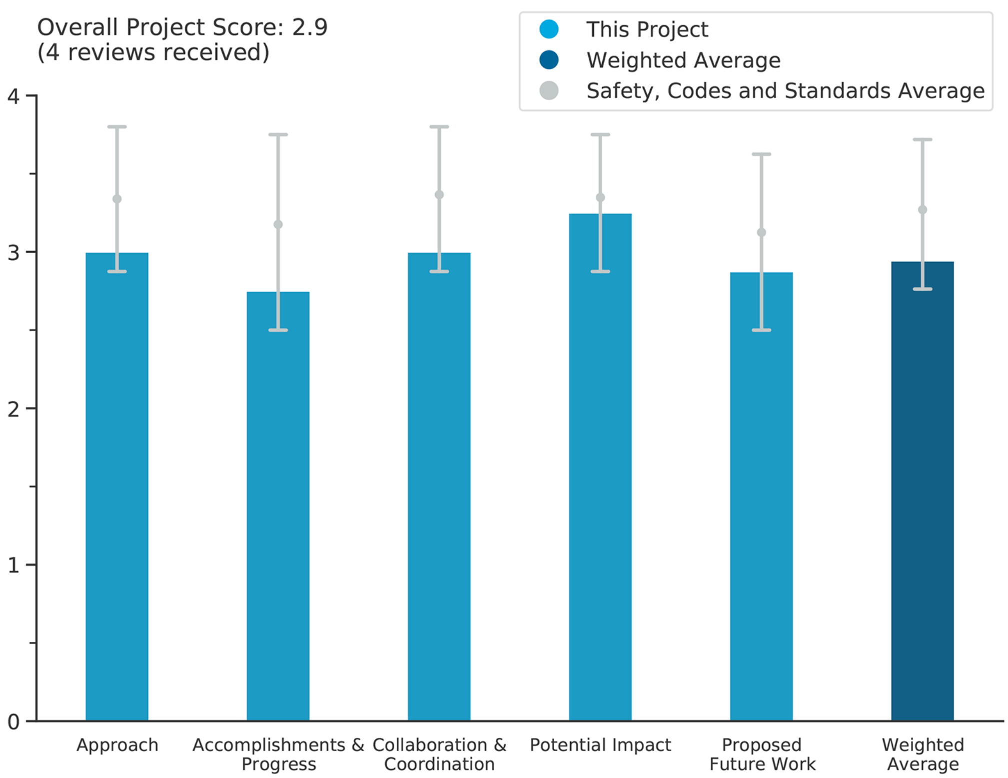
Brian Ehrhart, Sandia National Laboratories

| | |
|---|---|
| **DOE Contract #** | NL0038749 |
| **Start and End Dates** | 2/1/2022–11/21/2024 |
| **Partners/Collaborators** | Wabtec Corporation |
| **Barriers Addressed** | • Lack of requirements for new applications<br>• Lack of scientific bases for defining requirements<br>• 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




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Since this is an analysis-only project, a safety review of the project is not required; however, since the subject is a key part of conducting a safety analysis and design, it would be valuable to state how this process (quantitative risk assessment [QRA]) is used to promote a safe design. Otherwise, the approach makes sense (conduct a qualitative risk analysis, then quantify risks identified using existing fault tree/ event tree analysis, then perform a code review)—although some additional details about how those steps are accomplished would be helpful.
- Conducting an FMEA followed by a fault tree analysis is a well-planned holistic approach. Safety details (slide 5) and diversity, equity, inclusion, and accessibility (DEIA) planning (slide 15) should be equally represented—safety even more so, since the purpose of risk planning is safety. While there are no criteria for a safety plan since the project is analysis only, more details on the effects toward minimizing safety issues could be presented, especially highlighting Wabtec Corporation's (Wabtec's) safety culture in applying risk assessment results. Posting presentation slides as a "poster" limits the communication of this project's value and impact. The project team should consider preparing an actual poster for future poster sessions while still including the slides on the side of the presentation space. The project should use the poster to highlight significant accomplishments and issues and include quick-response (QR) coding for visitors to access key documents or resources. Slide 2 includes the only identification of system design—and that, only by an artist's diagram. The presentation should qualify the design scope and identify any unknowns associated with the planned layout as barriers, siting, firm inexperience, operational issues, and throughputs, which would impact overall risk assessment.
- The project report would benefit from a clear specification in terms of flow rates, fill times, storage quantities, and other assumed fill parameters. The project might have benefited from considering and analyzing current trailer fill operations that have similar quantities dispensed. While not as fast as desired for locomotives, these activities might be a better starting point than traditional J2601 fueling protocols. There certainly would also be learnings in terms of equipment, safety features, potential failure rates, and incidents. Verbal conversations with the project members indicate the flow rates were very large, which clearly puts them out of the range of existing (or even under-development) fueling hoses and hardware. This is a major barrier that should be clearly communicated. The barrier makes it more difficult to evaluate risk at this stage. The project did not require a safety plan. Progress on the DEIA plan is lagging but has a clearly specified timeline.
- The use of FMEA, HAZOP, and Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) are advertised. The technical details provided about the approaches are so general and non-specific that little insight can be gained. The terminology used is ambiguous. The presenter was unable to provide further specifics about how the methods were conducted, which raises questions about the team's proficiency with the methods.

### Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- The project lists several codes and standards but does not provide detailed next steps or recommendations. For example, for National Fire Protection Association (NFPA) 2, a recommendation for how best to accommodate locomotive fueling is needed (e.g., a separate chapter, specifically written sections within chapters 10 and 11, ways to use existing code with minor modifications, etc.) Given that the nature of the activity may be substantially different from other heavy-duty applications, a separate chapter might be appropriate. Similarly, the reference to Occupational Safety and Health Administration (OSHA) process safety management (PSM) was vague, but it is likely, given that this is a non-retail activity and that the quantities are so large, that OSHA PSM will be required and also recommended. The project could also include a more detailed analysis regarding J2601 since heavy-duty vehicle fueling protocols (not light-duty vehicle fueling protocols) are the logical starting point.
- The project team has completed two of the three project objectives (FMEA and fault tree analysis), while the third objective (codes and standards gap analysis) is nearing completion. The current progress on codes

and standards gaps is unimpressive. There is minimal guidance on liquid hydrogen (LH2) storage and use in NFPA and the Compressed Gas Association (CGA), while there is no guidance for rail usage, operation, fill, or maintenance in hydrogen regulations, codes, and standards. The presentation does not identify these issues but uses language like "may require additional review." These issues and barriers should be clearly noted rather than suggested. It is hoped that the final report clearly outlines the gaps and provides recommendations for improvements to codes and standards. Future effort highlights a need for vent stack modeling with no detail explaining the issue (e.g., design, siting, and codes and standards) or interface with NFPA or CGA. It is unclear whether this is a critical barrier discovered through risk assessment or gap evaluation.

- The project needs to further explain how the chart showing "Number of Scenarios in Each Risk Category" was derived and how the investigators interpreted those results. The only general conclusion that can be drawn from the chart is that the number of scenarios with moderate and severe consequences decreased after applying the mitigation strategies. The next page provided some additional details on the FMEA process, but the origin of the risks being assessed is still not very clear.
- The project is significantly behind schedule with its milestones, without explanation. The project has produced one presentation in two years of work and $450,000 in funding. The work does not appear to be on track to produce results that advance DOE goals. The work lacks specificity necessary to provide meaningful insights.

### 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 partners are closely coordinated.
- Wabtec was an excellent partner to collaborate with on this project, but it would have been helpful to receive input from other organizations that are also designing or building hydrogen locomotives. Other logical partners might be organizations that currently fill other large vehicles, such as LH2 or gaseous hydrogen (GH2) trailers, at relatively similar quantities. There is also a lack of experience in fuel station design to help evaluate the equipment that might be required for the desired fill times, as well as creation of the process flow diagram, siting criteria, and methods that might be used for large transfers.
- The noted collaborative organizations are very good but could be improved. It is unclear if the noted presentations in the fourth bullet (slide 15) are final products or being used as peer reviews. The project could improve its conclusions by interfacing with organizations related to safety, codes and standards (e.g., the Hydrogen Safety Panel and Fuel Cell and Hydrogen Energy Association). In addition, review of international standards and interface with international sources would improve overall conclusions since the hydrogen rail industry is more advanced in Europe. The project could have also reached out to firms involved in hydrogen rail efforts in the United States, such as the California Zero-Emission Multiple Unit project.
- The project has two collaborators and plans to present to several other institutions, in addition to the presentation at the Annual Merit Review. It is not entirely clear from the presentation what information or activities from Wabtec were used in the analysis.

### Question 4: Potential impact

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

- Rail applications and LH2 usage are areas in which best practices must be identified and codes and standards must be improved, which aligns excellently with overall goals of the Hydrogen Program.
- Rail is clearly a market that aligns with a high potential for amenability for hydrogen, based on the energy needed and the difficulty to decarbonize with batteries. Both the impact of hydrogen on rail and the impact of rail on the hydrogen market are significant.
- Demonstrating a toolset that industry can use to support compliance with standards and enhance safety in high-volume hydrogen fueling applications will be very valuable as more industries and companies enter the heavy-duty transport, rail, marine, and aviation spaces with hydrogen projects.

- The alignment with DOE goals is not clear. The project does not appear to identify DOE barriers being addressed. It appears to be a project to engage a national laboratory in consulting for Wabtec.

### Question 5: Proposed future work

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

- The future work looks like it rounds out what was planned for the overall project.
- The project is near completion, with successful implementation of scope to achieve its three key objectives. Barriers identified in prior reviewer comments appear to be addressed. The basis for vent stack modeling is unclear. What would also be appropriate is to identify implementing actions to key codes and standards gaps; it is hoped that the final report has such recommendations.
- The future work should also list other future gaps, such as refueling hardware, particularly with regard to its large size. While not directly related to fueling, it would also be helpful to list other potential safety issues with large storage on locomotives, such as travel through tunnels, highly populated areas, and derailment hazards.
- To the extent that this was an experiment in collaboration between laboratory and industry, the lessons learned should be documented.

### Project strengths:

- The project has suitable expertise and attention for performing a quality risk analysis. A fault tree analysis, along with the FMEA, addresses FMEA weaknesses in documenting systemic hazards. The planned completion of a codes and standards gap analysis is valuable.
- QRA is an important tool that is often requested in standards and best practices; it is very helpful to make it more understandable and available to a wider group of users.
- This project is a creative exploration of industry and laboratory partnerships; it resulted in a close partnership.
- This project is a good first step to consider safe refueling of freight locomotives.

### Project weaknesses:

- These locomotives will use a large quantity of hydrogen, so the large flow rates and available hardware should be listed as barriers. There was no discussion or assessment of mobile fuelers, which might be a preferred solution for many railyards, particularly at the beginning while still in demonstration mode.
- FMEAs and QRAs are not as thorough in qualifying system hazards as other methods, especially if data are limited on specific failures. These types of analyses focus on addressing individual equipment failures rather than cascading issues, common cause problems, and overall design inadequacies. The project has done a good job of seeking failure data but has not outlined the sensitivities of the incomplete data. It is hoped that the final report documents sensitivity analyses to qualify the value of the assessment. The system design should hopefully be more detailed in the final report, with qualifications about what specific scope was considered (e.g., complete system, engine fueling, LH2 storage, and engine fuel cell operation).
- It is difficult to follow the process that one would use in applying QRA to a project. While it might be difficult to reduce the process into a “cookbook” approach, it would be helpful if a more step-by-step walkthrough of what was done could be provided. The discussion did not provide an understanding of how locomotive/tender fueling and storage designs were made safer by this work.
- The work does not appear to be on track to produce accomplishments or overcome barriers that advance the Hydrogen Program.

### Recommendations for additions/deletions to project scope:

- If it is not already, the project should complete sensitivity analyses to qualify assumptions and poor-quality failure data. An idea for adding to the scope is to develop and implement a communication and action plan for improving codes and standards, beyond simply publishing data.

- The project should consider adding a "framework" process document above the reports that are noted in the "Proposed Future Work" slide. The document should make the process easier to follow and more applicable to other projects' use.
- The project should provide a clear comparison of relative risk among the various fueling options: H35, H70, and LH2.[1]
- The project should document what was learned and refocus on work more aligned with Hydrogen Program needs.

[1] The numbers in H70 and H35 refer to the pressure at which hydrogen is dispensed.

# Project #SCS-034: Large-Scale Hydrogen Storage – Risk Assessment Seattle City Light and Port of Seattle

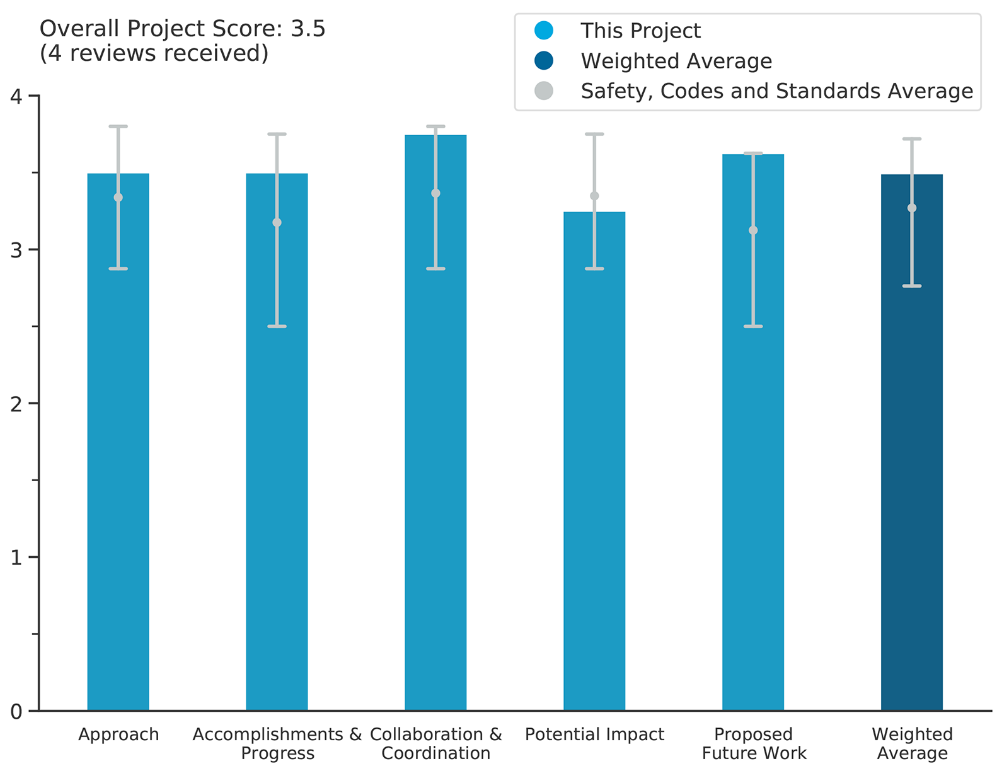
Arun Veeramany, Pacific Northwest National Laboratory

| | |
|---|---|
| **DOE Contract #** | WBS 6.2.0.703 |
| **Start and End Dates** | 9/30/2022–10/16/2024 |
| **Partners/Collaborators** | Sandia National Laboratories, Seattle City Light, Power of Seattle |
| **Barriers Addressed** | • Availability of exact system architecture<br>• Uncertainty in associating multiple hydrogen carriers with various maritime applications<br>• Need for increasing public confidence and understanding in hydrogen as a fuel |

## Project Goal and Brief Summary

This project is performing a preliminary risk assessment of large-scale hydrogen storage, examining early-stage component and system designs. The deployment of hydrogen at the Port of Seattle is a part of a larger vision of using hydrogen to address a range of issues, such as large-scale fueling of heavy-duty vehicles, resilience, and establishment of energy storage as a grid resource. The success of these activities is underpinned by the deployed storage capacity to facilitate large-scale deployment of hydrogen systems. The physical infrastructure and hydrogen use cases for the Port will be analyzed, and a risk assessment for compressed hydrogen, liquified hydrogen, and liquid organic hydrogen carrier (LOHC) storage will be performed. These risk assessments will be useful for understanding how each of these technologies would perform in terms of facility and public safety. The project will also evaluate scalability.

## Project Scoring




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### 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 work combines quantitative risk assessment (QRA), fire modeling, and community engagement with a focus on enabling deployment decisions in the Port of Seattle. The work uses International Organization for Standardization (ISO) 31010 risk assessment techniques, along with Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) modeling capabilities. Of the QRA projects reviewed this week, this project is the most well-considered and reflects understanding of the engineering methods necessary to do the risk analyses correctly using a broad range of models and data, following standardized methods. The project couples this methodology with a well-developed community engagement strategy and a technical advisory board.
- The project barriers are well-identified as a lack of hydrogen infrastructure architecture for large-scale storage of hydrogen, an uncertainty as to which hydrogen carrier would be most effective in maritime locations, and a lack of public understanding and confidence of hydrogen as a fuel. The team does an excellent job of comparing maturity and hazard levels for multiple storage media. The use of cascading failures to support an understanding of the overall risk of release and fire/explosion is a very sound approach.
- The process barriers and objectives were clearly identified.
- While the project is analysis-based, the entire focus of risk management is safety. Slide 6 should be populated with description of the safety culture behind the project team and risk assessment approach. It is understood that the project involved the Hydrogen Safety Panel for independent review; however, the panel’s perspective on the assessment is not discussed in the presentation. There are almost three dozen risk assessment techniques listed in Annex B of ISO/IEC (International Electrotechnical Commission) 31010, including hazard and operability studies, failure mode and effects analyses, and what-ifs. However, the presentation does not identify the techniques used in the analysis or the process for qualifying their usage. Slide 7 notes that “the overall risk estimation is out of scope but can be determined by aggregating risk taking into consideration [an] exhaustive set of initiating events from the master logic diagram.” It is unclear why an overall risk estimation is out of scope for storage. If it is out of scope, it is unclear why it is addressed and how an aggregate could be established just by looking at an exhaustive list of initiating events. The project team clearly defined the barriers. However, these barriers are high-level and not focused on storage-related barriers (focus of risk assessment) or production-related barriers (a major source of other risks).

### Question 2: Accomplishments and progress

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

- The project has made major strides in concluding its tasks, including developing risk scenarios associated with hydrogen releases, comparing multiple storage media and hazards, and understanding how cascading failures can facilitate system design improvement. One notable observation that the project team makes is that current stored fuel quantity thresholds are not risk- or consequence-informed. The team should engage with codes and standards and regulatory committees to address this deficiency.
- The project makes good progress toward setting an example of how QRA can be used to inform public dialogue and adoption in the private sector. The project provides a nice focusing point for bringing together national lab capabilities to do an applied problem, while also transitioning some of those capabilities into the private sector. Meaningful results on slide 11 show nuanced, valuable tradeoffs of different component configurations. However, there are errors on this slide, particularly with respect to counting joints. The risk profiles produced are not particularly insightful; they just multiply the number of components by a random factor. The chart on slide 9 is particularly helpful. The reviewer anticipates even more accomplishments next year.
- The project met its target and objectives and clearly demonstrated its achievements. The poster/presentation listed barriers, challenges, and potential solutions, as well as potential next steps.
- The project poster is well-done and was more than just a reprint and mounting of the presentation slides. A cybersecurity risk assessment is identified as complete on slide 5, yet there are no results noted in the

presentation, nor is there an explanation of why it is used as a discriminator for risk planning. It is unclear why the project is focusing on fuel quantity threshold unknowns since current regulations, codes, and standards should be sufficient at this level of risk assessment for general storage requirements. The pros and cons listed in the table on slide 9 are unclear. It is unclear if they are representative of a risk basis, life cycle cost analysis, energy efficiency, or hazard basis. The fuel equivalency pie charts (slide 4) are great data, but the conversion basis should be referenced (validated generally from https://h2tools.org/hyarc/calculator-tools/energy-equivalency-fuels). The uncertainties included on slide 16 are well-thought-out.

### 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 team has yielded successful results, partly owing to a well-rounded collaborative/cooperative approach with key industry stakeholders that include national labs, utilities, industry, and codes and standards committees. This effort is outstanding.
- One of the project objectives was to include public consultations and discussions. Collaboration is a key aspect of the project and was well-demonstrated. The project also highlights and clearly explains the approach taken with Sandia National Laboratories, the port authorities, and all the impacted parties.
- This project has a strong stakeholder engagement strategy that engages many types of organizations. The use of an advisory board is beneficial
- The stakeholder listing on slide 14 is impressive. The report should qualify the interface scope for each of the listed stakeholders. It is unclear, since the listed firms are identified only as “stakeholders,” what collaborative organizations are involved with review. The presentation could be enhanced by identifying collaborative partners for developing/interpreting failure data and peer review.

### Question 4: Potential impact

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

- The project is impactful and relevant to locations and surrounding regions where large-scale hydrogen storage is necessary to meet the needs of port authorities and utilities trying to decarbonize their footprints. There is also a need to educate the public to gain its confidence and trust in the use of hydrogen as a fuel. The project achieves DOE goals related to greenhouse gas reduction, risk assessment to support codes and standards, and stakeholder engagement.
- The identification of risk factors associated with maritime and city storage applications directly supports DOE goals. The project would be enhanced if a clearer focus on regulation, codes, and standards gaps were identified and planned.
- The project team is making good progress toward identifying risks associated with these large-scale facilities and driving specific, actionable risk-mitigation insights for specific applications.
- Hydrogen deployment is a sensitive topic, even more so within such a specific environment, with a long list of potentially impacted parties. It is essential to develop communication and public awareness. Risk management is key.

### Question 5: Proposed future work

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

- The project team has identified a few remaining challenges and barriers, including identifying operational risks, determining storage footprint (because the energy storage medium of the future is still unknown), and identifying gaps in codes and standards. The team has planned to address operational risks and footprint sizes for various storage media in the coming year.
- The project is planned to end soon, but the team still took a great approach by listing potential future work and barriers to explore.

- The project is near completion. Slide 17 adequately identifies the team's effort to complete the current project scope, but there are no items for potential future scope. It would be valuable to consider formally listing identification of gaps in regulations, codes, and standards for maritime usage, while developing a communications and implementation plan for these gaps..
- The project team needs to significantly scale up the number of scenarios and should address an expanded set of initiating events and system configurations. Overall aggregate risk is not an appropriate technique for driving real-world insights. There should be a focus on using the results of this project to identify scientific gaps and needs that drive further research. For example, the team experienced challenges due to lack of QRA tools. Solving this problem is within DOE's purview and would enable broader impact on the industry. The project team needs to become clearer on failure modes versus mechanisms versus hazards, which are distinct concepts.

### Project strengths:

- The project includes well-developed technical plans, a systematic approach, and efficient use of a technical advisory board. Coupling these strengths with community engagement makes the project quite unique and points to high impact.
- The project has a huge, collaborative interface and strong connections to community input. The final report should describe the effectiveness of the collaborative programs in detail. Using risk-based analysis, patterned after the nuclear industry, can provide a quality high-level evaluation.
- Project strengths include the high impact of the barriers this project is trying to address, namely the safe siting of various hydrogen carriers in large quantities, minimization of risk uncertainty by deriving risk assessment methodologies, and promotion of public awareness through engagement with various stakeholders.
- Risk and safety in-port is currently understudied and an essential part of the hydrogen economy. This project supports exports.

### Project weaknesses:

- This project has no weaknesses.
- It is unclear in some of the scope how risks are being identified and what discriminators are used in qualifying storage risk ranking. The final report should qualify design approaches (e.g., storage volumes) and clear up how the discriminators are used in the table comparisons. In addition, the final report should footnote its references for data in the comparison tables (e.g., explosion hazard bases). The following key risk issues should be discriminators in the evaluation comparison: emergency response; safety issues related to supply access through trucking, rail, or barge; permitting; and workforce experience and training.
- This project is mainly a modeling exercise. The team might face more challenges when implementing large-scale storage in a port.
- The project team needs to resolve some technical limitations of the work.

### Recommendations for additions/deletions to project scope:

- The project is near completion, but the report should ensure that gaps and standards are identified for storage weaknesses in a city and a maritime environment. A follow-up report should qualify optimizing storage approaches for minimizing risk and life cycle cost savings rather than (apparently) sizing only for energy equivalence.
- The project team should focus on using the results of this project to identify scientific gaps and needs that drive further research.
- The project team should continue to look at the remaining challenges and determine the best options and approaches.

# Project #SCS-035: Modeling and Risk Assessment of Hydrogen–Natural-Gas Blends

Austin Glover, Sandia National Laboratories

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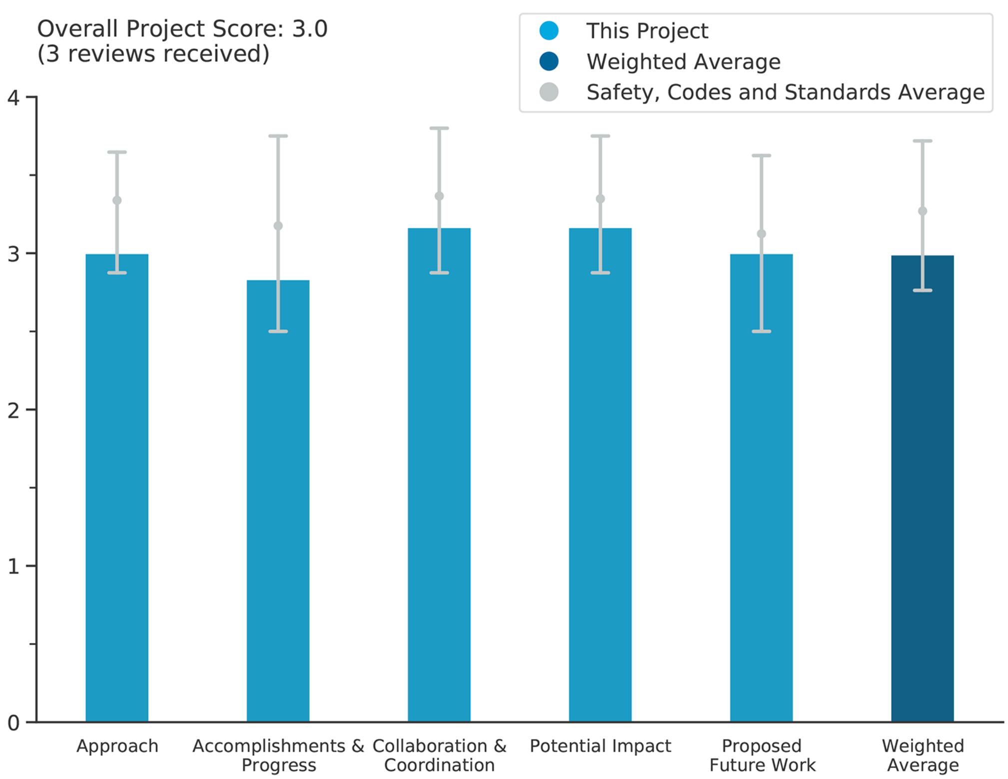
|---|---|
| **DOE Contract #** | DE-NA0003525 |
| **Start and End Dates** | 12/13/2022–11/15/2024 |
| **Partners/Collaborators** | Pipeline Research Council International |
| **Barriers Addressed** | • Risk informed codes and standards<br>• Safe deployment of new blend technologies<br>• Harmonization of electrical codes |

## Project Goal and Brief Summary

The project aims to develop a rigorous scientific and engineering foundation for assessing the safety risks associated with blending hydrogen into natural gas systems. The project seeks to inform and harmonize regulations, codes, and standards (RCS) to support the safe deployment of hydrogen–natural-gas blend technologies. It addresses critical barriers in the safe deployment of hydrogen blending technologies, providing essential data and analysis to inform RCS. By enhancing the safety framework for hydrogen–natural-gas blends, the project supports the broader adoption of hydrogen as a clean energy solution.

## Project Scoring




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- This project intends to develop a rigorous scientific and engineering basis for assessing the differential safety risk of natural-gas–hydrogen blends compared to traditional natural gas compressor stations and investigate the impact of blends in electrical code classification. The approach to performing the work was clear and well-presented. The objectives are clearly identified, and barriers are correctly addressed. This project was not required to submit a safety plan to the Hydrogen Safety Panel (as the work includes only analysis tasks). A diversity, equity, inclusion, and accessibility plan was not required.
- This is a good project about investigating the impacts of hydrogen blends in natural gas pipelines.
- The project objectives are clear but lack a defined pathway for how the outcomes of the project will be validated with real-world performance data from current natural gas compressor stations. Additionally, compressor station component leak data and emission factors do not appear to be incorporated, even though operators are required, via federal code (i.e., 40 Code of Federal Regulations part 98 subpart W), to collect that information.

### Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and DOE goals.

- The project team achieved good progress toward project goals, as detailed in the bullets below.
    - The typical component definition for compressor stations has been developed through a literature survey, expert elicitation, and walkdowns.
    - Leak frequency methodology has been developed, and multiple additional data sources have been identified. Implementation of these sources into the existing data is ongoing.
    - The project team identified multiple methods to calculate blend percentage threshold and performed calculations.
- This project is in one of the research focus areas to meet DOE goals in achieving zero emissions. The project team has demonstrated leadership in the international harmonization of standards for natural-gas–hydrogen blending.
- The still-pending completion of the probabilistic leak rate comparisons (i.e., hydrogen vs. natural gas components) is of some concern, as it appears to be a critical milestone toward conducting the quantitative risk assessment (QRA) of compressor-station-specific components. The final analysis and suggested modifications for electrical classification/group requirements appear to be well within schedule, and the current progress plus proposed future work directly addresses the identified challenge/barrier.

### 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 team has done great collaborative work with Pipeline Research Council International (PRCI) through a cooperative research and development agreement, industry, and work on general design criteria.
- The collaboration with PRCI is effective and well-coordinated.
- The project team's strategy of connecting and coordinating with PRCI members is excellent for obtaining the most comprehensive information from natural gas compression operators that are also forward-looking in the sense of research and development (R&D) investments and implementation of decarbonization strategies. However, there are still many natural gas companies and utilities that operate legacy equipment and may have outdated technologies that may need to be considered for component QRA. One suggestion for the project team is to reach out also to the Interstate Natural Gas Association of America or American Gas Association for additional input.

### Question 4: Potential impact

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

- The project is very supportive of developing risk-informed codes and standards that can be directly applied by natural gas operators seeking to incorporate hydrogen safely. The harmonization of electrical classification codes incorporating hydrogen–natural-gas blends specifically is also a critical area that this project aims to address on behalf of the industry.
- The project aspects align with the Hydrogen Program's goals and objectives in terms of facilitating the creation, adoption, and harmonization of RCS for hydrogen and fuel cell technologies. The project is performing R&D to inform deployment and enable compliance with RCS.
- This project team has done a great job facilitating the creation, adoption and harmonization of RCS for hydrogen. In addition, the project team is performing R&D to inform compliance with the regulations.

### Question 5: Proposed future work

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

- The proposed future work is to complete the critical tasks laid out at the onset of the project. A more detailed plan on how the results of this work will be communicated to various codes and standards organizations would help operators understand the timeline for having such documentation available for them to reference and what specific steps they can take to support that effort.
- The future work presented is correctly mapped out and detailed, focusing on two areas: differential risk assessment and electrical code classification.
- The project team is conducting significant work on risk assessment modeling and electrical code classification.

### Project strengths:

- The project attempts to address a critical gap for existing natural gas compressor operators considering blending increasing concentrations of hydrogen into natural gas. Neither the current electrical classifications nor the current fire codes properly address hydrogen–natural-gas blends. Additionally, having a harmonized risk assessment method and recommendations for component modification has the potential to streamline the energy transition for a traditionally slow-moving industry.
- One strength of the project is the team's effort to validate reduced-order models and tools to support a safer deployment of new natural-gas–hydrogen blend technologies.
- This is another great project on modeling the risks of hydrogen blending.

### Project weaknesses:

- Although holistically the project aims to address knowledge gaps for natural gas compressor stations, the two primary objectives are distinct enough that they warrant dedicated project scopes. Electrical classification for compressor station components is ultimately governed by the National Fire Protection Agency code committee comprising various industry stakeholders. Without their involvement with this project, the industry (i.e., natural gas compressor operators) will be hard-pressed to convince the code committee to make any recommended changes using the outcomes of this project alone. Related to the risk assessment model this project aims to develop, a missing component to the scope of work is ultimately validating the end results against current natural gas compressor station characteristics, which vary widely from operator to operator and across the country.
- One weakness of the project is the limited availability of natural-gas–hydrogen blend leak frequency data for relevant conditions.
- Some of the potential weaknesses or challenges are the lack of frequency data for pipelines and assessment of the uncertainty in leak frequency methodology for the differential risk assessment.

### Recommendations for additions/deletions to project scope:

- The project team should extend this work to international codes and standards (the current focus is on the United States only). There should be exchanges with working groups on the international harmonization of standards for natural-gas–hydrogen blends, including compressor stations. HyRAM is an integration model of different sub-models (all sub-models validated). This model can be used to simulate scenarios. A good addition to the project scope would be a real validation of HyRAM in a facility.
- The project team should incorporate guidance for codes and standards organization front-end involvement and feedback and establish a communication channel between codes and standards organizations, operators, and the national lab.

# Project #SCS-036: Electrical Hydrogen Sensor Technology with a Sub-Minute Response Time and a Part-Per-Billion Detection Limit for Hydrogen Environmental Monitoring

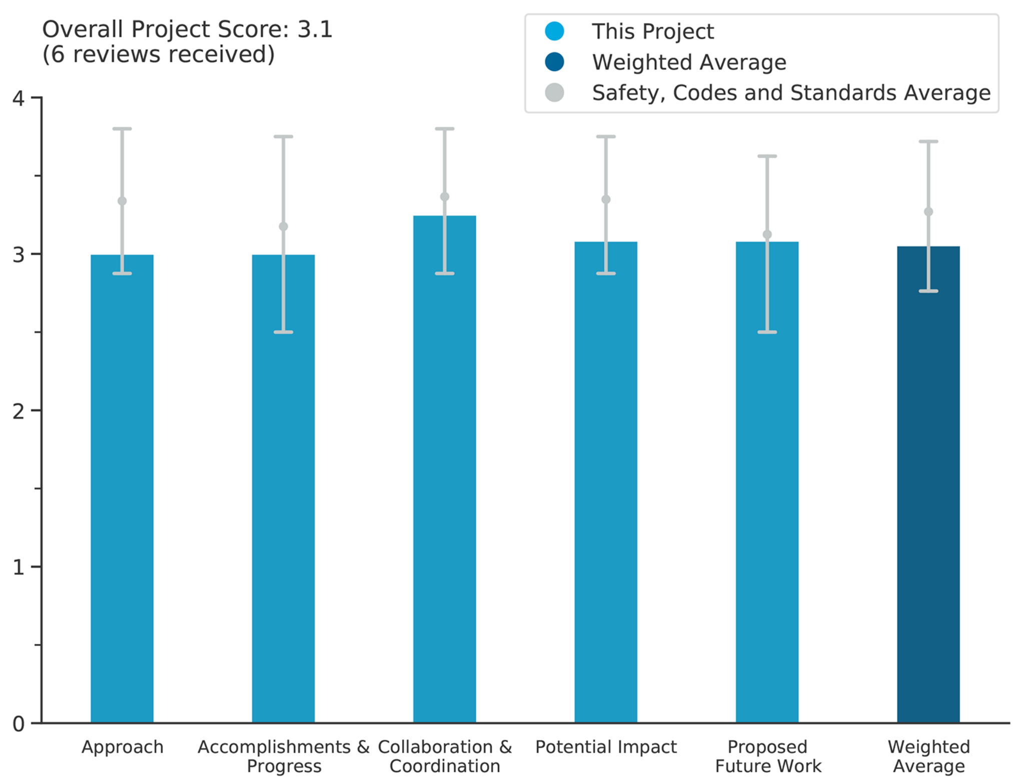
Tho Nguyen, University of Georgia

| | |
|---|---|
| **DOE Contract #** | DE-EEDE-EE0010743 |
| **Start and End Dates** | 10/1/2023–9/30/2026 |
| **Partners/Collaborators** | Savannah River National Laboratory, Southwest Research Institute, National Renewable Energy Laboratory, Pacific Gas & Electric Company, Indrio Technologies |
| **Barriers Addressed** | • Using a single sensor to simultaneously achieve the response time of <30 seconds at sub-parts-per-million hydrogen concentration, parts per billion limit of detection, and a 10-year lifetime |

## Project Goal and Brief Summary

This project is addressing the challenge of hydrogen environmental monitoring by developing a field-deployable hydrogen sensor with a sub-minute response time and a parts-per-billion (ppb) detection limit, enhancing safety and efficiency in hydrogen infrastructure. The project also focuses on overcoming key challenges such as achieving sub-parts-per-million (ppm) sensitivity, ppb limit of detection (LOD), and a 10-year lifespan. Utilizing nanosphere lithography and glancing angle co-deposition, the project optimizes nanostructures (e.g., nanowires and nanoholes) to minimize surface-to-volume ratio. Metal hydride composites and multilayers such as $Pd_{80}Co_{20}$ are fine-tuned to enhance reaction kinetics and resistance to environmental factors.

## Project Scoring




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Project SCS-036 intends to develop a field-deployable hydrogen sensor with environmental monitoring capabilities by exploring novel nano-designs, optimal composite hydrides, innovative polymer coatings, and appropriate sensor packaging and integration. The approach to performing the work was clear and well-presented. The objectives are clearly identified, and barriers are correctly addressed. The project is structured in different sub-tasks tackling the different areas of the project: research and development of high-performance sensors (University of Georgia [UGA], Savannah River National Laboratory [SRNL]); sensor integration (UGA, Indrio Technologies [Indrio]); and simulated field testing (Southwest Research Institute [SwRI], Pacific Gas & Electric Company [PG&E], and the National Renewable Energy Laboratory). This project was required to submit a safety plan for review by the Hydrogen Safety Panel (HSP). The comments from the HSP will be studied and addressed in the revised safety plan. A diversity, equity, inclusion, and accessibility (DEIA) plan was required by this project. The milestones are below:
    - DEIA training is followed by the principal investigator (PI), co-PI, and task leaders. They will craft presentations tailored for specific target audiences. Team members have established connections with minority-serving institutions (MSIs), facilitating the identification of target audiences for the outreach effort.
    - Four MSIs (Clark Atlanta University, Georgia Gwinnett College, Savannah State University, and Fort Valley State University) in underserved areas were identified to develop a relationship for giving presentations. Each of the four home base cities of the team will receive a presentation.
    - Two presentations for educational purposes will be developed in each billing period.
- The approach seems well-thought-out and efficient. The project has both a safety plan, which has been reviewed by the HSP, and a DEIA plan. The team claims to have addressed the issues raised during the safety plan review. The summary slide for safety in the presentation is done well, and the project appears to have adequately addressed the issues. The DEIA summary does about as much as can be done for a highly technical research project. No information is provided regarding a future field deployment and testing, as described on slide 5.
- The project has defined very clear targets for success with specific measurable goals/metrics. The project appears to have put together a robust safety plan and placed a high priority on safety with all involved parties.
- The approach is one of systematically changing parameters to get the desired response from the material—in this case, $Pd_{80}Co_{20}$. The innovation here is to optimize the nanostructure design (sensing material, support, and coatings). The nanostructure, responsive material, and kinetics improvement will be sought after by systematically changing the control parameters of the system. There was a nice discussion on DEIA.
- The project vision includes a good deal of ground to cover in creating a "hydrogen sensor with environmental monitoring capabilities by exploring novel nano-designs, optimal composite hydrides, innovative polymer coatings, and appropriate sensor packaging and integration." Consequently, it became unclear at times how to weigh the nanostructure design improvements as a path to improvement vs. other approaches. If it is a complicated multi-parameter space, it is not clear how will it be optimized—and with what experimental design approach.
- The project needs to look at commercialization of the technology with industry partners, which is missing. There is too much focus on research-related issues.

### Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- The project accomplishments to date have demonstrated the feasibility of achieving overall project success of 30-second response time at 600 ppb.
- The project has systematically enhanced the surface-to-volume ratio (SVR) and hydrogen kinetics in the composite nano-hole arrays (CHA) sensor and has achieved the milestone proposed in the statement of

project objectives. The result provides a positive trend to achieve the ultimate goals by further maximizing the SVR, optimal sensing composite, and appropriate polymer/molecule coatings.

- This project just got started (October 2023). The results so far are promising.
- This was clearly presented. It was helpful to see the performance data.
- Moderate progress has been made, but there are weaknesses that need to be addressed. The main achievements include controlling the thickness and hole diameter of the CHA sensors to maximize the SVR and achieved the proposed milestones for the quarter ($t_{90}$= 2 s at $10^3$ ppm).
    - The response time decreases and the sensitivity increases for better SVR CHA structures.
    - The project achieves $t_{90}$=460 s at 500 ppb, which is still much larger than the final goal of 30 s at 600 ppb.
    - Sensitivity of 0.11% at 500 ppb with the high signal-to-noise ratio shows promise of achieving the LOD of several ppb.
    - Current results indicate that the approach to achieve the goals (response time of 30 s at ~600 ppb and 10 ppb LOD) is feasible.

  A comprehensive plan for achieving the ultimate goals has been outlined. However, there is a considerable amount of work ahead to achieve the ambitious targets in just two years. New composites (PdxAy) need to be developed and tested. Only composites with cobalt (PdxCoy) have been tested. Composites using gold (PdxAuy) and silver (PdxAgy) have long response times, so they are not promising. However, there is potential for composites with V, Ti, or Mg. The development and testing of these composites must accelerate to achieve the targets.

- The project has provided numerous accomplishments and a summary explaining each one. The sensor is described as low-cost and affordable, but there are no details provided to compare this new sensor to existing technologies to confirm. No economic analysis is included.

### 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.

- The project has a variety of institutional partners that are well-suited and qualified for the topic. The presentation also included a comment that additional organizations will be included as needed as the project progresses, as well as an excellent slide specifically targeted at evaluating effectiveness. Including a sensor manufacturer is an excellent step to hopefully assess the technology in a practical and pragmatic manner.
- The collaboration is effective, and the coordination is fostered by sharing resources and exchanging researchers and by holding regular group meetings. There are updates on new achievements, facilitating the exchange of ideas, materials, and equipment within a group or between the groups/teams. Each group at its own research institution meets once a week, the sensor research and development group holds a monthly meeting, and all project partners participate in a bimonthly group meeting.
- The project demonstrates very strong collaboration by pulling together many key stakeholders and subject matter experts by leveraging each of their expertise toward the established goal.
- The team consists of university, national laboratory, and industrial partners. All are appropriate and add value to the team.
- This is early, and while the roles are clear in the plan and approach, the activities at this stage are light. At this point, the activities are not tightly linked to milestones or commercialization outcomes. Hopefully as much collaboration emphasis is given to the market and commercialization aspects as to the fundamental research aspects.
- The PI is Tho Nguyen and the co-PI is Yiping Zhao, of UGA. Other team members include George Larsen and Taylor Guin or SRNL; Matthew Gacek, Angel Wileman, and Sarah Wheeler of SwRI; William Buttner and David Peaslee of SRNL; Kevin Pease of PG&E; and Rito Sur of Indrio. The partners are mainly academic or research institutions. The team is weak on industry and commercialization partners.

### Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- The project aspects align with the Hydrogen Program's goals and objectives in terms of advancing hydrogen sensor technology for high hydrogen sensitivity and selectivity. The project has the potential to overcome current barriers on fast and accurate sensing of hydrogen losses at the ppb level by developing novel sensor composites (nano-designs and free-standing nanostructures) and an innovative approach on sensor integration.
- The development of this technology has the potential to make a deep impact on the success of the growing hydrogen economy. Having affordable and reliable hydrogen sensor technologies capable of detecting at the ppb level will inform climate science and enhance the science community's understanding of hydrogen's true indirect global warming impact.
- This project is clearly targeted at getting very low detectability suitable for environmental leaks to get a handle on the greenhouse gas (GHG) consequences of a hydrogen leak. While hydrogen itself is not a GHG, it can and does interact with other species such as OH in the atmosphere, creating water, which is a very strong GHG. Understanding this is critically important to the advancement of hydrogen as an energy carrier.
- The impact and advantages of being able to detect and measure ppb levels of atmospheric hydrogen can be significant. However, slide 8 mentions the use for leak detection but does not explain why detection levels that low would be additionally useful when compared to more traditional high ppm detectors from a safety perspective.
- Some improved clarity on benchmarking against the state of the art along all the market adoption considerations might be helpful. Some recently published work (https://pubs.acs.org/doi/suppl/10.1021/acssensors.4c00251/suppl_file/se4c00251_si_001.pdf) should have been referenced. Clearer reference to a probability of detection that is associated with a given level of detection might help translate the lab results into a more explicit deployment context.
- The anticipated impact of proposed research is to achieve a low-cost, high-performance hydrogen sensor for hydrogen component leak rate quantification. Specifics are missing.

### Question 5: Proposed future work

This project was rated **3.1** for effective and logical planning.

- The plan for future work has several goals and milestones that are directly applicable to the project goals. Importantly, the project also provides quantified goals with a clear metric for success.
- The project has a very detailed and specific set of next steps for future work toward achieving project overall goals.
- The proposed future work is appropriate for this effort.
- The future work presented is detailed, and sub-tasks have been provided. It will focus on three tasks:
    - Achieving high-performance electrical hydrogen sensors with a response time of 1 s and LOD <10 ppb by (1) optimizing SVR, composition, polymer coatings of the CHA sensors and (2) developing a one-dimensional (1D) nanowire array and two-dimensional (2D) nanowire network.
    - Achieving high-stability sensors against environmental atmosphere changes and improving hydrogen (de)sorption kinetics.
    - Designing and building an integrated hydrogen sensor system and evaluating the sensors in indoor and outdoor simulated tests.

  However, there is a considerable amount of work ahead to achieve the ambitious targets in just two years. New composites (PdxAy) need to be developed and tested. Only composites with cobalt (PdxCoy) have been tested so far. Composites using gold (PdxAuy) and silver (PdxAgy) have long response times, so they are not promising. However, there is potential for composites with V, Ti, or Mg. The development and testing of these composites must accelerate to achieve the targets.

- The proposed future work highlights continuing work on the subtasks outlined in Task 1.0 of the project: "To achieve high-performance electrical H2 sensors with response time of 1 s at CH2 = 1×102 ppm or lower and LOD <10 ppb (until March 31, 2025)." The specific plan is:
    - To continue optimizing the SVR, composition, polymer coatings of the CHA sensors.
    - To achieve a high-performance sensor with a 1D nanowire array and 2D nanowire network. These structures might provide a better SVR and hence better performance.
    - To start working on Task 2.0: "To achieve sensors with high stability against environmental atmosphere changes and improve H2 (de)sorption kinetics (January 1, 2024 −March 31, 2026)." The specific plan is (1) to improve hydrogen sorption/desorption kinetics by depositing a novel polymer coating to get a fast response time t=90~30 s at $CH_2$ <10 ppm; and (2) to enhance the sensor's resistance to poisons ($O_2$, CO, $CO_2$, hydrocarbons, and humidity) by depositing novel multilayer nanocomposite coatings.
    - To design and build an integrated hydrogen sensor system and to evaluate the sensors in the indoor and outdoor simulated tests (Task 3: November 2025). The project needs to look at commercialization of the technology with industry partners, which is missing.
- Regarding technology transfer, it is noted that alternative funding sources will be sought. It is unclear what role Indrio is playing or whether Indrio intends to help with commercialization.

## Project strengths:

- The team is solving key challenges (sub-minute response time [t 90 at sub-ppm $H_2$ concentration], ppb LOD, high selectivity, and long lifetime) for a field-deployable hydrogen sensor with environmental monitoring capabilities. The approach involves exploring novel nano-designs, optimal composite hydrides, innovative polymer coatings, and appropriate sensor packaging and integration.
- The project has a sound plan for achieving success with clear metrics. The project also has a very robust collaboration network established to leverage critically diverse skillsets across research and industry communities.
- The project is developing innovative sensor composites based on nanocomposites and nanostructures. The sensors will be evaluated in indoor and outdoor simulated tests.
- The project team is broad and certainly encourages further collaboration as needed. The team also has demonstrated technical competency.
- This is an important activity and is planned for execution in a rational, systematic manner.
- The project clearly intends to cover much of the parameter space for the technical approach.

## Project weaknesses:

- No significant project weaknesses were identified.
- An economic analysis is needed to validate the claim that the new technology is affordable. This claim should be backed up with manufacturing cost estimates, along with a fully packaged target price to the market. Often the "sensor" is inexpensive, but the fully packaged price is no better than today's technology.
- There is a considerable amount of work ahead to achieve the ambitious targets in just two years. Significant barriers still need to be overcome to achieve the project targets (e.g., significantly reducing sensor response time at the required LOD).
- The project needs to look at commercialization of the technology with industry partners, which is missing. There is too great of a focus on research-related issues. The DEIA can be strengthened.
- Attention to ownership/roles in commercialization seems secondary at this point, which may be appropriate given the early stage, but some commercialization activities can take a long time and should be pursued in parallel where possible.

### Recommendations for additions/deletions to project scope:

- There are no recommendations at this time, other than an encouragement to accelerate commercialization considerations. The benefits and needs are already called out under the Potential Impact slide of the presentation.
- The project should develop a detailed cost estimate for a completed sensor package. The project should provide details of the proposed test of an autonomous sensor at an industrial location to validate its robustness and suitability in the field.
- Assessment and validation of sensor lifetime should be added to the project scope, as a lifetime target of 10 years is to be achieved. Assessment of sensor costs should be added to the project scope.
- The team needs to look at commercialization of the technology with industry partners, which is missing. The DEIA can be strengthened.

# Project #SCS-037: Sensing Hydrogen Losses at One-Part-Per-Billion Level for Hydrogen-Blending Natural Gas Pipelines

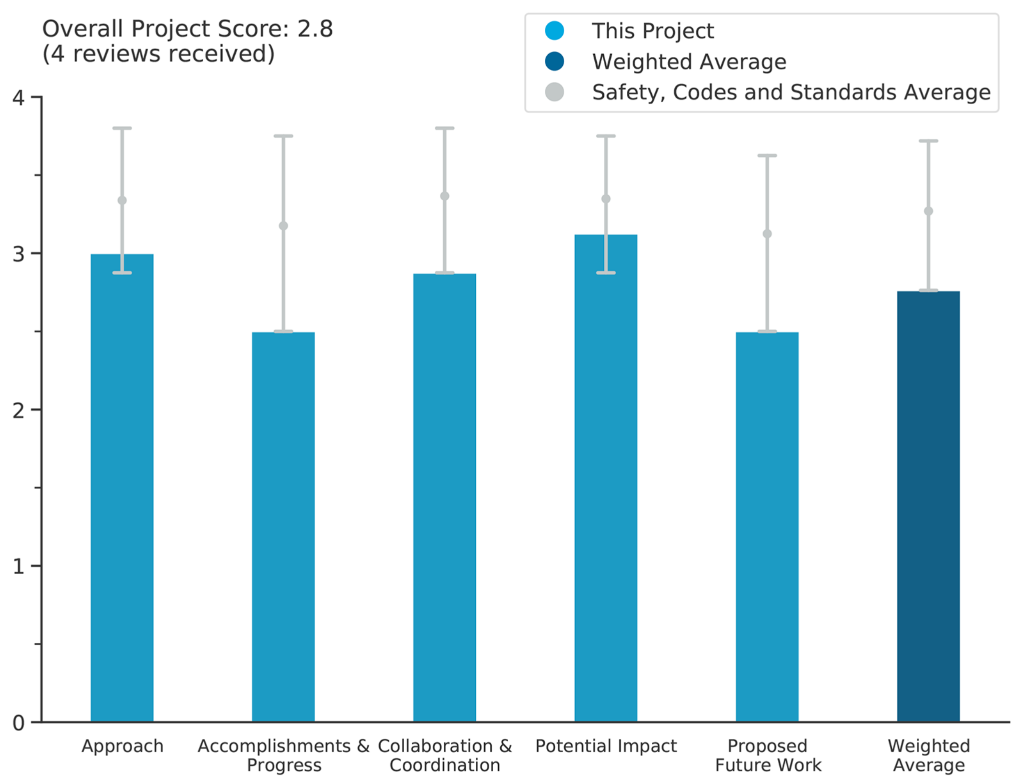
Shan Hu, Iowa State University

| | |
|---|---|
| **DOE Contract #** | DE-EE0010742 |
| **Start and End Dates** | 10/1/2023–9/30/2024 |
| **Partners/Collaborators** | Michigan Technological University, National Renewable Energy Laboratory, Pacific Gas & Electric Company, Wichita State University |
| **Barriers Addressed** | • Commercial sensors with detection limits in parts per million level and environmental hydrogen concentration in parts per billion (ppb) level<br>• Low sensing accuracy and selectivity at ppb level<br>• Signal drift in outdoor application with fluctuating environment |

## Project Goal and Brief Summary

This project is addressing the challenge of accurately quantifying hydrogen losses at the parts-per-billion (ppb) level from hydrogen-blending natural gas pipelines, where current commercial sensors detect only at parts-per-million (ppm) levels and suffer from low accuracy and signal drift in fluctuating environments. This project also integrates a hydrogen pump to selectively purify and concentrate ppb-level hydrogen to ppm levels in the sensor chamber, a nanostructured metal oxide semiconductor sensor for accurate and fast detection, and machine learning modules to predict hydrogen concentration and offset drift caused by ambient condition changes. The sensor aims for a sensing limit of 1 ppb, a range of 1–10,000 ppb, and a response time of ≤30 seconds.

## Project Scoring




The vertical hash-lines represent the highest and lowest average scores received by Safety, Codes and Standards projects.

### Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing objectives and barriers and for project design, feasibility, and integration with other relevant efforts.

- Project SCS-037 intends to develop an integrated solution to perform fast and accurate quantification of hydrogen losses from hydrogen-blending natural gas pipelines with high selectivity against interferent gases (e.g., components of natural gas) and high robustness against ambient parameter changes. The approach to performing the work is well-presented. The objectives are clearly identified and barriers correctly addressed. The project is structured into different sub-tasks tackling the different areas of the project: hydrogen sensor (Iowa State University [ISU]) and hydrogen pump development (Wichita State University [Wichita State]); hydrogen pump sensor integration (ISU and Wichita State); sensor data analytics (Michigan Technological University [Michigan Tech]); third-party validation (National Renewable Energy Laboratory [NREL]); and field testing (Pacific Gas & Electric Company [PG&E]).
    - This project was required to submit a safety plan for review by the Hydrogen Safety Panel (HSP). The team received review comments on February 14, 2024, and is still working on addressing all the comments. The project is incorporating best safety practices and lessons learn to prioritize safety by (1) performing leak tests on gas lines every month and each time gas cylinders are changed; (2) installing a hydrogen gas leak detector near the cylinders to alarm researchers when hydrogen concentration exceeds 25% of the lower explosive limit and establishing an emergency response; and (3) having each organization develop plans for reporting incidents and near-misses.
    - A diversity, equity, inclusion, and accessibility (DEIA) plan was required by this project. The progress has been constant. Three milestones were set: (1) recruiting researchers from underrepresented groups in science, technology, engineering, and mathematics (STEM) into the project team by delivering recruitment materials encouraging applicants from underrepresented minority (URM) groups to minority-serving institutions and campus minority-serving organizations (Women in Science and Engineering); (2) fostering an inclusive and safe environment for all researchers to thrive by providing researchers with training opportunities on diversity, equity, and inclusion (DEI) (e.g., "Diversity Awareness at Work" and "Unconscious Bias"); and (3) collaborating with campus diversity groups for education and outreach activities to encourage URM students to pursue STEM careers.
- The project team's approach is very sound, incorporating a diverse set of feedback loops, including participation of a national lab and an industry partner, utilization of the HSP's expertise, and third-party field test validation for continuous improvement of sensor technology.
- The project utilizes a unique approach to achieve ppb-level sensitivity using the hydrogen pump. The principle, function, and design of the hydrogen pump needs to be better explained in future updates. Selectivity against other gases relies on the catalyst, especially methane ($CH_4$), considering the application in loss monitoring of hydrogen–natural-gas blending. Additionally, the response time needs to consider the response time from the integrated system, including the hydrogen pump. Similarly, the hydrogen pump must be considered in cost and size of the integrated system.
- The project is developing an integrated solution to perform fast and accurate quantification of hydrogen losses from hydrogen blending in natural gas pipelines with high selectivity against interferent gases (e.g., components of natural gas) and high robustness against ambient parameter changes.

### Question 2: Accomplishments and progress

This project was rated **2.5** for its accomplishments and progress toward overall project and DOE goals.

- Considering this is a new project, it has made good progress in simulation of the hydrogen pump and the prototype of the ppm-level hydrogen sensor. If the hydrogen pump can work as modeled and expected, this approach would work.
- The project has completed multiphysics simulation of the hydrogen concentration ramping by the hydrogen pump operation; developed a design of the hydrogen pump geometry and operation conditions to achieve 10 ppb to 11.6 ppm; hydrogen concertation ramping from the external to internal chambers; synthesized hydrogen-sensing materials and fabricated a hydrogen sensor electrode; and conducted a lab test of the first-generation hydrogen sensor electrode, which delivered a detection limit as low as 1 ppm.

- It is a very short project (one year), and significant progress has been made, but there are weaknesses that need to be addressed to improve the rate of progress and overcome some barriers. The results obtained are positive, demonstrating the innovative concept of an integrated hydrogen pump and hydrogen sensor coupled with machine learning to achieve the ambitious sensing limit, accuracy, and selectivity. The hydrogen pump can sustain a hydrogen concentration of 11.6 ppm in the internal sensing chamber when there is 10 ppb hydrogen in the external chamber. Novel hydrogen sensing materials were synthesized and hydrogen sensor electrodes fabricated. Lab tests of the first-generation hydrogen sensor electrode were conducted, delivering a detection limit as low as 1 ppm. However, there are only few months left, and considerable work is pending (e.g., reducing sensor response time, third-party lab testing, and field testing).
- Project progress to date appears reasonable, although it is not clear what the initial expectations and key milestones were. Also, the full project timeline appears to only be one year, and with only half of that timeline remaining, it is uncertain whether there is sufficient time for thorough field trials with continuous improvement to reach core targets.

### 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 are numerous partners in the project: ISU is in charge of hydrogen sensor development; Michigan Tech is tackling sensor data analytics; NREL is conducting third-party validation; PG&E Company is a field test partner; and Wichita State is in charge of the hydrogen pump development. The collaboration seems smooth and fairly well-coordinated.
- The partners are Iowa State University (Shan Hu), doing project management, coordinating, reporting, and leading development of the hydrogen sensor; Michigan Tech (Yixin Liu), a subcontractor leading machine learning sensor data analytics; NREL (William Buttner), a subcontractor conducting third-party validation of sensing performance; PG&E (Kevin Pease), a subcontractor acting as a partner for field testing and demonstration; and Wichita State (Shuang Gu).
- This project demonstrates strong collaboration between the research community and industry stakeholders; however, it is not clear at what stage industry partners are engaged in development of the technology.
- The team consists of partners from other universities, industry, and NREL.

### Question 4: Potential impact

This project was rated **3.1** for supporting and advancing progress toward Hydrogen Program goals and objectives.

- This project directly addresses the DOE objective to develop hydrogen sensor technology capable of reliably detecting and quantifying at the ppb level. Additionally, this project specifically targets hydrogen–natural-gas blending applications, which is of rapidly growing interest in the natural gas industry as gas operators seek to decarbonize their systems. Having reliable technology for a future with hydrogen–natural-gas blends in energy delivery is a key enabler of such applications.
- The project aspects align with the Hydrogen Program’s goals and objectives in terms of advancing hydrogen sensor technology for high hydrogen sensitivity and selectivity. The project has the potential to overcome current barriers on fast and accurate sensing of hydrogen losses at the ppb level by using strategic integration of a hydrogen pump, hydrogen sensor, and machine learning.
- Hydrogen has an indirect impact on global warming. Measuring and quantifying hydrogen loss from infrastructure contribute to evaluating and addressing the global warming impact of hydrogen technologies. The commercial hydrogen safety sensor’s detection limit is at the ppm level. Atmospheric hydrogen concentration is at the ppb level.
- The impact would be to improve hydrogen sensitivity and might enable other types of ppb sensors if the hydrogen pump method works.

### Question 5: Proposed future work

This project was rated **2.5** for effective and logical planning.

- Future work involves designing a new generation of hydrogen pump electrodes that have much lower background current, stabilizing the hydrogen sensor electrode's baseline resistance, developing a strategy to reduce the response time, and establishing a clear plan for commercialization of the technology missing. There is a need to strengthen DEI initiatives.
- The proposed future work does address specific challenges identified in the project's progress to date.
- Proposed future work aligns with the objective and is based on the progress and lessons learned so far. The hydrogen pump working principle needs to be better explained and validated in future updates.
- There are only a few months left on the project, and there is considerable work pending (reduced sensor response time, lower background current on the hydrogen pump, third-party lab testing, field testing, etc.). The future work presented is detailed and will focus on three areas: designing a new generation of hydrogen pump electrodes that have much lower background current, establishing the hydrogen sensor electrode's baseline resistance, and developing a strategy to reduce the response time. The current response time of the sensor is about 300 s, and the target value is one order of magnitude lower (30 s). Additionally, third-party lab testing and field testing of the prototype are not mentioned and seemed to be delayed, if performed at all within the project.

### Project strengths:

- The project's greatest strength is taking direct aim at a very real and immediate barrier for the natural gas industry to help grow the hydrogen economy. The development of these types of sensing technologies will have a direct impact on how quickly natural gas operators can evolve into transporters of hydrogen molecules safely and reliably. The project demonstrates awareness of such by including a natural gas operator as one of its collaborators.
- The concept for sensing low concentrations of hydrogen is innovative. The developed prototype will be subjected to third-party and field testing.
- The approach with the hydrogen pump method is interesting. The team has also shown strength in hydrogen sensing materials and prototyping.
- The project develops an integrated solution to perform fast and accurate quantification of hydrogen losses from hydrogen blending in natural gas pipelines with high selectivity against interferent gases (e.g., components of natural gas) and high robustness against ambient parameter changes.

### Project weaknesses:

- The project duration is only one year, and there is still much work to be done with the few months left. It seems that third-party lab testing and field testing will not be carried out since they were not mentioned. Significant barriers still need to be overcome to achieve the project targets (e.g., reduced sensor response time).
- Perhaps it is not a weakness at this time, but the short timeline for achieving all project objectives may lead to rushed analysis or even incompleteness. This is an important project for the industry, and helping this technology reach its full potential should be prioritized.
- The hydrogen pump, as the unique part of the system, needs more progress. Also, the integrated system needs a holistic design (at least a conceptual design) early in the project.
- The research has too much of an academic focus. A clear plan for commercialization of the technology is missing. The DEIA initiatives need to be strengthened.

### Recommendations for additions/deletions to project scope:

- One recommendation to the project team is to seek industry partner (i.e., PG&E) feedback early in the development process to ensure both the sensing elements and hydrogen pump progress in a way that will be compatible with operator requirements. If the project aim is to develop a portable hydrogen sensing tool, the operator's feedback on how such tools are typically utilized and handled may heavily influence the practicality of the technology.
- There is a need to engage industry partners. A clear plan for commercialization of the technology is missing. The DEIA initiatives need to be strengthened.
- An assessment of sensor lifetime is needed. It is a short project to assess durability, but this is an important requirement that should be added to the project scope.
- There are no recommendations at this point.